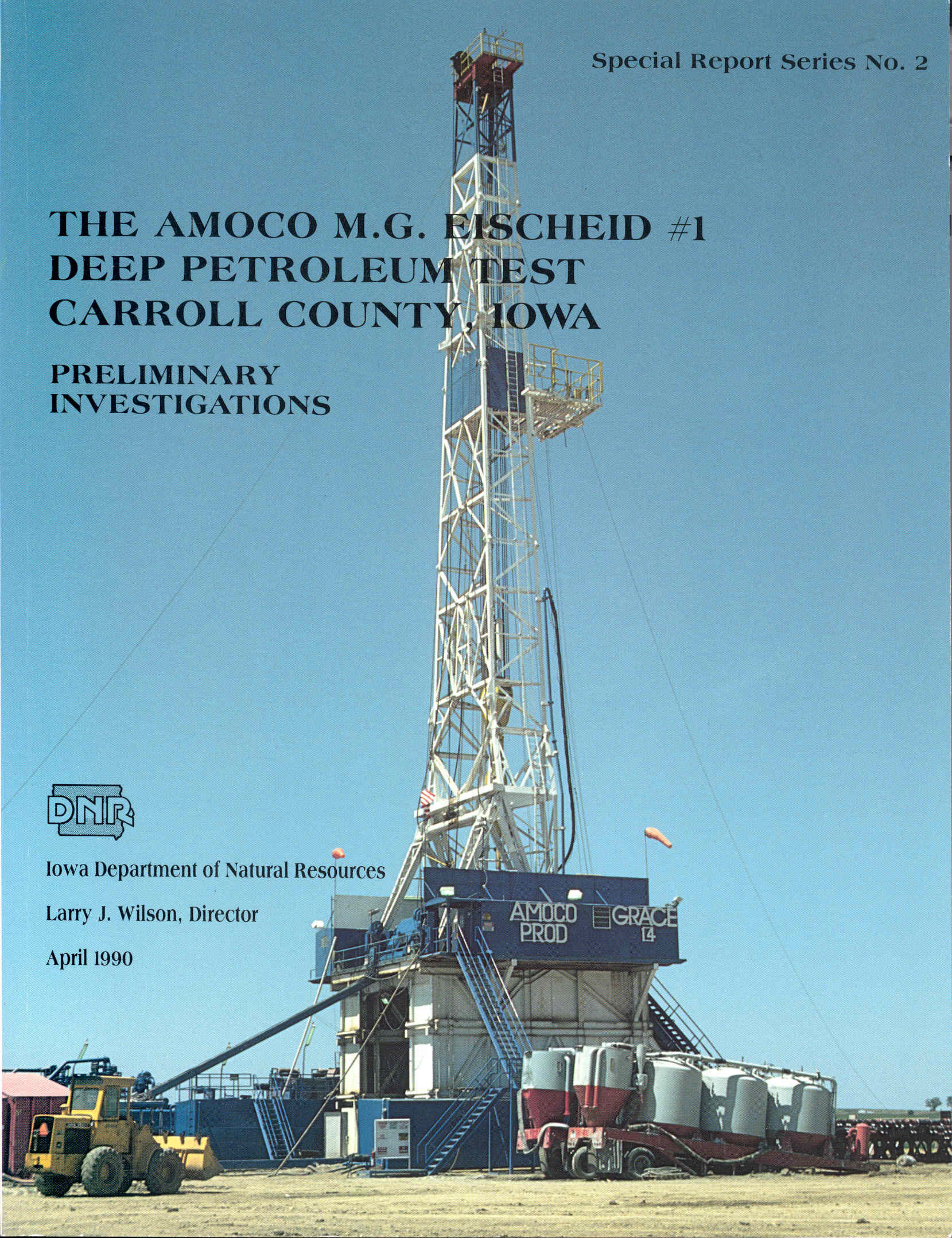
Special Report Series No. 2

THE AMOCO M.G. EISCHEID #1 DEEP PETROLEUM TEST CARROLL COUNTY, IOWA

PRELIMINARY INVESTIGATIONS



Iowa Department of Natural Resources

Larry J. Wilson, Director

April 1990

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Edited by
Raymond R. Anderson

Energy and Geological Resources Division
Geological Survey Bureau

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EXECUTIVE SUMMARY

INTRODUCTION

In 1987, Amoco Production Company drilled the M.G. Eischeid #1 petroleum exploration well northeast of the town of Halbur in west-central Carroll County, Iowa (NW 1/4, NW 1/4, SE 1/4, Sec. 6, T.83N., R.35W.). The Eischeid well was Amoco's first test of the petroleum potential of the Midcontinent Rift System (MRS), a failed rift in the crust that formed about one billion years ago and which extends from central Lake Superior to central Kansas. The history of the MRS is reviewed by Anderson (Review of Precambrian...," this volume) and its structure is discussed by Anderson ("Interpretation of geophysical data...," this volume). Although petroleum is unusual in rocks as old as those of the MRS, small amounts of oil have been collected from MRS clastic rocks (sandstones, siltstones, and shales) in the Lake Superior area.

The Eischeid well reached a total depth of 17,851 feet, far surpassing the 5305-foot depth of the previously deepest well in Iowa. The well penetrated 2802 feet of Phanerozoic (540 million old years to present) sedimentary rocks, 14,898 feet of Proterozoic (2500 to 540 million years old) MRS clastic rocks, and 185 feet of Proterozoic igneous intrusive rocks. No liquid petroleum was reported during the drilling, but minor occurrences of gaseous hydrocarbons were detected within the Proterozoic. The well was subsequently plugged and abandoned.

Drill cuttings were collected generally at 10-foot intervals; five cores totalling 72 feet in length were drilled; and a series of down-hole logs were produced. These data were released to the Iowa Department of Natural Resources Geological Survey Bureau (GSB) in the fall of 1989 for study and the preparation of this volume. Under the direction of the GSB, a series of investigations was initiated by geologists from the GSB, U.S. Geological Survey, and from the academic community. These studies were primarily directed toward evaluating the petroleum potential of the MRS clastic rocks encountered in the drilling.

RESULTS OF INVESTIGATIONS

Witzke (this volume) studied the stratigraphy of the rocks encountered during the drilling of the Eischeid well. The Phanerozoic section was typical of the rock strata encountered in other wells in the area. Only the basal Phanerozoic unit, the Cambrian Mt. Simon Sandstone, produced any new interpretations. Based on new information from a related study (McKay, this volume) only 20 feet of Mt. Simon strata were identified in the Eischeid well. The underlying 813 feet of clastic sediments (initially thought to be a part of the Mt. Simon) were identified as pre-Mt. Simon.

The 14,898 feet of MRS clastic rocks, informally known as "Red Clastics," is by far the thickest section of these rocks encountered in Iowa, and the thickest section known from anywhere along the trend of the MRS. Witzke subdivided the "Red Clastics" in the Eischeid well into two informal groups, the Upper "Red Clastic" Sequence and the Lower "Red Clastic" Sequence. The groups were further subdivided into informal formations and members, and the lithologic characteristics of each unit were described. One unit in the Lower "Red Clastic" Sequence, Unit C, is dominated by dark gray to black organic-rich shales and siltstones that appeared to offer good source-rock potential.

Below the MRS clastic rocks, the Eischeid well penetrated 151 feet of relatively fresh, undeformed gabbro. This unit was described by Van Schmus and others (this volume) who interpreted it as a dike. They analyzed zircon crystals from the dike and used uranium-lead isotope concentrations to calculate an age of 1281 million years for the rock. This age indicates that the dike predated the formation of the MRS, and probably is an element of a suite of dikes that is widespread through North America, known collectively as the Mackenzie dike swarm.

Petrologic studies of thin-sections produced from Eischeid drill-cutting samples by Ludvigson and others (this volume) and from core samples by Barnes (this volume) were used to characterize the MRS clastic rock sequence. These studies led to the interpretation of the depositional environments of the rocks and identified the differences and similarities between the MRS clastic rocks in the Eischeid well and related units observed in their exposure area in the Lake Superior Basin.

The Proterozoic clastic rocks in the Eischeid well, especially in the Lower "Red Clastic" Sequence, were investigated by Palacas and others (this volume) for their potential to produce hydrocarbons. They analyzed samples from 58 depth intervals for total organic carbon (TOC) content and selected samples for other parameters including maximum pyrolysis temperature (T_{max}), genetic potential, hydrogen index, and chloroform-extractable bitumens. They found that Unit C was the most organic unit, with TOC values ranging up to 1.4% and averaging 0.6%. These values are low, but many geologists consider 0.5% to be a minimum value for a rock unit to be considered a petroleum source rock. T_{max} values averaged 503° C indicating that the rocks in the Eischeid well were overmature with respect to hydrocarbon generation.

This advanced stage of thermal maturity was corroborated by several other researchers. Barker (this volume) investigated fluid inclusions in calcite and quartz veins. He measured two-phase fluid inclusion homogenization temperatures of selected samples and identified two temperature populations, an earlier 200° C event and a later 140° C event. He verified the 200° C event peak by bitumen reflectance (vitrinite reflectance equivalent) measurements. Ludvigson and Spry (this volume) conducted additional measurements of two-phase and other fluid inclusions in tectonic veins. They identified temperatures ranging from 125° to 178.6° C near the top of Unit C, and reported that many inclusions are filled by methane or carbon dioxide gas. They used coordinated fluid inclusion homogenization and stable isotopic (oxygen and carbon) data to suggest that petroleum may have migrated from the axis of the rift to its outer margin. Pollastro and Finn (this volume) used clay geothermometry to calculate paleotemperatures for Unit C samples. They calculated a minimum paleotemperature of 175° to 180° C from samples near the top of Unit C, and used this information to estimate a minimum bottom hole (17,851 feet) paleotemperature of 192° to 197° C.

Palacas and others (this volume) also calculated a genetic potential of 0.1 to 0.4 HG/g and hydrogen indices from 20 to 80 HC/g TOC for carbon-rich intervals of Unit C. They concluded that "at present, these shale beds have no potential of generating commercial petroleum...," but they suggested that significant amounts of hydrocarbons may have been generated in the geologic past.

Another important characteristic in evaluating the petroleum potential of the Eischeid "Red Clastic" rocks is their porosity. Schmoker and Palacas (this volume) studied a variety of down-hole geophysical logs to calculate the porosity of sandstone units in the "Red Clastic" rocks. They calculated porosities ranging from 1 to 6% (averaging 2.3%) within the interval from 14,450 to 17,340 feet in the Eischeid well, with 14% of that section averaging 3.5% porosity or greater. However, Ludvigson and others (this volume) and Barnes (this volume) noted that no optically observable porosity was identified below 8000 feet. Anderson

("Review of current studies...," this volume) suggested that the porosity identified by Schmoker and Palacas might be present as microporosity or as gas and/or liquid-filled inclusions.

CONCLUSIONS

Data and samples collected during the drilling of the Amoco M.G. Eischeid #1 deep petroleum test well facilitated the preliminary division of the "Red Clastic" sequence in Iowa into two informal groups, the groups into eight informal formations, and the formations into thirteen informal members. The "Red Clastic" rocks in Iowa are similar in many ways to the Oronto and Bayfield groups, MRS clastic rocks exposed in the northern Wisconsin area. They appear to have similar depositional environments and probably are nearly coeval. Some differences between the lithology and petrology of the Eischeid MRS strata and those observed in the Lake Superior region can primarily be attributed to their locations in different areas of the rift.

The MRS clastic rocks encountered in the Eischeid well presently have almost no potential for producing hydrocarbons, but they have apparently generated significant volumes of petroleum at some time in the geologic past. It is possible that similar rock sequences located at a greater distance from the axis of the rift may still contain economic volumes of petroleum, but a concerted exploration effort will be required to locate such resources.

PREFACE

The Amoco M.G. Eischeid #1 deep petroleum test well, with a total depth of 17,851 feet, is one of the most important drill holes ever to penetrate the rocks of the Midcontinent Rift System (MRS). It penetrated the thickest section of MRS clastic rocks encountered by drilling anywhere along the structure, and it provides an excellent opportunity to compare MRS rocks from the deep Iowa subsurface with related units exposed to the north in the Lake Superior area. It also affords an excellent opportunity to evaluate the petroleum potential of these ancient rocks in Iowa.

This volume presents the results of investigations of rock samples and other data released by Amoco to the Iowa Department of Natural Resources Geological Survey Bureau (GSB). These studies were primarily directed toward investigating the stratigraphy and petrology of the rock units encountered during the drilling, and various factors related to the petroleum potential of the Proterozoic section. The authors who investigated these rocks were required to complete their studies in a very short time in order to make this volume available as soon as possible following the release of the data from confidential status. Although these studies are complete and provide a wealth of information, they are considered preliminary by most researchers, since follow-up studies will probably refine the data and interpretations presented here. Core and drill cuttings from the M.G. Eischeid #1 well are reposited at the GSB research facility near Iowa City and are available for additional research projects.

The first two papers by Anderson describe the Precambrian geological setting of the MRS in Iowa and the structure of the rift as interpreted from geophysical data. A paper by Witzke describes the stratigraphy of the strata encountered during the drilling. McKay discusses the problems of identifying the contact of the basal Cambrian Mt. Simon Sandstone with the underlying MRS clastic rocks. His paper was a late addition to this volume, and some reports were completed prior to his identification of basal Mt. Simon contact. Initial stratigraphic picks had indicated that the base of the Mt. Simon Sandstone was much deeper than McKay placed it. Consequently, some papers report a deeper-lying top or a thinner total thickness for the "Red Clastic" strata.

Van Schmus and others describe the gabbro encountered at the crystalline surface in the Eischeid well and its age and affinity. Ludvigson and others, and Barnes, present the results of their petrographic studies of the Eischeid drill cuttings and core samples.

The petroleum source-rock potential of the "Red Clastic" rocks is investigated by Palacas and others; porosity is discussed by Schmoker and Palacas; and Pollastro and Finn report on the clay mineralogy and bulk rock composition of selected intervals of the strata. Ludvigson and Spry discuss the tectonic and paleohydrologic significance of carbonate veinlets in the "Red Clastics" and Barker reports on his study of fluid inclusions. Finally, Anderson reviews and summarizes the papers that comprise this volume.

All depths used in the papers in this volume are measured from the Kelly bushing of the drilling platform, 29 feet (8.8 m) above the ground. To obtain depth from ground level subtract 29 feet (8.8 m) from the stated depth.

To improve readability, several articles in this volume express depth and distances only in English units, without the metric equivalents that traditionally are included. To obtain the metric equivalents the following formulas should be used:

centimeters = inches x 0.394
meters = feet x 0.305
kilometer = miles x 1.61

REVIEW OF THE PRECAMBRIAN GEOLOGICAL HISTORY OF THE CENTRAL UNITED STATES AND THE MIDCONTINENT RIFT SYSTEM

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INTRODUCTION

The Midcontinent Rift System (MRS) developed about one billion years ago, initially in response to extensional stresses probably related to the Grenville Orogeny. The rift cut through a number of Archean and Proterozoic terranes over its 940 mile length from central Lake Superior to central Kansas (Fig. 1). The structural grains of these terranes exerted significant influence on the morphology and trend of the MRS, and led to the development of four distinct segments, each with characteristic structural attributes.

Exposures of MRS volcanic, plutonic, and sedimentary rocks are limited to the Lake Superior area where they have been extensively studied for many years. These studies have led to the interpretation of a sequence of events that led to the initial deposition of a thin suite of sedimentary rocks followed by the emplacement of a thick sequence of mafic-dominated bimodal volcanic rocks that have been divided into two suites. The cessation of MRS development is marked by the deposition of two distinct suites of clastic sedimentary rocks.

The Iowa segment of the MRS is characterized by an axial horst, the Iowa Horst, and deep, clastic-filled flanking basins. The Amoco M.G. Eischeid #1 petroleum test well was drilled into one of these flanking basins (Figs. 1 and 2), and it provided the deepest penetration of MRS clastic rocks anywhere along the trend of the structure. The clastic rocks observed in the Eischeid well are similar in many ways to the MRS clastics that are exposed in the Lake Superior area.

MIDCONTINENT RIFT SYSTEM NOMENCLATURE

Midcontinent Rift System

In their Lake Superior exposure belt, the rocks of the Midcontinent Rift System were recognized as constituting a structural basin by Foster and Whitney (1850) and Irving (1883), with "rift faulting" postulated by Van Hise and Leith (1911). As the rift origin of the Keweenawan rocks came into general acceptance (Black, 1955), the name "Midcontinent Rift" was applied to the feature (King and Zietz, 1971). Later, as associated clastic rocks were interpreted as post-rift deposits, the entire package of rocks was frequently referred to as the "Midcontinent Rift System" (Van Schmus and Hinze, 1985), or sometimes the "Mid-Continent Rift System" (e.g., Chandler et al., 1989). Other names were also applied to the feature including "Lake Superior-Keweenawan rift system" (McGinnis, 1970), "Keweenawan aulacogen" (Milanovsky, 1981), and the "Central North American Rift System" (Halls, 1978; Dutch, 1983). Since the name Midcontinent Rift System has been widely used, is now being used by most geologists involved in active research on the feature, and is similar to the term applied to it's geophysical signature, the Midcontinent Geophysical Anomaly, the name Midcontinent Rift System will be applied in this article.

Midcontinent Geophysical Anomaly

The nomenclature used in discussing the geophysical signature of the Midcontinent Rift System is varied and sometimes confusing. The gravity signature of the rift was first identified by Woollard (1943) and first called the "Mid-continent Gravity High" by Theil (1956). The feature was later named the "Greenleaf Anomaly" and identified as a "tectogene" by Lyons (1959), who subsequently (Lyons, 1970) identified the feature as a rift. The name "Greenleaf Anomaly" was not applied in subsequent literature, but the name "Midcontinent Gravity High" prevailed (King and Zietz, 1971). After the association of a magnetic anomaly with the feature the name "Midcontinent

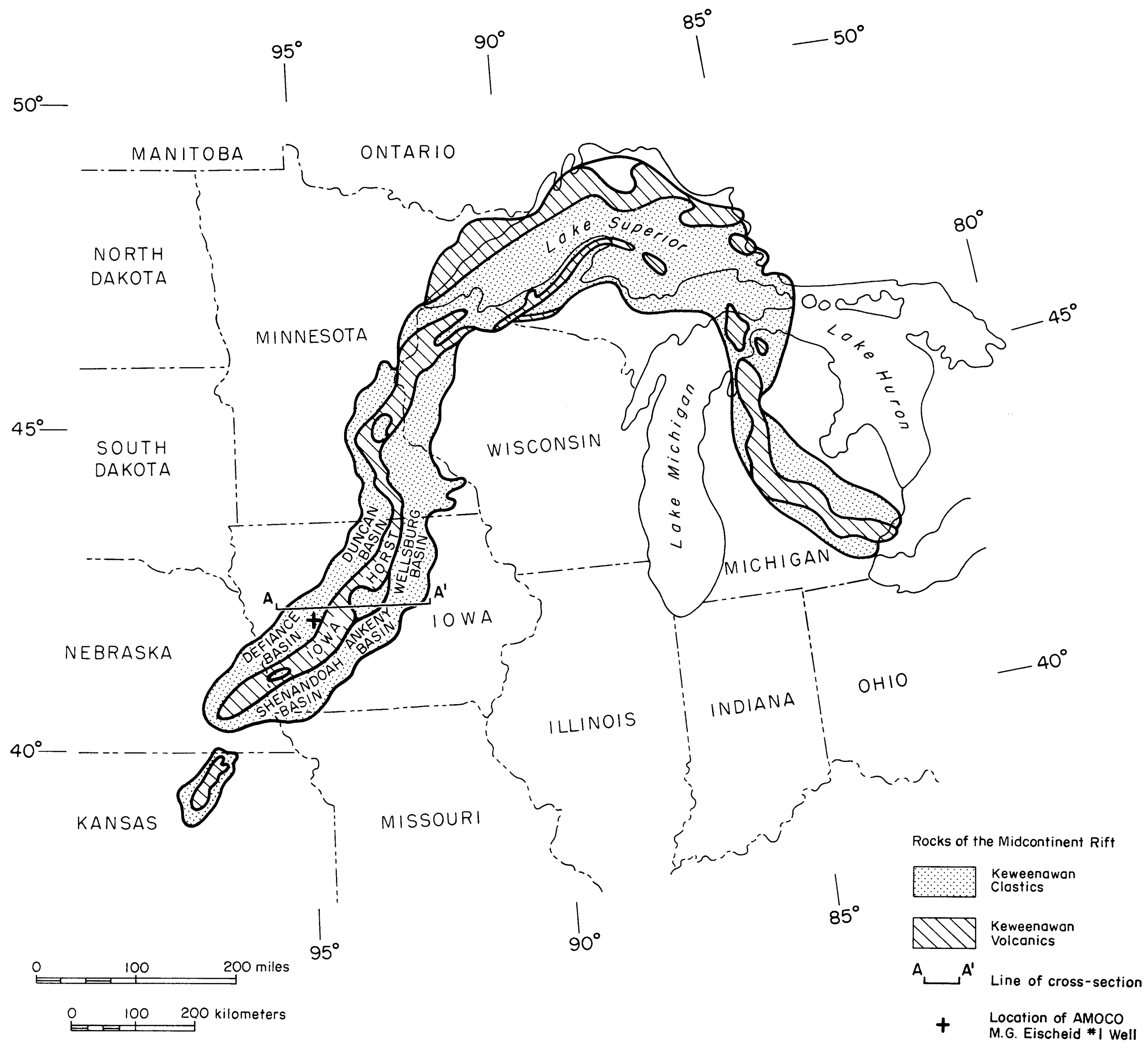

Figure 1. Location of Midcontinent Rift System (from Palacas et al., this volume).

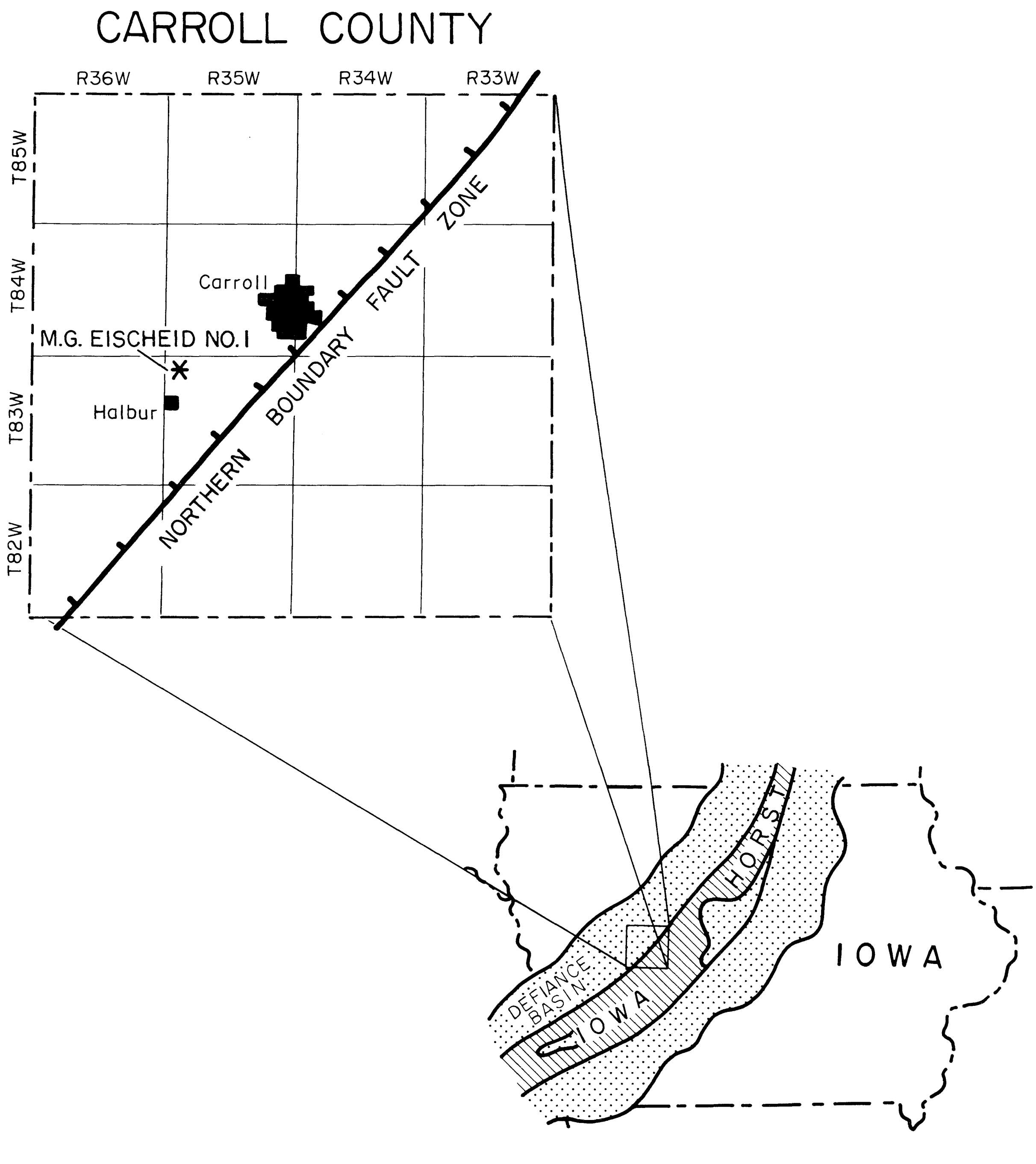

Figure 2. Location of the M.G. Eischeid #1 deep petroleum test well.

Geophysical Anomaly" began to be used (e.g., Anderson and Black, 1982; Serpa et al.,1984; Hicks, 1985). In the following discussion, the name "Midcontinent Geophysical Anomaly" (MGA) will be applied to the geophysical expression of the Midcontinent Rift System.

Keweenawan Supergroup

The names "Keweenaw" and "Keweenawan" have been applied to the rocks of the MRS since Hunt (1873) first used the term "Keweenaw Group" to identify the copper-rich rocks (known today as the Portage Lake Volcanics and Oronto Group) exposed on the Keweenaw Peninsula of upper Michigan. About the same time Brooks (1876) suggested that the period of time that these rocks were deposited should be called the "Keweenawian" or "Keweenian," and Irving (1883) suggested the term "Keweenawan." This was the beginning of a long period during which similar names were applied to both lithostratigraphic and chronostratigraphic units. Goldich (1968) suggested the use of the term Keweenawan Supergroup for rocks associated with the MRS, and King (1978) applied the term. The history and a documentation of the usage of the name "Keweenawan" were reviewed by Morey and Green (1982) who suggested that its appropriate usage was as a lithostratigraphic term having supergroup status, and that usage of the term to describe chronostratigraphic units should be abandoned. However, such a chronostratigraphic term is useful in discussions of the MRS, and since a comparable chronstatigraphic term has not yet been proposed, use of "Keweenawan" to describe the period of time during which the MRS developed will continue. Also, in this article the term Keweenawan Supergroup will be applied to the rocks associated with the MRS, including those in the subsurface in Iowa.

GEOLOGIC HISTORY OF THE MIDCONTINENT REGION

Pre-Midcontinent Rift History of the Midcontinent

Supercycles in Continental Development

The concept of supercycles was first proposed by Worsley and others (1984) and subsequently expanded by a number of workers (e.g., Nance et al., 1988; Hoffman, 1988, 1989). It developed from the concept of a Wilson Cycle, the opening and closing of ocean basins by the plate tectonic processes originally proposed by Wilson (1963). The expanded theory of the supercycle recognizes the opening and closing of oceans as a global phenomena and also includes periods of supercontinent uplift and volcanism and periods of rifting between ocean cycles (Fig. 3).

An ideal supercycle can be divided into three major periods. The first is *Anorogeny*, a period of supercontinent uplift and erosion, high heat flow, and anorogenic magmatism driven by high concentrations of heat at the crust-mantle boundary. The heat is concentrated by the insulating effect of the large mass of sialic crust produced by the joining of continental fragments to form a supercontinent. The mass of rock acts to prevent the normal venting of mantle heat through mid-ocean ridges and other heat sinks. The second is *Taphrogeny*, a period of rifting and ocean development, driven initially by mantle heat flow beneath the continent and then by plate tectonic processes. The third is *Orogeny*, the closing of the interior ocean basins leading to the accretion by collision of island arcs, arc basins, and rifted continental masses to reform a supercontinent.

Rocks and processes typically associated with the three stages of a supercycle include: (1) *Anorogeny*--continental uplift, deep weathering, and the emplacement of anorogenic (felsic dominated) plutons and volcanic rocks, with an associated widespread increase in heat flow and the thermal disruption of less refractory isotopic systems; (2) *Taphrogeny*--the development of intercratonic rifts, with their associated mafic dike complexes, bimodal volcanics, and sedimentary rocks, eventually leading to the break-up of the supercontinent with the opening of internal ocean basins and associated passive margin sedimentation, sometimes including widespread sequences of quartzose sandstones; and (3) *Orogeny*--subduction leading to the formation of island arcs and their associated volcanic, plutonic, and sedimentary rocks, and arc basins and their associated sediments and mafic magmas. Arcs are accreted to the continents as the internal ocean basins close, producing structures related to compressional teconics. The North American midcontinent contains rocks that are the product of five Proterozoic supercycles.

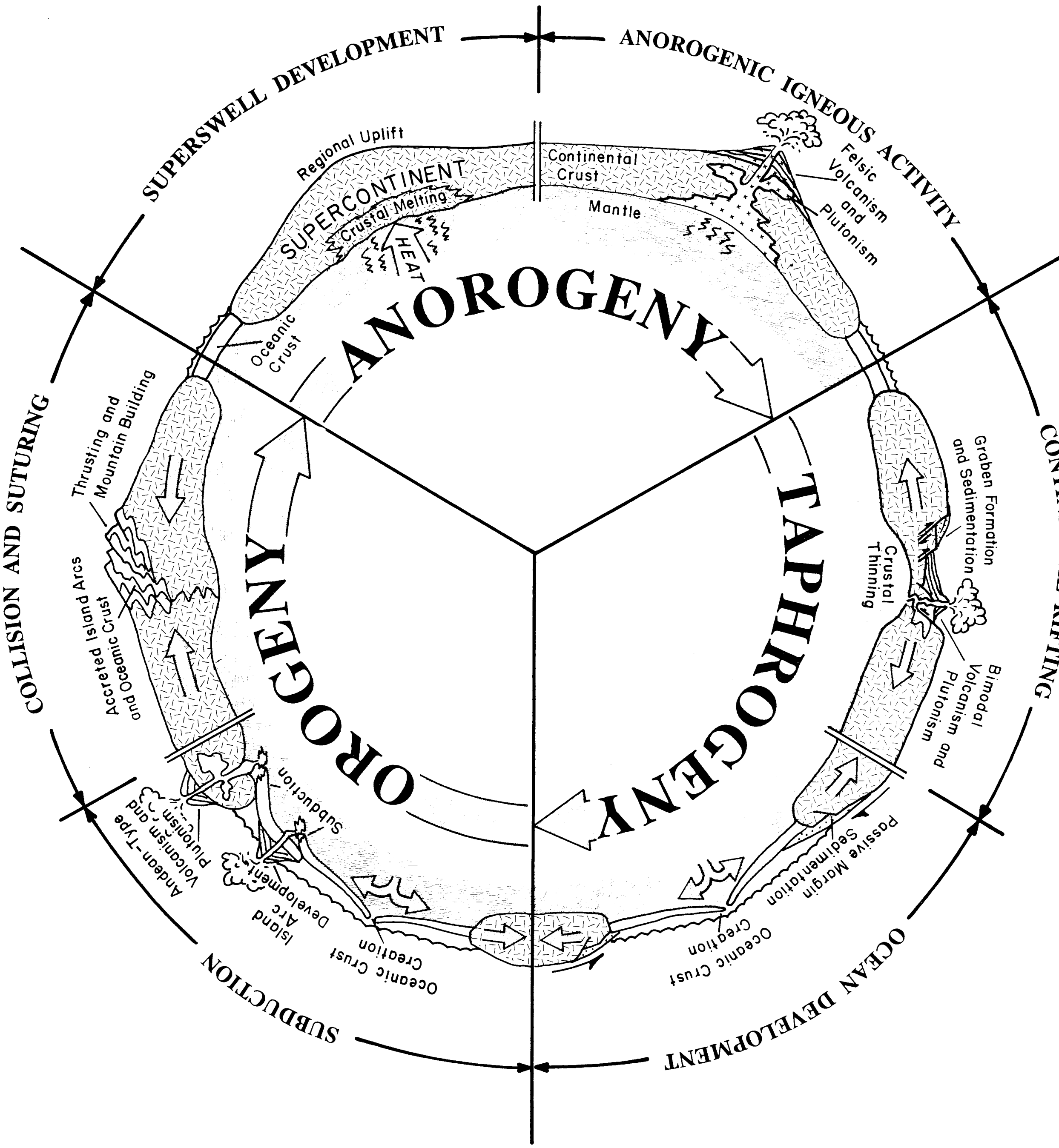

Figure 3. Components of a supercycle and some characteristic geological processes (from Anderson, 1989).

GEOLOGIC SETTING OF THE MIDCONTINENT RIFT SYSTEM

The MRS is a failed rift system that developed about one billion years ago, apparently in response to stresses associated with the Grenville Orogeny, the closing of a proto-Atlantic Ocean. It extends from central Lake Superior in a southwesterly direction to central Kansas (Fig. 1). The rift is naturally divided into four segments (from north to south) the Lake Superior segment, the Minnesota segment, the Iowa segment, and the Kansas segment. Additionally, some workers recognize a second arm of the rift extending from Lake Superior in a southeasterly direction across Michigan and into Ohio where it terminated near the Grenville Front. This review will not address the Michigan segment of the rift since its relationship to the main body of the MRS is not well established.

The structural geometry of the MRS is characterized by a series of central horsts, dominated by mafic extrusive rocks, locally overlain by late rift clastics, and flanked by a series of asymmetric basins that deepen towards the horsts in a half-graben configuration and are filled with sequences of coarse to fine clastic rocks. The volcanic rocks of the central horsts reach estimated maximum thicknesses in excess of 35,000 feet and, with the addition of associated intrusive rocks, total over 100,000 cubic miles of igneous rocks in the Lake Superior area alone (Green, 1982). The central horsts are separated from the flanking clastic basins by high-angle reverse faults with displacements estimated to exceed 10,000 feet in some places. Late-rift clastic rocks are locally preserved on the central horsts. The Lake Superior segment preserves a much thicker sequence of clastic rocks on the central horst than do the other segments. Over most of its length, the rocks of the MRS are overlain by Phanerozoic sedimentary rocks and glacial drift deposits. The best exposures of MRS rocks can be observed along the north and south shores of western Lake Superior in Minnesota, Wisconsin, and upper Michigan.

Midcontinent Precambrian Terranes

The development of the MRS was strongly controlled by the five Precambrian terranes in which it developed. The terranes include two Archean continental terranes and three Proterozoic orogenic belts (Fig. 4). These terranes were the building blocks that were assembled to form the midcontinent basement on which subsequent geologic features were superimposed.

Greenstone-Granite Terrane (Archean 3000-2700 Ma)

The northern-most of the terranes in which the Midcontinent Rift developed is the Greenstone-Granite Terrane. This terrane includes the area of Lake Superior, the northern half of Minnesota and most of eastern Canada (Fig. 5). Together with the Minnesota Terrane of the southern Minnesota region it comprises the Superior Province, one of the seven (Hoffman, 1989) or eight (Anderson, in prep.) major Archean blocks that form the nucleus of North America. The Greenstone-Granite Terrane is composed of a series of subparallel, east-northeast-trending belts of contrasting lithology, age, and/or metamorphic grade (Card, 1989). These belts include (Card, 1989): (1) volcanic-plutonic terranes, which resemble island arcs; (2) metasedimentary belts, with the appearance of accretionary prisms; (3) plutonic complexes; and (4) high-grade gneiss complexes, which appear to be deeper erosion levels of the other belts (Percival, 1989). These terranes were assembled about 2700 Ma ago (Card, 1989) by an accretionary process that progressed from north to south (Krogh and Davis, 1971).

Minnesota (Gneiss-Migmatite) Terrane (Archean >3600 Ma)

The oldest terrane in which the MRS developed is the gneiss and migmatite-dominated Minnesota Terrane (Hoffman, 1989) of southern Minnesota and adjacent areas of Iowa, Nebraska, and South Dakota (Fig. 5). This terrane is characterized by tonalitic to granodioritic orthgneisses and amphibolites (Morey and Hanson, 1980) whose protoliths crystallized at least 3660 Ma ago (Goldich and Fischer, 1986) and have subsequently undergone multiple periods of deformation. This terrane is located on the southwest corner of the Superior Province and is sutured to the Greenstone-Granite Terrane along the Great Lakes Tectonic Zone (Sims et al., 1980), a northeast trending structure that dips at about 30^{o} to the northwest (Gibbs et al., 1984). It is generally believed that the Minnesota Terrane was welded to

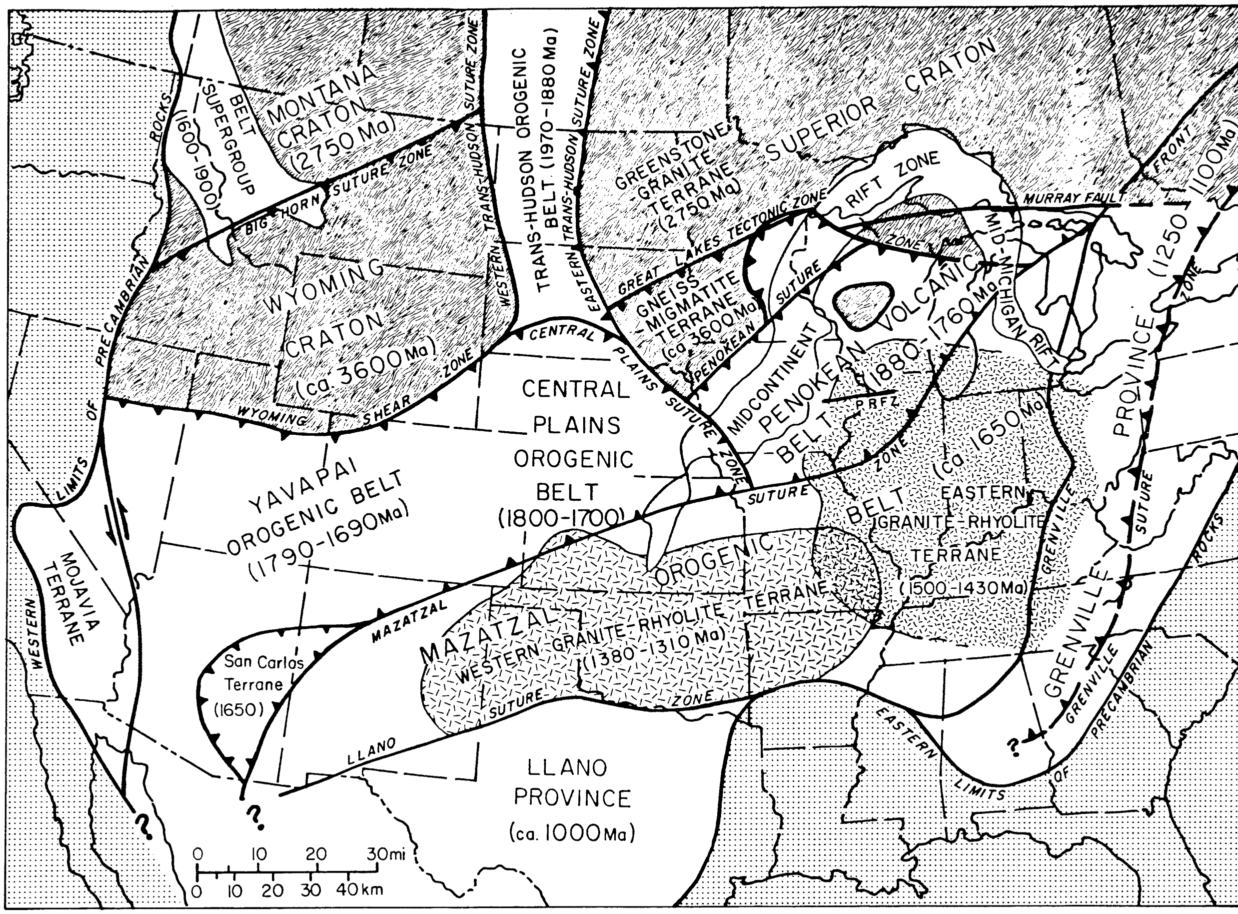

Figure 4. Precambrian terranes of central North America (from Anderson, 1989).

the Greenstone-Granite Terrane about 2700 Ma ago when the Greenstone-Granite Terrane was thrust upon it (Hoffman, 1989).

Penokean Volcanic Belt (1860-1800 Ma)

The Penokean Volcanic Belt (PVB) of Greenberg and Brown (1983), also known as the Wisconsin Magmatic Zone (Sims and Peterman, 1984), is an orogenic belt composed of a series of metamorphosed island arc sequences, including volcanic, plutonic, and sedimentary rocks, and associated fore-arc and back-arc basin deposits. The PVB extends south and west from north-central Michigan to northern Missouri and southeast Nebraska (although the exact limits of the terrane are not well defined because much of it subcrops beneath Phanerozoic strata). A nearly contemporaneous series of orogens also expanded the western, northern, and eastern margins of the Superior Province during its most active period of growth. In the central Wisconsin area, the closing of the Penokean Ocean apparently began about 1860 Ma ago, with initial closure facilitated by a north-dipping subduction zone that produced a volcanic arc. Following the collision of the arc with a small exotic block of Archean rocks informally called the "Wisconsin block," a south-dipping subduction zone developed north of the arc, and the complex closed on the Superior Craton (LeBerge, 1986). A third, south-dipping, subduction zone then developed south of the Wisconsin block subsequent to its collision with the Superior Province. In eastern Minnesota, recent work by Southwick and others (1988) interpreted the collision of a Penokean island arc complex with the Superior Province along a north-dipping subduction zone beneath an obducted back-arc basin. Little is known about the PVB in other regions where it is buried by Phanerozoic sedimentary rocks.

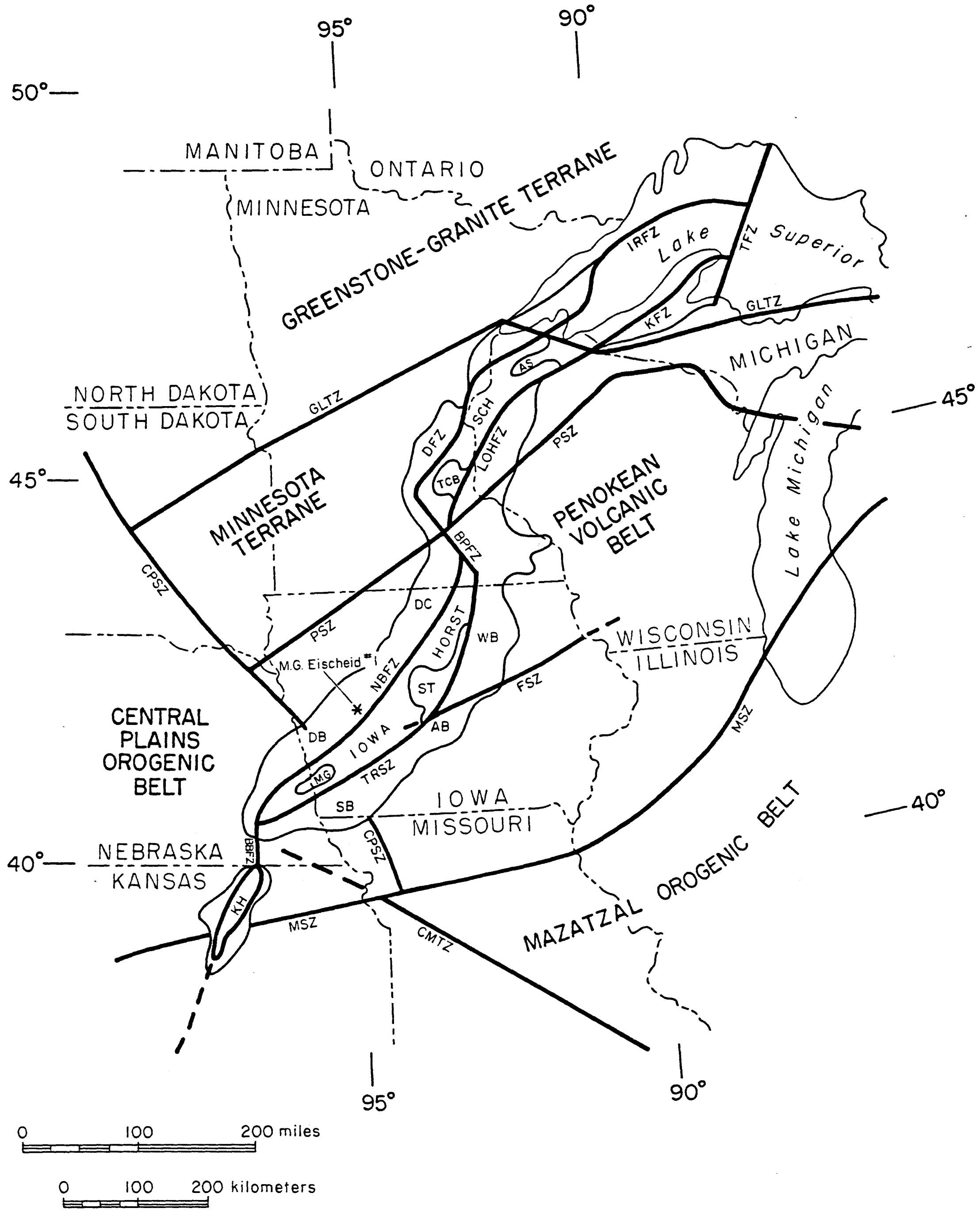

Figure 5. Structural components of the Midcontinent Rift Zones and related features. TFZ=Theil Fault Zone, IRFZ=Isle Royale Fault Zone, KFZ=Keweenaw Fault Zone, DFZ=Douglas Fault Zone, LOHFZ=Lake Owen-Hastings Fault Zone, BPFZ=Belle Plaine Fault Zone, NBFZ=Northern Boundary Fault Zone, TRSZ=Thurman-Redfield Structural Zone, BBFZ=Big Blue Fault Zone, SCH=St. Croix Horst, KH=Kansas Horst, GLTZ=Great Lakes Tectonic Zone, PSZ=Penokean Suture Zone, FSZ=Fayette Structural Zone, CPSZ=Central Plains Suture Zone, MSZ=Mazatzal Suture Zone, CMTZ=Central Missouri Tectonic Zone, ARZ=Anadarko Rift Zone, DB=Defiance Basin, DC=Duncan Basin, SB=Shenandoah Basin, AB=Ankeny Basin, WB=Wellsburg Basin, TCB=Twin City Basin, AS=Ashland Syncline, ST=Stratford Basin, MG=Mineola Graben.

Central Plains Orogenic Belt (1800-1700 Ma)

The Central Plains Orogenic Belt (CPOB) (Sims and Peterman, 1986) and its western extension, the Yavapai Orogenic Belt, occupy an area in the center of the United States from southern South Dakota to central Nevada (Fig. 4). CPOB rocks are completely buried by overlying Phanerozoic sedimentary rocks, except in the Rocky Mountains where Laramide structures expose them at numerous locations. In the mdcontinent, where they are known only from samples recovered by drilling, petrographic studies have characterized them as dominated by metavolcanic, metasedimentary, and gneissic granitoid rocks, with textures ranging from granoblastic to cataclastic and mylonitic (Sims et al., 1987).. These rocks are apparently the product of the accretion of a series of island arcs, with their associated arc basins, to the rapidly expanding proto-North American continent. This accretion occured as a complex series of poorly-understood of events between about 1800 and 1700 Ma ago.

Mazatzal Orogenic Belt (1650-1620 Ma)

The Mazatzal Orogenic Belt (MOB) (Karlstrom and Bowring, 1988) formed with the closing of an ocean on the southern margin of proto-North America between about 1650 to 1620 Ma (Hoffman, 1988). The MOB is juxtaposed against the CPOB along a zone from central Arizona to northwest Missouri and against the PVB across northern Missouri and Illinois to north-central Michigan (Fig. 4). The belt is exposed only sporadically in Arizona and New Mexico where metaturbidites and metavolcanics have been interpreted as an accreted island arc and related facies (Anderson, 1986). The MOB is covered elsewhere by Phaneroizoic rocks.

Other Proterozoic Rocks in the Midcontinent

In addition to the three Proterozoic orogenic rock sequences already described (the Penokean, Central Plains, and Mazatzal) anorogenic and taphrogenic rocks from these and two additional Proterozoic supercycles, the Huronian and the Grenville, are present in the midcontinent.

Huronian Cycle (2400-2100 Ma)

The Huronian Cycle is not well known, since most of its rocks were apparently lost to erosion or buried by rocks emplaced during the subsequent Penokean Cycle. The rocks of the Mille Lacs Group in Minnesota and the Chocolay Group in the upper peninsula of Michigan are passive margin deposits associated with the opening of the Huronian Ocean and the earliest known sediments deposited in the Lake Superior Basin.

Penokean Cycle (2100-1800 Ma)

An extensive series of taphrogenic rocks were deposited in the Lake Superior region as basins developed in response to extensional stresses prior to the opening of the Penokean Ocean. Reactivation and extensive development of the Lake Superior Basin is apparent in the thick sequences of sediments and bimodal volcanics of the Marquette Range Supergroup of Michigan. The North Range and Animikie groups of Minnesota may also be a part of this taphrogenic cycle, although recent work by Southwick and others (1988) suggest that some rocks may have been produced during the Penokean Orogeny. Similar rocks are also preserved in southwest Minnesota and adjacent Iowa.

Central Plains Cycle (1800-1700 Ma)

Anorogenic rocks of the Central Plains Cycle include a suite of anorogenic volcanic and plutonic rocks in South Dakota, Iowa, Minnesota, and Wisconsin. These rocks were emplaced between about 1780 and 1720 Ma ago and are frequently preserved beneath quartzite sequences such as the Sioux in the southwest Minnesota area and the Baraboo Quartzite of Wisconsin.

Mazatzal Cycle (1700-1600 Ma)

The anorogenic phase of the Mazatzal Cycle is known primarily from a suite of felsic plutons that were emplaced between 1690 to 1660 Ma in Colorado and western Kansas (Van Schmus et al., 1987). The taphrogenic phase of the cycle included the deposition of an extensive suite of quartz arenites and related sediments on the passive continental margins of the opening ocean basin. These sediments are preserved today as a series of quartzite-dominated outliers including the Baraboo, Waterloo, and Sioux quartzites (Dott, 1983). Finally, a thermal overprinting of lower refractory isotopic systems that occurred in much of the midcontinent about 1650 Ma, may have been associated with the Mazatzal Orogeny (Anderson and Ludvigson, 1986).

Grenville Cycle (1600-1000 Ma)

The Grenville Cycle produced a number of significant geologic features in the midcontinent and much of southern and eastern North America. Anorogenic features include voluminous "anorogenic" volcanic and plutonic rocks that have been subdivided into two suites. The Eastern Granite-Rhyolite Terrane (Bickford and Van Schmus, 1985) includes a belt of felsic plutons and associative extrusive rocks emplaced in Proterozioc accretionary terranes from southern California to Laborador between about 1500 to 1430 Ma ago. This suite includes the rocks of the St. Francois Mountains of Missouri and the Wolf River Batholith of Wisconsin. The second suite, the Western Granite-Rhyolite Terrane (Bickford and Van Schmus, 1985) includes felsic volcanic and plutonic rocks emplaced between about 1380 to 1310 Ma along an east-west trending belt from central Colorado to the St. Francois Mountains in Missouri. Rocks of these suites, especially the eastern suite, are common constituents of the crystalline basement of Iowa, northern Illinois, and southern Wisconsin.

Preserved rocks emplaced during the Grenville Taphrogeny in the midcontinent of North America includes the products of passive margin sedimentation and rifting. The Huronian Supergroup of southern Ontario are the best known of an extensive suite of passive margin deposits associated with the Grenville Taphrogeny. In the area of northern Lake Superior a failed rift led to the deposition of the Sibley Group about 1339 Ma ago (Franklin et al., 1980). This rift may be the northern extension of the Mid-Michigan Rift, the aulocogen of one of a series of triple junctions associated with the opening of the Grenville Ocean. Other possible aulacogens that may be associated with these triple junctions include the Fort Wayne rift in Indiana and the Rough Creek rift in Kentucky.

Later, several suites of plutonic and volcanic rocks and mafic dikes were emplaced, apparently in association with late stages of the Grenville Taphrogeny or early Grenville Orogeny. These include 1290 to 1280 Ma old igneous rocks in the Central Metasedimentary Belt of the Grenville Province, the Mackenzie diabase dike swarm that extends from north-central Canada to Iowa, emplaced between about 1267 to 1281 Ma ago, and the Sudbury Dikes of southeastern Canada, intruded about 1238 Ma (Van Schmus, this volume).

The MRS (ca. 1000-1100 Ma) may also have been a product of the Grenville Orogeny (ca. 1120-1230 Ma, Windley, 1989). A nearly contemporaneous orogeny, the Llano Orogeny, included the accretion of the Llano Province of Texas and Mexico between about 1100 and 1000 Ma.

STRATIGRAPHY OF THE MIDCONTINENT RIFT SYSTEM

In this article the many stratigraphic units that comprise the Keweenawan Supergroup (Fig. 6) are organized into five major units (Table 1) that represent the five major phases of rift history. They include, from the base upward: (1) the Nopeming Formation, a sequence of sandstones that were deposited along the axis of the rift prior to initiation of rift volcanism; (2) the Powder Mill Group, the initial sequence of reversely polarized, mafic-dominated, extrusive rocks; (3) the North Shore Volcanic Group, a normally-polarized suite of mafic-dominated, volcanic rocks that are separated from the underlying, Powder Mill volcanics by a disconformity; (4) the Oronto Group, a sequence of rift-filling clastics that marked the end of rift volcanism; and (5) the Bayfield Group, fluvial clastics that are separated from the Oronto Group by a disconformity and local unconformities. A more detailed description of the rocks associated with the MRS as they have been described in the outcrop belt and nearby subsurface of Wisconsin, Michigan, and Minnesota is shown in Table 1.

The units that comprise the Keweenawan Supergroup are disusssed in inverse order (oldest to youngest) to expedite the discussion of the sequence of events that led to their deposition.

Nopeming Formation

The Nopeming Formation, exposed southwest of Duluth, is one of a series of

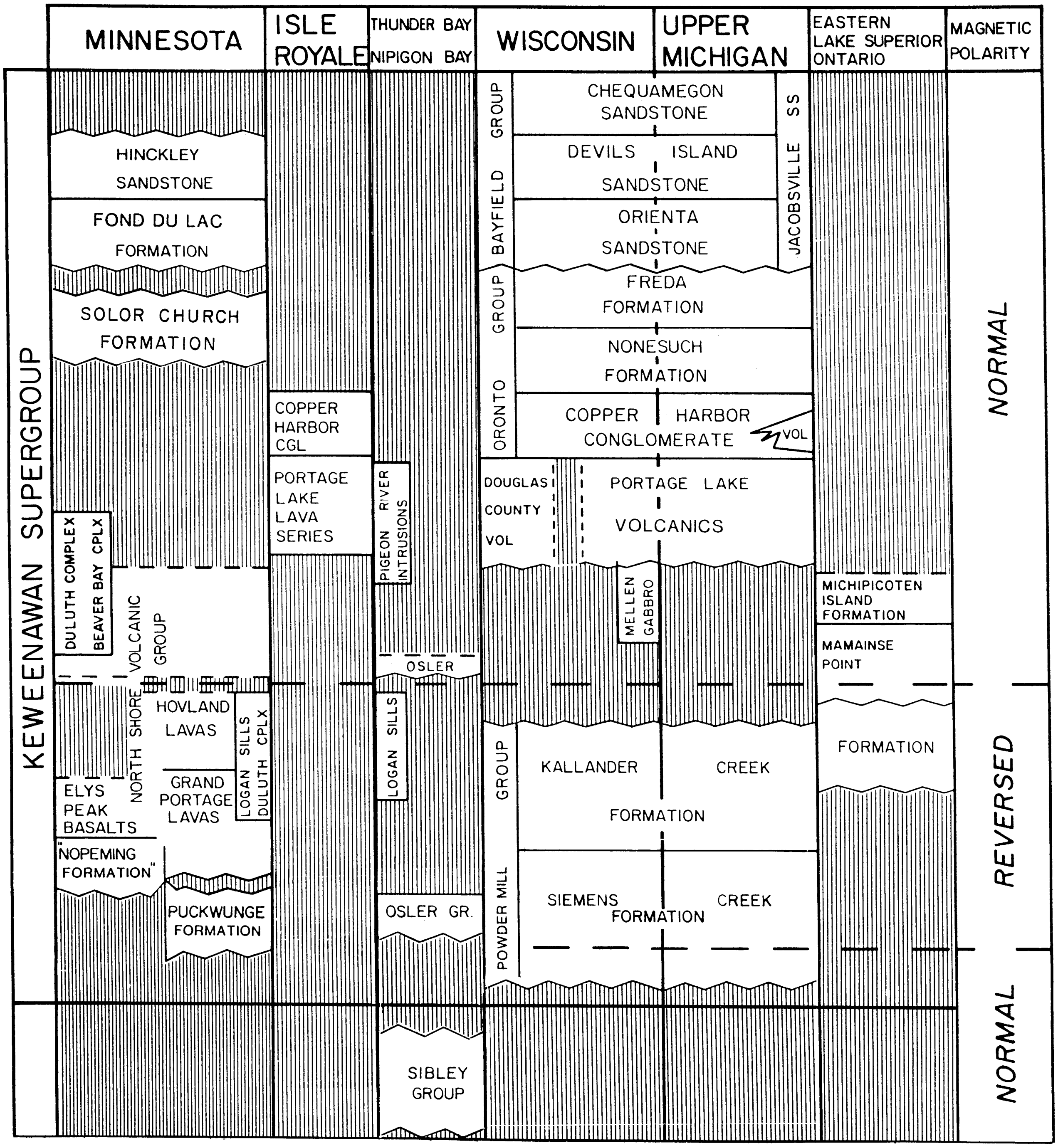

Figure 6. Comparative Keweenawan Stratigraphy of the Midcontinent Rift Zone in the Lake Superior region (modified from Green, 1982).

Table 1. Keweenawan Supergroup stratigraphy in the Lake Superior area as used in this report (in normal stratigraphic order).

I. Bayfield Group
- A. Chequamegon Sandstone
- B. Devils Island Sandstone
- C. Orienta Standstone

II. Oronto Group
- A. Freda Formation
- B. Nonesuch Formation
- C. Copper Harbor Conglomerate

III. North Shore Volcanic Group

IV. Powder Mill Group

V. Nopeming Formation

sandstone-dominated units that directly underlie the basal Keweenawan volcanic rocks. Correlative units include the Puckwunge Formation of northeastern Minnesota, the unnamed basal Osler Group sandstones near Thunder Bay, Ontario (Fig. 6), and the Bessemer Quartzite of northwestern Wisconsin.

All of these units were described by Ojakangas and Morey (1982a) as relatively mature, quartzose sandstones with mature basal conglomerates and thin argillaceous beds near their tops. The units are probably not exactly coeval but are nearly contemporaneous and occupy the same lithostratigraphic positions. They reach maximum thickness of generally less that 1100 feet and have been interpreted primarily as fluvial deposits, showing structures suggesting deposition by braided streams flowing generally southward into a large body of water on the axis of the rift in which the Bessemer Quartzite was deposited. Many of these units display evidence of soft sediment deformation by pressure from the overlying Keweenawan lavas, so they were probably not lithified before the initiation of volcanic activity (Ojkangas and Morey, 1982a). These sandstones apparently represent material deposited in a subsiding basin which was produced by early rift-basin subsidence prior to volcanism.

Powder Mill Group

The initial outpouring of volcanic rocks associated with the opening of the MRS created number of individual lava plateaus in the Lak Superior area, grouped for this paper under th name Powder Mill Group. Nearly all of these rock contain a remanent magnetic field indicating tha the Earth's magnetic field was reversed when the cooled. The only exception is the basal 1400 feet c the Powder Mill Volcanics in north-centra Wisconsin and upper Michigan that display normal polarity, having apparently been extrude just prior to the reversal (Halls and Pesonen, 1982) The Powder Mill Group, as used in this article includes the Powder Mill Group of uppe Michigan, northern Wisconsin and east-centra Minnesota, the lower North Shore Volcanic Grou and Ely's Peak Basalt of northeastern Minnesota the lower Osler Group volcanics of the Thunde Bay and Nipigon Bay area, and the lower Mamainse Point Formation of the eastern Lake Superio region of Ontario (Fig. 6).

The various units that comprise the Powder Mill Group were erupted as a series of discrete volcanic plateaus, each with their own temporal and petrogenic histories. The volcanic rocks include a wide range of compositions from mafic to felsic. Proportions of different compositions vary between and within individual lava plateaus, but in total, the compositions define a distinctly bimodal suite, characteristic of rift environments, with a broad, high peak in the mafic field and a significant, but lower rhyolitic peak (Green, 1982). The most abundant composition observed is olivine tholeiite (ibid.).

Intrusive rocks are associated with the extrusive rocks of the Powder Mill Group. These include the Logan sills and dikes of northeastern Minnesota and adjacent Ontario.

Interflow sedimentary rocks have been identified in association with extrusive rocks in all lava plateaus. These have been most thoroughly studied by Merk and Jirsa (1982) and Jirsa (1984) who described them as coarse, immature, polymictic red-bed clastic rocks, whose sources are almost exclusively from the volcanic terranes. They were deposited by streams that cut into the lava flows, generally draining toward the axis of the rift. These clastic rocks constitute an average of less than 5% of the rock section in the volcanic plateaus, although locally they may range up to 24% of the section.

North Shore Volcanic Group

The North Shore Volcanic Group includes a suite of extrusive (and associated intrusive and sedimentary) rocks that captured a normally polarized remanent magnetic component upon cooling. They are separated from the underlying Powder Mill Group by a disconformity. The North Shore Group includes rocks in the upper half of what has traditionally been called the North Shore Volcanic Group in northeastern Minnesota, the volcanic rocks of the Douglas, Minong, and St.Croix ranges and the Chengwatana Volcanics of northwestern Wisconsin and east central Minnesota, the Portage Lake Volcanics of north-central Wisconsin and upper Michigan, and the upper Mamainse Point and Michipicoten Island formations in the eastern Lake Superior region of Ontario (Fig. 6). These units are similar to the rocks of the Powder Mill Group in appearance and composition.

Individual flows range in thickness from less than three feet to more than 1200 feet with individual plateaus displaying cumulative exposed thicknesses ranging up to 35,000 feet (Green, 1982). In the Lake Superior area, Green (1982) estimated that the volcanics of the Keweenawan Supergroup cover an area of about 40,000 square miles and involve well over 100,000 cubic miles of extrusive and intrusive rocks.

Intrusive rocks of the North Shore Volcanic Group include the Duluth Complex, Beaver Bay Complex, and Pigeon River Intrusives in northeastern Minnesota and adjacent areas of Canada, and the Mellen Gabbro in northwest Wisconsin and neighboring areas of Michigan (Fig. 6). These rocks were summarized by Weiblen (1982).

Oronto Group

The Oronto Group, as described in its outcrop belt in west-central Wisconsin by White (1972) and Craddock (1972), includes three formations. From the base up they include the Copper Harbor Conglomerate, the Nonesuch Formation, and the Freda Formation (Table 1). In the subsurface of east-central Minnesota a correlative unit, the Solor Church Formation was defined by Morey (1977).

The Oronto Group has been interpreted as a basin-fill sequence related to thermal subsidence of the MRS region immediately following the cessation of rift volcanism. Paleocurrent direction studies by a number of workers indicate that the Oronto detritus was transported toward the axis of the rift (Ojakangas and Morey, 1982b). All exposures and known subsurface occurrences of Oronto Group and equivalent rocks in the Lake Superior region are confined to positions on the central horsts of the MRS.

Copper Harbor Conglomerate

The Copper Harbor Conglomerate is a fining-upward sequence of conglomerate, sandstone, and siltstone that is about 7000 feet thick. The rock is texturally and compositionally immature (Daniels, 1982), being composed dominantly of clasts of earlier Keweenawan Supergroup volcanic rocks with subordinate quartz and feldspar grains. Conglomeratic facies are dominant in the lower half of the unit, with coarse to medium sandstones present as discontinuous lenses. This portion of the unit has been interpreted as the product of coalescesing gravel bars on "piedmont fans" (White and Wright, 1960) deposited by streams flowing toward the axis of the rift. Near the base of the unit interbedded mafic to intermediate volcanic rocks are present suggesting a gradational boundary with the underlying volcanic group. The upper portion of the unit is dominated by coarse- to medium-grained sandstones deposited by meandering streams. The sandstones at the top of the unit are interbedded with fine-grained, possibly lacustrine, clastics similar to lithologies characteristic of the overlying Nonesuch Formation.

Nonesuch Formation

The Nonesuch Formation was originally named Nonesuch Shale by Irving (1883), but renamed Nonesuch Formation by Lane and Seaman (1907), a more appropriate name since shales are subordinate to siltstone in the unit. The Nonesuch is composed of organic-rich shaley siltstones, carbonate laminites, shales, mudstones, and minor sandstones (Milavec, 1986) and varies in thickness from about 250 feet to 700 feet. The gray to black color of Nonesuch rocks makes them easily distinguishable from the red to brown color of the bounding units. The Nonesuch generally displays a greater textural and compositional maturity than the Copper Harbor except for rare, thin, coarse, poorly-sorted sandstone lenses (Daniels, 1982).

A number of depositional environments have been proposed to explain the character of the Nonesuch Formation. These include estuarine (White and Wright, 1954), lacustrine (Pettijohn, 1957; Milavec, 1986; Elmore, 1981), marine (Jost, 1968), and deltaic (Ehrlich and Vogel, 1971). Most active workers accept the lacustrine model for Nonesuch deposition.

The gray to black coloration of much of the Nonesuch Formation is due to high concentrations of preserved organic carbon, which averages 0.5% by weight in the rock (Ensign et al., 1968). The organic material was studied in detail by Moore and others (1969) who identified both matrix masses and remarkably well-preserved, recognizable, organic-walled microstructures such as bacterial cells, algal-like units, and fungal hyphae, preserved by a bituminization process. They concluded that the organic material was consistent with deposition in a lake, swamp, or tidal-flat, and that most of the organic material was developed in place. This organic-rich rock also hosts economic concentrations of copper in Ontonagon County, Michigan, where it is produced at the Copper Range (formerly White Pine) Mine. Barghorn and others (1965) concluded that the copper precipitation was directly facilitated by the intimate presence of the organic material.

The organic material in the Nonesuch Formation has also produced petroleum at the Copper Range Mine. Small amounts of solid and liquid hydrocarbons are found associated with vugular porosity and fractures in the cupriferous zone in the mine (Dickas, 1986).

Freda Formation

The Freda Sandstone was named by Lane and Seaman (1907) for exposures near the town of Freda, Michigan. Hamblin (1965) and other workers have proposed changing the name of the unit to Freda Formation since exposures display >10% siltstone. Accordingly, Freda Formation will be used in this article. It has been characterized as a fining-upward sequence grading from highly cross-bedded, coarse- to fine-grained sandstone and subordinate conglomerates to siltstones and red, ferruginous shale facies (Daniels, 1982). Its lower contact with the Nonesuch Formation is gradational, but its upper contact has not been observed. The maximum observed thickness of the Freda is about 5000 feet (Lane, 1911), however, the unit may reach thicknesses i excess of 14,000 feet (Hamblin, 1961).

Most recent workers studying the Fred Formation (e.g., Daniels, 1982) evoke a fluvi depositional setting for the unit. A paleomagneti pole determination by Henry and others (1977 placed the Freda at a subequatorial latitud (1.2° N), presuming that the primary magnetizatio was acquired during or shortly after depositior They also reported that the Freda Formation on th Keweenawa Peninsula in Michigan was intruded b the Bear Lake Rhyolite, that had been dated by S Chaudhuri at 1007±25 Ma (Rb-Sr), yielding minimum age for the unit. For their study Henr and others (1977) assumed an age of 1060 Ma fo the Freda, based on the age of the underlyin Nonesuch Formation (about 1075 Ma).

Bayfield Group

The youngest sequence of sedimentary rock associated with the MRS is the Bayfield Group o Wisconsin (Thwaites, 1912) and its correlative unit in Minnesota, the Fond du Lac Formation (Morey 1967; originally Fond du Lac Sandstone, Winchell 1899) and Hinckley Sandstone (Winchell, 1886) and in Michigan, the Jacobsville Sandstone (Lan and Seaman, 1907) (Fig. 6). The Bayfield Grou has been subdivided into three formations, the basal Orienta, the Devils Island, and the Chequamegon sandstones (Table 1). Because of the relative uniformity in composition of the three formations that constitute the Bayfield Group, the are frequently discussed as a single unit (e.g. Dickas, 1986). Exposures of the Bayfield Group are limited to the Bayfield Peninsula area of Wisconsin, with the correlative Jacobsville Formation exposed along the southern edge of the Keweenawan Peninsula of Michigan and the adjacent Lake Superior shore line east of the peninsula. The Fond du Lac Formation and Hinckley Sandstone are exposed in east-central Minnesota. All generally are relatively flat-lying units, in contrast with nearby exposures of frequently steeply-dipping Oronto Group strata. Although the contact between the two units is not exposed, the Bayfield Group apparently is separated from the underlying Oronto Group by an angular unconformity (Ojakangas and Morey, 1982b). In areas where the two groups are exposed near one another, they appear to be separated by high-angle reverse faults, with the steeply-dipping

Oronto Group strata exposed on the up-thrown block and flat-lying Bayfield Group rocks on the down-thrown block. The Bayfield Group and its equivalents may reach thicknesses in excess of 10,000 feet (Kalliokoski, 1982). The Bayfield is compositionally more mature than the underlying Oronto Group (Fig. 7A). Meyers (1971) concluded that the clastics of the Bayfield Group were primarily the product of reworking of Oronto Group sediments, although a large component of first cycle, quartz-rich sediments derived from surrounding granitic terranes may also be present.

Orienta Sandstone

The basal unit of the Bayfield Group is the Orienta Sandstone (Thwaites, 1912), a fine- to coarse-grained, angular to well-rounded, fairly well sorted, massive- to thick-bedded, brick red to buff, arkosic sandstone that may reach thicknesses up to 3500 feet (Thwaites, 1912). The Orienta is exposed on the western side of the Bayfield Peninsula and at Amnicon Falls and Pattison state parks in Wisconsin. Although Thwaites (1912) suggested that there are difficulties in differentiating the Orienta from the Freda, Mudrey and Ostrom (1986) showed that the Orienta generally is compositionally more mature than the Freda, with a lower lithic grain component (Fig. 7A). The Fond du Lac Formation of Minnesota is correlated with the Orienta Sandstone by most workers (e.g., King, 1978; Green, 1987). It is generally interpreted as a fluvial deposit (Dickas, 1986).

Devils Island Sandstone

The Devils Island Sandstone (Thwaites, 1912) is a well-rounded, medium-grained, thin-bedded, quartz arenite that is exposed only along a narrow belt extending southwestward from Devils Island, the northern-most of the Apostle Islands, into the center of the Bayfield Peninsula in Wisconsin. It is distinguished from other formations of the Bayfield Group by its high quartz content (averaging 99% according to Meyers, 1971), thin bedding, white color (except for minor local iron staining which produces a pink color), and ripple marks with morphologies suggestive of formation in a standing body of water (Thwaites, 1912). Most workers attribute a lacustrine origin to the Devils Island Sandstone. Ostrom (in Mudrey and Ostrom, 1986) recognized stratigraphic relationships in the Lake Superior area that suggested that the Devils Island might be eqivalent to the Upper Cambrian Galesville Formation, but most workers include the unit with other Keweenawan Supergroup clastic rocks. The Hinckley Sandstone of east-central Minnesota is correlated with the Devils Island Sandstone (Morey and Ojkangas, 1982).

Chequamegon Sandstone

Generally regarded as the uppermost unit in the Bayfield Group, the Chequamegon Sandstone (Thwaites, 1912), reaches a thickness of about 1000 feet. It is similar in appearance and composition to the Orienta Sandstone (Mudrey and Ostrom, 1986) and may in fact be equivalent to the Orienta (Mudrey, 1979). Ostrom and Slaughter (1967) suggested that the Chequamegon may have a Cambrian age. The unit is most prominently exposed on the eastern edge of the Bayfield Peninsula of Wisconsin where it was quarried extensively as brownstone dimension stone.

Southern Ontario Alkaline Plutonic Rocks

A suite of alkaline plutonic rocks occurring in two zones north and east of Lake Superior have often been associated with the MRS (Weiblen, 1982). These rocks include the Coldwell, Prairie Lake, Killala Lake, and Chipman Lake complexes north of Lake Superior and a suite of nephelinitic and carbonotitic intrusive complexes along the trend of the Kapuskasing Structural Zone northeast of the lake. Many of these plutons have been dated using K-Ar techniques (Gittens et al., 1967), yielding ages between 1185 to 1010 Ma. Uncertainties associated with the interpretation of K-Ar ages in the midcontinent make determination of the actual age of emplacement of these plutons questionable (Van Schmus and Hinze, 1985).

EVOLUTION OF THE MIDCONTINENT RIFT SYSTEM

A great many questions remain in trying to understand the evolution of the MRS. Much of the development of the MRS apparently took place over a very short period of time (Van Schmus and Hinze, 1985). Silver and Green (1972) have shown through the use of U-Pb geochronology on zircons that most of the Keweenawan igneous activity in the western Lake Superior region took place over a

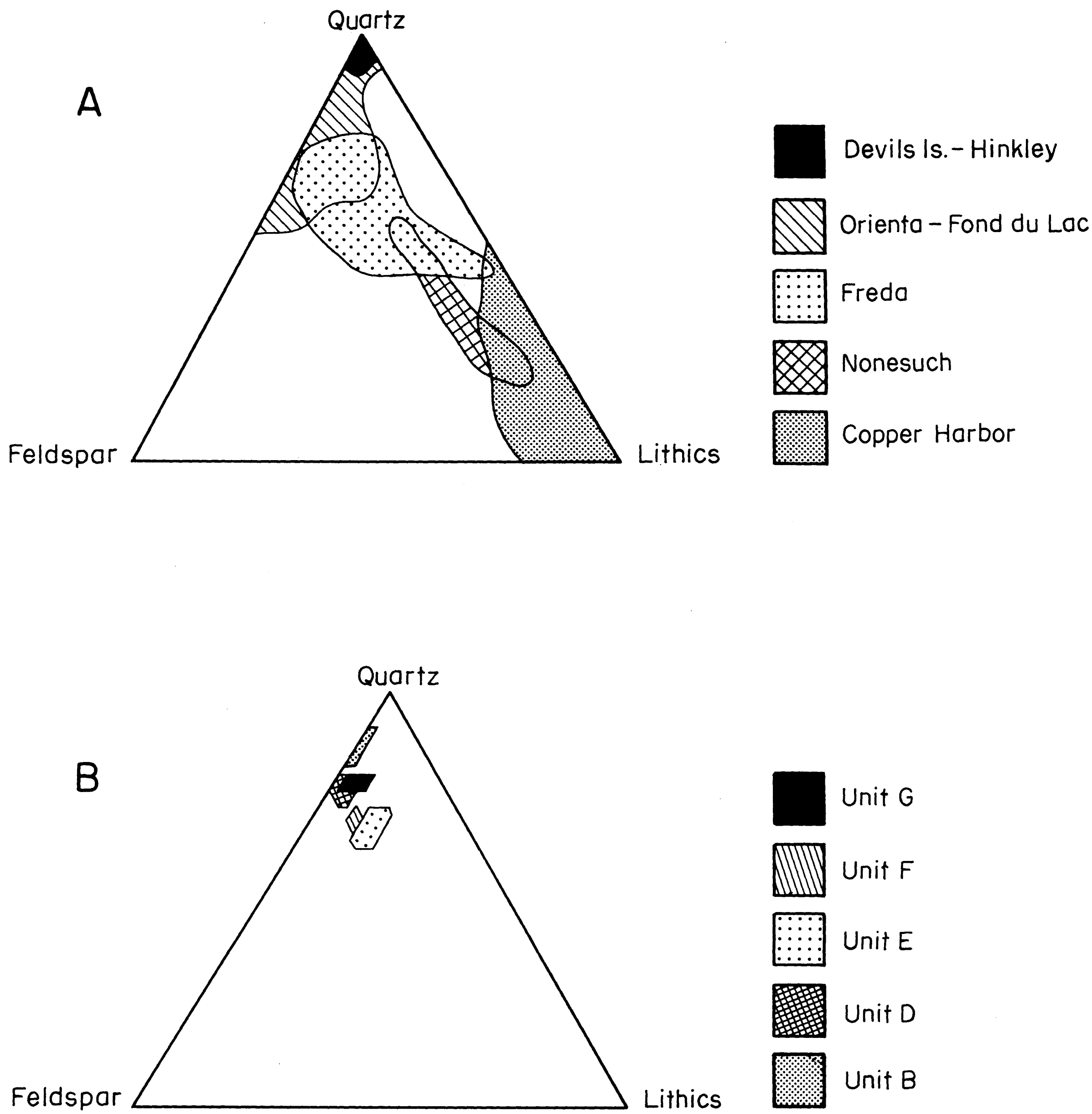

Figure 7. Quartz-feldspar-lithic fragment (QFL) diagrams for Keweenawan Supergroup clastic rocks from (A) the Lake Superior area (modified from Ojakangas, 1986) and (B) the Eischeid well (modified from Ludvigson et al., this volume).

very short period of time, about 1110±10 million years ago. This includes the extrusion of rocks with both a reverse and normal remanence. The sedimentary rocks of the Nopeming Formation and related rocks were apparently deposited only shortly before the onset of volcanism since they commonly show signs of soft-sediment deformation by the overlying volcanic flows. The ages of deposition of the post-volcanic sedimentary sequences, the Oronto and Bayfield groups and equivalents, have not been determined, except for an apparent minimum age of oil in fluid inclusions in the Nonesuch Formation, dated at 1047±35 Ma (Kelly and Nishioka, 1985). The minimum age of the strata may be constrained by an early Late Proterozoic glaciation about 850 Ma ago (Stewart, 1972) that deposited tillites in eastern Washington (Scott Member of the Pocatello Formation), British Columbia (Shedroof and Toby Conglomerates of the Windermere Group), northern Utah (Mineral Fork and Dutch Peak tillites), and possibly the Appalachians of southern Virginia and adjacent Tennessee and North Carolina (Mount Rogers Formation) (see Hambrey and Harland, 1981). The presence of these tillites at about the same latitudes both east and west of the MRS suggest a continent-wide glaciation. Such a glaciation would likely have deposited similar tillites and related units in any actively subsiding basins associated with the MRS. To date no unit of the Keweenawan Supergroup has been interpreted as a tillite, except for very early interpretations of the Copper Harbor Conglomerate. This evidence suggests that the deposition of the Oronto and Bayfield groups was completed before the onset of glaciation about 850 Ma ago.

Extensional tectonic activity that affected the Lake Superior area about 1350 Ma ago which led to the deposition of the Sibley Group is generally considered a part of the MRS because it pre-dates the volcanic activity by about 150 Ma. Additionally, the mafic dikes of the Mackenzie dike swarm (1281-1267 Ma) and Sudbury dikes (1238 Ma) also pre-date the formation of the MRS.

The MRS appears to be the product of two major stress regimes, an initial extensional phase followed by a compressional phase. The details of these stress regimes, their origins and the details of their structural manifestations within the MRS are only poorly understood. The timing of the initial extensional phase (ca. 1110-1050 Ma as estimated from the age of Keweenawan Supergroup volcanics) is coincident with the terminal Grenvillian Ottawan Orogeny (1120-1030 Ma, Windley, 1989). Windley (1989) proposed that the MRS may have been produced by this episode of orogenic activity in much the same way that the Rhine Graben was produced by the Eocene Alpine Orogeny.

The genetic processes responsible for the second phase of MRS development, the compressional phase, are even more speculative. It may represent some change in the direction or magnitude of Grenville orogenic stresses, or it may have been the product of crustal stresses related to the Llano Orogeny, the collision of an island arc and continental mass (South America?) with proto-North America in the Texas region (Fig. 4) 1000 to 1200 Ma (Coffman et al., 1986). If, as Chase and Gilmer (1972) determined, the opening of the Midcontinent Rift can be represented by a dextral rotation of the southeastern portion of the continent by approximately 1.2° about a pole of rotation located in north-central New Mexico, then northerly-directed compressive stresses related to the Llano Orogeny in the Texas region could have acted to reverse the rotation and compress the rift. Much remains to be learned about the tectonic history of the MRS.

Extensional Phase

The first manifestation of the extensional stresses that ultimately led to the formation of the MRS was the initial development of a basin, along what would be the axis of the MRS, due to extensional thinning of the crust in the Lake Superior Basin and presumably along the entire trend of the rift. This basin was the site of deposition of fluvial and lacustrine rocks of the Nopeming Formation and related units

This early clastic sedimentation was followed shortly by the initial volcanic flows, indicating the breaching of the crust by feeder dikes that combined to create a series of flood basalt plateaus that generally thickened towards the axial basin. A number of plateaus developed in the Lake Superior region, with volcanism occurring at various times between about 1100 and 1000 Ma ago, separated by minor periods of erosion and the local deposition of interflow clastic rocks. Individual flows range in thickness from a few feet to hundreds of feet (Green, 1982) and varied in composition from pyroxine, olivine basalt cumulates to rhyolites, with an average tholeiitic composition. Each plateau eruption was accompanied, and followed, by a gentle local subsidence, with plateaus eventually merging into a continuous mass of volcanic flows, generally confined to the limits of the basin. These extrusives eventually accumulated to thicknesses in excess of tens of thousands of feet. Green (1982) reported that Keweenawan lavas in the Lake Superior area were deposited on a generally flat-lying surface (dipping slightly towards the axis of the basin) and show no evidence of fault-bounding or thermal doming prior to eruption. Petroleum industry seismic data show that the overall structure of the volcanic package is synclinal, with the axis of the syncline coincident with the axis of the rift. Interpretations of some of these seismic data collected in Iowa (Anderson, "Interpretation of geophysical data..." this volume) indicate that the volcanic rocks form a thick package, probably mostly contained between the bounding faults of the central graben, and no Keweenawan volcanic rocks have been identified beyond these faults along the interpreted seismic profiles. Although some extra-graben volcanic rocks may have been lost to erosion, it is possible that in Iowa, and other areas of the MRS, the graben-bounding faults were developed during volcanism.

As volcanism waned, the crust continued to subside under the loading of the thick mafic volcanic package in the axial basin, normal faults developed (or continued to develop) on the margin of the basin, and a series of central grabens formed along the trend of the MRS. Apparent coeval regional subsidence along the trend of the MRS may have resulted from crustal cooling that accompanied the cessation of igneous activity. Graben subsidence, however, soon began to out-pace regional subsidence, and erosion of volcanic rocks from the foot walls of the normal faults bounding the grabens were the source of a series of alluvial fans that prograded towards the graben axis (the Copper Harbor Conglomerate). Sediments became increasingly fine-grained towards the axis of the graben, grading from coarse conglomerates, to sandstones, and finally to siltstones and mudstones, deposited in a series of lakes that developed along the graben axis (the Nonesuch Formation). These warm tropical lakes harbored an abundant population of algae, fungi, and bacteria which were preserved. Outside of the graben, rivers deposited siliciclastic sediments, eroded from pre-MRS basement rocks, as the drained towards the interiors of the graben. Eventually the subsidence of the axial grabe slowed and the central lakes apparently coalesce and expanded beyond the limits of the graben resulting in the deposition of the carbonaceou lacustrine sediments of the Nonesuch Formatio and equivalent units to some unknown distanc beyond the central graben.

Finally, the axial lakes were filled and the fluvi sandstone-dominated facies (Freda Formation an equivalents) prograded from the rift margins int the center of the rift. Subsidence continued at slow rate as Freda rivers, flowing primarily dow the axis of the rift, deposited thick sequences c fluvioclastics.

Compressional Phase

The switch from extensional to compressiv stresses on the MRS probably occurred during, o very soon after, the deposition of the Freda Formation. The tectonic activity associated witl the compression is not well understood. Th activity included the reversal of the sense o movement on the normal, graben-bounding fault and uplift of the graben to create the central horst The continuous nature of the reflections from the basalt flows on the horst, as seen on petroleum industry Vibroseis data, attest to the uniformity o the uplift. On the St. Croix Horst Oronto Group sediments near the bounding faults were deformed to near-vertical orientations, while in other areas the units remained nearly horizontal. Deposition of the fluvially dominated clastic rocks that constitute the Bayfield Group and equivalent units began with Oronto Group sediments eroded from the horst, reworked, and combined with quartz-rich sediments eroded from the older rocks beyond the limits of the rift. Bayfield Group units were then deposited, primarily in basins flanking the horst and on local, down-dropped areas on the horst.

The basal unit, the Orienta Sandstone, is texturally and mineralogically more mature than Oronto Group sediments (Meyers, 1971). These sediments were deposited by meandering streams that were moving towards the axis of the rift and northward along the axis (Ojkangas and Morey, 1982b).

The Orienta grades upward into the quartz arenites of the Devils Island Sandstone and equivalents, the most mature rocks in the

Keweenawan Supergroup in the Lake Superior region. The Devils Island has been interpreted as a lacustrine deposit, possibly including reworked Orienta, that was further matured by wave and current action in the lake (Ojkangas and Morey, 1982b).

The apparent uppermost unit in the Bayfield Group, the Chequamagon Sandstone, is most easily explained as the equivalent of the Orienta Sandstone, exposed on the western limb of a synclinal feature on the Bayfield Peninsula, as proposed by Mudrey (1979). Alternatively, since it is so similar in appearance and composition to the Orienta, it may represent a return to the fluvial conditions that prevailed during the deposition of the Orienta.

TECTONIC SETTING OF THE MIDCONTINENT RIFT SYSTEM

The MRS appears to be strongly controlled by preexisting structures. The structural features that control the trend of the MRS are most evident on maps of magnetic anomalies of the region. These preexisting structures led to the natural division of the MRS into five segments.

Lake Superior Segment

At its northern end in the central Lake Superior region (Fig. 5) the MRS is characterized by a central horst bounded by the Isle Royale Fault Zone on the northwest, by the Keweenaw Fault Zone on the south, and apparently by the Thiel Fault Zone on the east (Dickas, 1986). This segment of the rift is usually called the Lake Superior segment. The rift system in this area generally follows the east northeast trend of the structural grain of the Wawa Subprovince of the Greenstone-Granite Terrane near whose southern margin it is developed. In this segment Oronto Group sediments are preserved on the central horst. At the western end of Lake Superior the rift crosses the Great Lakes Tectonic Zone, the suture between the Greenstone-Granite Terrane and the ancient Minnesota Terrane.

Minnesota Segment

The rift continues on a more southerly trend across the Minnesota Terrane (Fig. 5). This section of the MRS is called the Minnesota segment. The central horst in this area, the St. Croix Horst is bounded on the southeast by the Lake Owen-Hastings Fault Zone and on the northwest by the Douglas Fault Zone. It is flanked over most of its length by clastic-filled basins. The eastern clastic basin apparently is areally more extensive than the western basin, especially in southeastern Minnesota, and may indicate a pervasive asymmetry in that portion of the MRS. The St. Croix Horst is primarily capped by Keweenawan basalts and related igneous rocks but also includes several areas where later Keweenawan Supergroup clastic sedimentary rocks are preserved (Sims, 1990), including the Twin City Basin and Ashland Syncline.

The St. Croix Horst continues in a southwesterly direction to south-central Minnesota where it abruptly terminates against the Belle Plaine Fault Zone, at the approximate location of the Penokean Suture Zone (see Fig. 5). The Belle Plaine Fault Zone is a north northeasterly trending structure that separates the Minnesota segment of the MRS from the Iowa segment and displays apparent transform motion. It is composed of a series of subparallel faults that bound blocks capped with Keweenawan volcanic and clastic rocks (Sims, 1990).

Iowa Segment

The Iowa segment of the MRS extends in a southwesterly direction from the southern end of the Belle Plain Fault Zone just north of the Iowa border, about 80 miles southeast of the St. Croix Horst (Fig. 5). The Iowa segment is dominated by the Iowa Horst, bounded by the Thurman-Redfield Structural Zone on the southeast and the Northern Boundary Fault Zone on the northwest, and flanked by five clastic sedimentary basins. Three of these basins are located southeast of the Iowa Horst, from north to south the Wellsburg, Ankeny, and Shenandoah basins. Two basins are preserved northwest of the horst, north to south the Duncan and Defiance basins. The flanking basins are identified by their pronounced gravity minima interpreted as depressions filled with relatively low density clastic sedimentary rocks. The three eastern basins apparently are interconnected forming a continuous sequence of clastic rocks southeast of the Iowa Horst. The two western basins are connected in a similar fashion. The areal extent of the eastern basins is slightly greater than the western basins, but the Iowa segment is more symmetrical than the Minnesota segment

The trend of the MRS in the northern portion of the Iowa segment is subparallel to the southwesterly trend of the Penokean Suture Zone, and probably inherited the trend of the arc sequences that were accreted to the Superior Craton during the Penokean Orogeny. Near the center of Iowa, the rift intersects the western extension of the Fayette Structural Zone. In this area the trend of the Iowa Horst and the rift zone deflects to the west-southwesterly trend of the Fayette Structural Zone. The MRS continues to its intersection with the Central Plains Suture Zone, and across the suture into Nebraska to a point just north of the Kansas border.

The Keweenawan Supergroup sedimentary rocks once present on the Iowa Horst were erosionally removed from most areas. Clastic rocks are preserved on a step-faulted block on the eastern edge of the horst in central Iowa, in the Stratford Basin in the center of the horst, in the Mineola Graben on the axis of the horst at the Nebraska border, and possibly in several local areas in Nebraska.

The Iowa segment of the MRS is truncated in eastern Nebraska by a second major transform fault-like offset of the rift, a north northeast-trending structure, referred to here as the Big Blue Fault Zone, with a trend coincident with the Big Blue River. The western extension of a northwest-trending linear feature, the Central Missouri Tectonic Zone (Kisvarsanyi, 1984), also passes through the gap between the Iowa and Kansas segments of the MRS and may be a factor controlling the offset.

Kansas Segment

The Kansas segment of the MRS, like the other segments is dominated by a central horst flanked by clastic-filled basins (Sims, 1990). The horst is the smallest of any segment, extending only about 150 miles in a south southwesterly trend from the Nebraska border (Fig. 5). The trend of this segment of the rift is parallel to the Paleozoic Nemaha Ridge and Humboldt Fault Zone in Kansas. The first oil exploration well to test the deep clastic rocks of the MRS, the Texaco Poersch #1, was drilled in the northern end of the Kansas central horst and was summarized by Berendsen and others (1988). The well initially penetrated about 4500 feet of primarily mafic igneous rocks o the horst before passing into about 4000 feet o dominantllly sedimentary rocks, possibly younge Keweenawan clastic rocks that had been overridde by the reverse faults that bound the horst.

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INTERPRETATION OF GEOPHYSICAL DATA OVER THE MIDCONTINENT RIFT SYSTEM IN THE AREA OF THE M.G. EISCHEID #1 PETROLEUM TEST, CARROLL COUNTY, IOWA

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INTRODUCTION

Over most of its 940 mile (1500 km) length (from eastern Lake Superior to south-central Kansas) the rocks of the Midcontinent Rift System (MRS) lie buried beneath Phanerozoic strata that reach thicknesses in excess of 5000 feet (1500 m). Although Midcontinent Rift rocks in the Lake Superior area outcrop belt have been the focus of continuing studies since they were first described by Bigsby (1824), the magnitude of the structure and its extent to the south have only been recognized since the initiation of geophysical studies in the mid 1940s.

The MRS is characterized over much of its length by a pronounced gravity signature that includes a strongly positive axial anomaly flanked by parallel belts of gravity minima (Fig. 1). The feature in Iowa displays maximum Bouguer gravity anomaly values in excess of +65 milligals and less than -110 milligals. Magnetic anomaly maps show associated linear anomalies, becoming strongly positive in northern Iowa (Fig. 2) and Minnesota. These geophysical signatures have been called the Midcontinent Gravity Anomaly or Midcontinent Geophysical Anomaly (MGA) by geophysicists, names that are still often applied to the structure.

Woollard (1943) published a transcontinental gravity and magnetic profile that crossed the MRS in Kansas, providing the first look at its geophysical signature. In 1950, Lyons published the first map that showed the gravity anomaly extending from Kansas to Lake Superior. He later (Lyons, 1959) named the feature the Greenleaf Anomaly after the Kansas town where the anomaly reaches a local maximum value. A number of gravity anomaly maps of the region have been published subsequently, including a Bouguer Gravity Anomaly Map of Iowa (Anderson, 1981) compiled from a series of generally township-centered stations.

Following Woollard's 1943 magnetic traverse, a series of regional surveys defined the magnetic character of the MGA. Among these early studies were a series of three aeromagnetic surveys by the Iowa Geological Survey and U.S. Geological Survey (U.S.G.S.), conducted between 1958 and 1962. These analog surveys, flown at 1000 feet (300 m) above ground level and a one mile flight-line spacing, were compiled and published by the U.S.G.S. (Henderson and Vargo, 1965), and combined with additional data to create the Aeromagnetic Map of Iowa (Zietz et al., 1976).

One of the first seismic studies of the MGA was a series of refraction surveys conducted by Cohn (1966) in Minnesota, Wisconsin, and Iowa. These data were critical to the identification of the feature's mafic volcanic-dominated central horst and flanking clastic-filled basins and the interpretation of the feature as a rift (Ocola and Meyer, 1973). Recent interest in the petroleum potential of the MRS has led to the collection of thousands of kilometers of deep reflection data by exploration and service companies. Recently, some of this industry data have been released from confidential status and have become available for limited public examination and interpretation.

This article will report interpretations from reflection seismic data and 2-D gravity modelling of the MRS in the area of the Amoco M.G. Eischeid #1 petroleum test in Carroll County, Iowa. The reflection seismic data were originally collected by Petty-Ray Geophysical Geosource, Inc. and were released for this study by Halliburton Geophysical Services, Inc. Interpretations were constrained by magnetic data displayed on maps by Henderson and Vargo (1965) and Zietz and others (1976) and by drill data, including information from the Eischeid test.

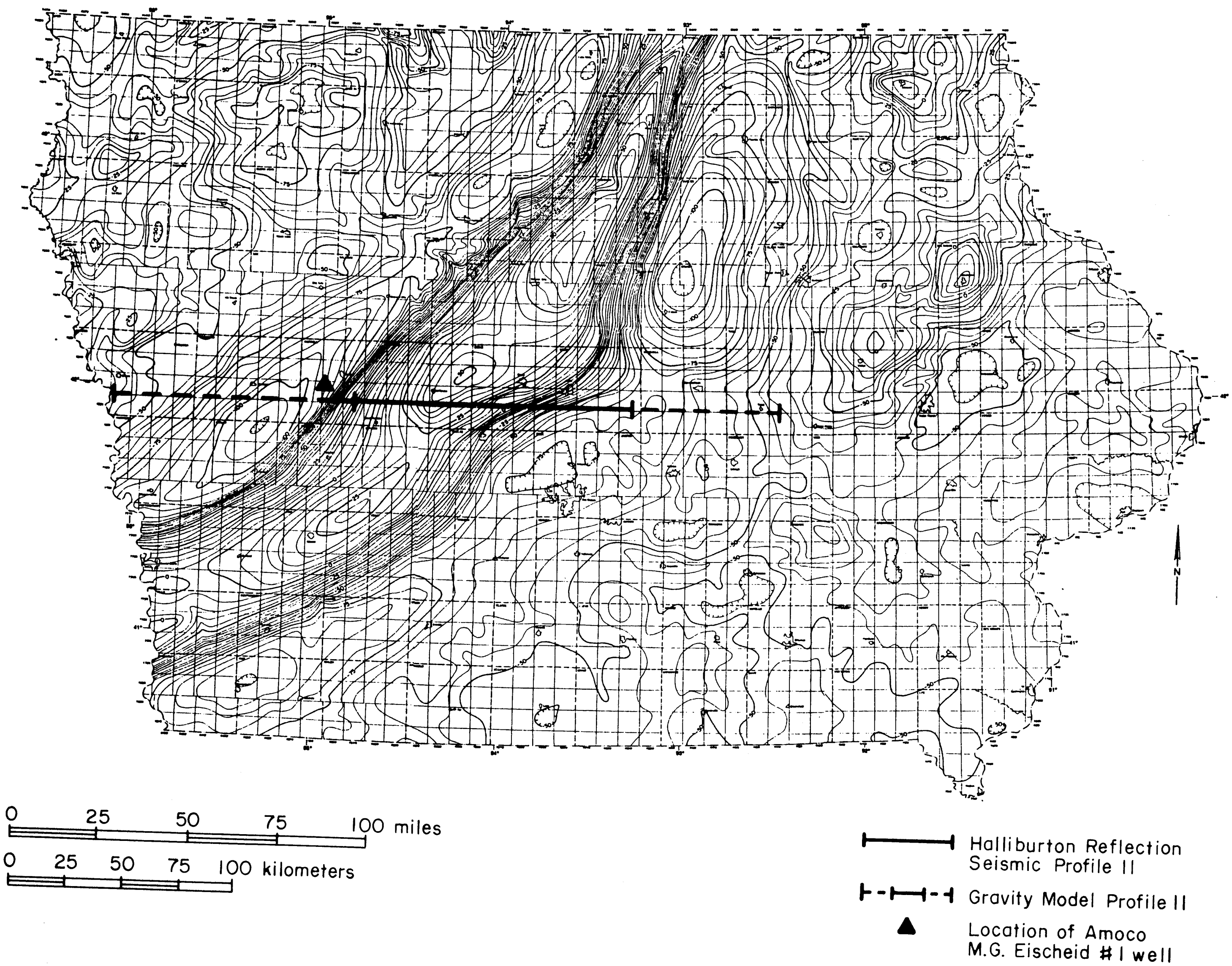

Figure 1. Bouguer gravity anomaly map of Iowa (Anderson, 1981) with Halliburton reflection Profile 11 and gravity model profile 11. Contour interval = 100 milligals.

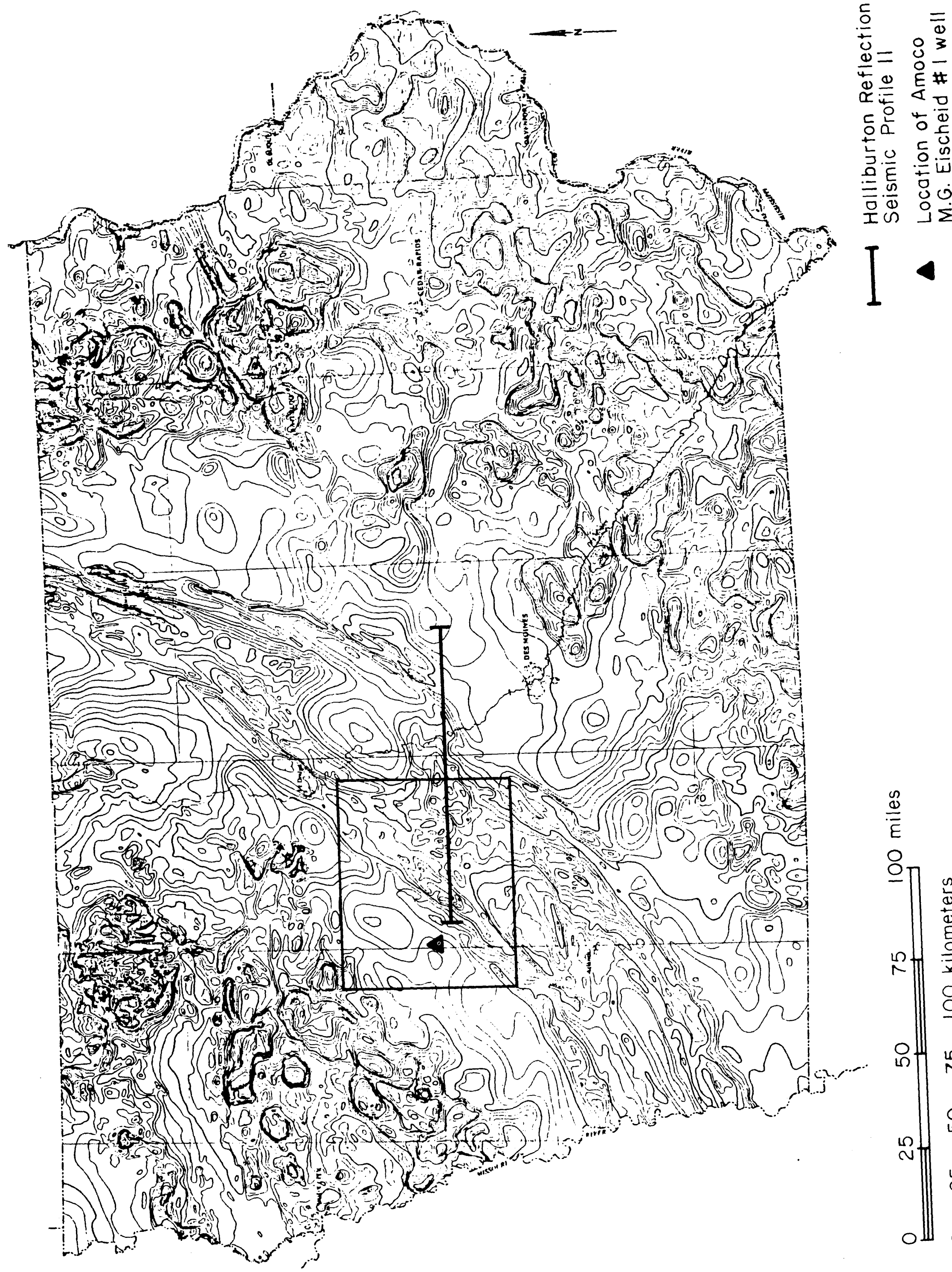

Figure 2. Aeromagnetic map of Iowa (Zietz et al., 1976) with Halliburton reflection profile 11. Box shows location of Fig. 3. Contour interval = 100 and 500 gammas.

GEOLOGY OF THE MIDCONTINENT RIFT SYSTEM IN IOWA

The geologic history of the MRS in Iowa as it is presently understood is detailed by Anderson ("Review of Precambrian...," this volume). In Iowa the rift consists of a central horst (named the Iowa Horst) flanked by a series of clastic-filled basins. The Iowa Horst appears to be dominated by basalt flows, similar to those observed in the rift's Lake Superior outcrop area, but also includes several plutons (mafic and felsic). Clastic rocks have been preserved on the horst in several areas. Flanking the horst are a series of five basins containing clastic sedimentary rocks with interpreted thicknesses of up to 30,000 feet (9 km) that include a dense basal and a less-dense upper sequence.

DRILL DATA

Although 72 drill holes penetrate through the Phanerozoic cover and into the rocks of the MRS, they are very poorly distributed and vast areas of the rift are unexplored by the drill. Most of these rift penetrations are clustered in a few areas where natural gas is stored in domes that developed in lower Paleozoic rocks over reactivated rift structures. The Amoco M.G. Eischeid #1 well was drilled about 5 miles (8 km) west of the Iowa Horst, into the northern end of the Defiance Basin, the horst-flanking basin in west-central Iowa. The Eischeid well penetrated about 3500 feet (1100 m) of Phanerozoic strata and about 14,200 feet (4400 m) of Midcontinent Rift clastic rocks, including about 7200 feet (2200 m) of the Upper "Red Clastic" Sequence rocks and about 7000 feet (2100 m) of the Lower "Red Clastic" Sequence.

GRAVITY MAP INTERPRETATION

Interpretation of the Bouguer Gravity Anomaly Map of Iowa (Anderson, 1981) clearly displays the major structures that characterize the MRS in Iowa. The strongly positive axial anomaly is the product of the thick, dense sequence of mafic-dominated volcanic and plutonic rocks that comprise the Iowa Horst, and its shallow location at the Precambrian surface. The flanking gravity minima are produced by the thick sequence of less dense, rift-related, clastic sedimentary rocks that are preserved in the basins marginal to the horst. The very steep gravity gradient between the axial high and the flanking lows attests to the al contact between the two features and disparate densities.

The Eischeid #1 well is located in the nor end of the Defiance Basin, (see Anderson, "R of Precambrian...," this volume). These b range in depth, as modelled, from about 10,0 30,000 feet (3 to 9 km) and cover a total of a 17,000 square miles (44,000 km^2) in Iowa. Gr modelling indicates that the Defiance Basin c an area of about 400 square miles (1000 km^2) reaches a maximum model depth of about 2 feet (7700 m) near the town of Defiance in Sh County, about 25 miles (40 km) southwest o Eischeid site.

The Iowa Horst ranges in width from abou to 55 miles (21 to 88 km) in Iowa, and it is abou miles (77 km) wide near the Eischeid Modelling controlled by seismic data indicates the horst margins are thrust over the clastic roc the flanking basins along a series of reverse fa which dip from about 15 to 70 degrees and h vertical displacements from about 15,000 to 30 feet (4600 to 9200 m) (although these may minimum values since post-uplift erosion removed an unknown thickness of rocks from top of the horst).

MAGNETIC MAP INTERPRETATION

Over most of its trend in Iowa the magn signature of the MRS is characterized by a serie linear anomalies following the trend of the gra anomaly with magnetic intensities similar state-wide regional values. The lack of a str magnetic signature associated with the gener highly magnetic mafic igneous rocks of the Io Horst can probably be attributed to its remane components. In the Lake Superior region igne rocks of the rift have been observed to displa strong remanent component, frequently twice large as the induced component of th magnetization. Also, the basal volcanic seque displays a reverse polarity in the reman component, while the upper part of the seque displays a normal polarity. In much of Iowa appears that the deeper reversely-polarized roc are more abundant on the central horst than are t upper normally-polarized rocks, producing a n magnetic signature that is very near region intensities. In northern Iowa and Minnesota, t signature of the central horst becomes strong positive, suggesting an increase in the thickness of the upper, normally-polarized rocks compared to the underlying, reversely-polarized rocks.

The clastic rocks that fill the flanking basins are magnetically transparent, and their impact on the observed magnetic field is to increase the depth of the underlying magnetic basement, lowering the field intensity and filtering out the shorter-wavelength components of the field. On the magnetic map of Iowa (Zietz et al., 1976) this effect can be seen as a series of smooth, low intensity magnetic minima with a general trend parallel to the axis of the rift. The small contour interval (20 gamma) on the Magnetic Anomaly Map of the Midcontinent Rift (Henderson and Vargo, 1965) clearly shows the limits of the magnetic (igneous) rocks of the Iowa Horst and their contact with the non-magnetic (clastic) rocks of the flanking basins (Fig. 3). The shallow depth of the magnetic rocks of the Iowa Horst produce a high-relief surface characterized by closely-spaced, tightly-curving contours. Off the horst, the greater depth of the magnetic basement beneath the clastics produces a much lower relief surface with more widely-spaced, smoothly-curving contours.

REFLECTION SEISMIC INTERPRETATIONS

Reflection seismic profile 11 begins at a point about 20 miles (32 km) east of the Iowa Horst, and continues westward for about 80 miles (128 km), ending about 3 miles (5 km) east of the western margin of the horst and 8 miles (13 km) east of the Eischeid well (Fig. 1). Interpretations were made on a migrated section that displayed six seconds of 24 fold Vibroseis data.

On reflection profile 11 the continuous, parallel reflectors that are evident at the top (0.9 seconds) of the sections identify the Paleozoic marine sedimentary units that overlie the rocks of the MRS (Fig. 4). The most prominent features below the Paleozoic reflectors are long, nearly continuous, parallel reflectors that characterize the basalt-dominated volcanic rocks of the Iowa Horst. These reflectors indicate that the lava flows are nearly horizontal except at the western end of the seismic line where a large synformal structure appears in the volcanic rocks (Fig. 5). Near the eastern edge of the Iowa Horst on profile 11 a large down-dropped block was encountered (Fig. 4). The block is overlain by two seismic units, a lower sequence characterized by discontinuous, wavy, parallel reflectors, and an upper sequence with very discontinuous, short wavy reflectors (Fig. 6). These two sequences are interpreted as clastic units, possibly similar to the two clastic units associated with the MRS in the Lake Superior area, called the Oronto and Bayfield groups in Wisconsin. They apparently have been structurally preserved from the erosion that removed the sedimentary rocks from the rest of the horst along the section. Reflectors similar to those of the upper and lower clastic sequences are also present to the east of the down-dropped block, in the eastern flanking basin.

The juxtaposition of the clastic rocks on the eastern down-dropped block with correlative units in the eastern flanking basin indicates that the rocks of the Iowa Horst are thrust over the rocks of the flanking basin. Indications of the same thrust relationship can be seen on the far western edge of seismic profile 11 (Fig. 5), where reflectors similar to those characteristic of the lower and possibly upper sequence rocks can be observed below the Iowa Horst basalt flows.

2-D GRAVITY MODELLING ALONG SEISMIC PROFILE 11

For 2-D gravity modelling across the MRS a profile was constructed along seismic profile 11 but extended further east and west. The gravity profile begins on the western edge of the Defiance Basin, about 45 miles (72 km) west of the western edge of the Iowa Horst, and continues eastward for 175 miles (280 km), beyond the limits of the eastern flanking basin, to a point about 65 miles (104 km) east of the eastern edge of the horst. For control, a true depth model of interpreted seismic profile 11 (Fig. 4 B) was constructed using velocities displayed in Table 1. The true depth model was expanded east, west, and down (to include the entire crust). Upper (0 -8 miles, 0 - 13 km), middle (8 - 14.5 miles, 13 - 23 km), and lower (14.5 - 30 miles, 23 - 48 km) crustal depths were delineated. Densities similar to those measured for similar rocks in the Lake Superior outcrop belt, and utilized in similar modelling projects (e.g., Chandler et al., 1989), were assigned to each rock sequence identified in the model (Table 1), with densities increasing with crustal depth.

Gravity modelling was conducted using GRAVMAG, a 2-D modelling program created in part from GRAV2D (obtained from Purdue University where it had been adapted and

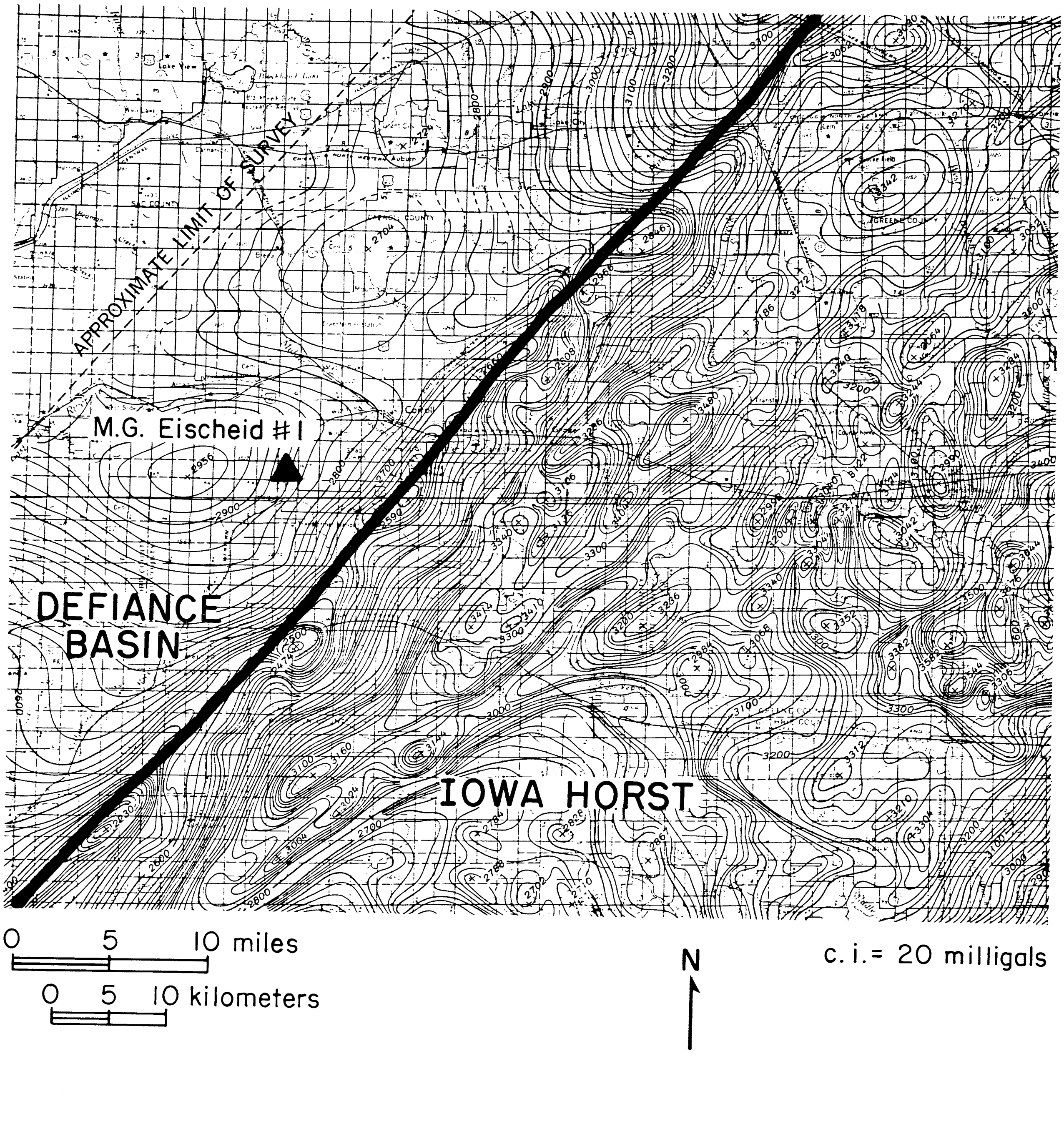

Figure 3. Aeromagnetic map of a portion of west-central Iowa (Henderson and Vargo, 1965) showing interpreted western margin of Iowa Horst.

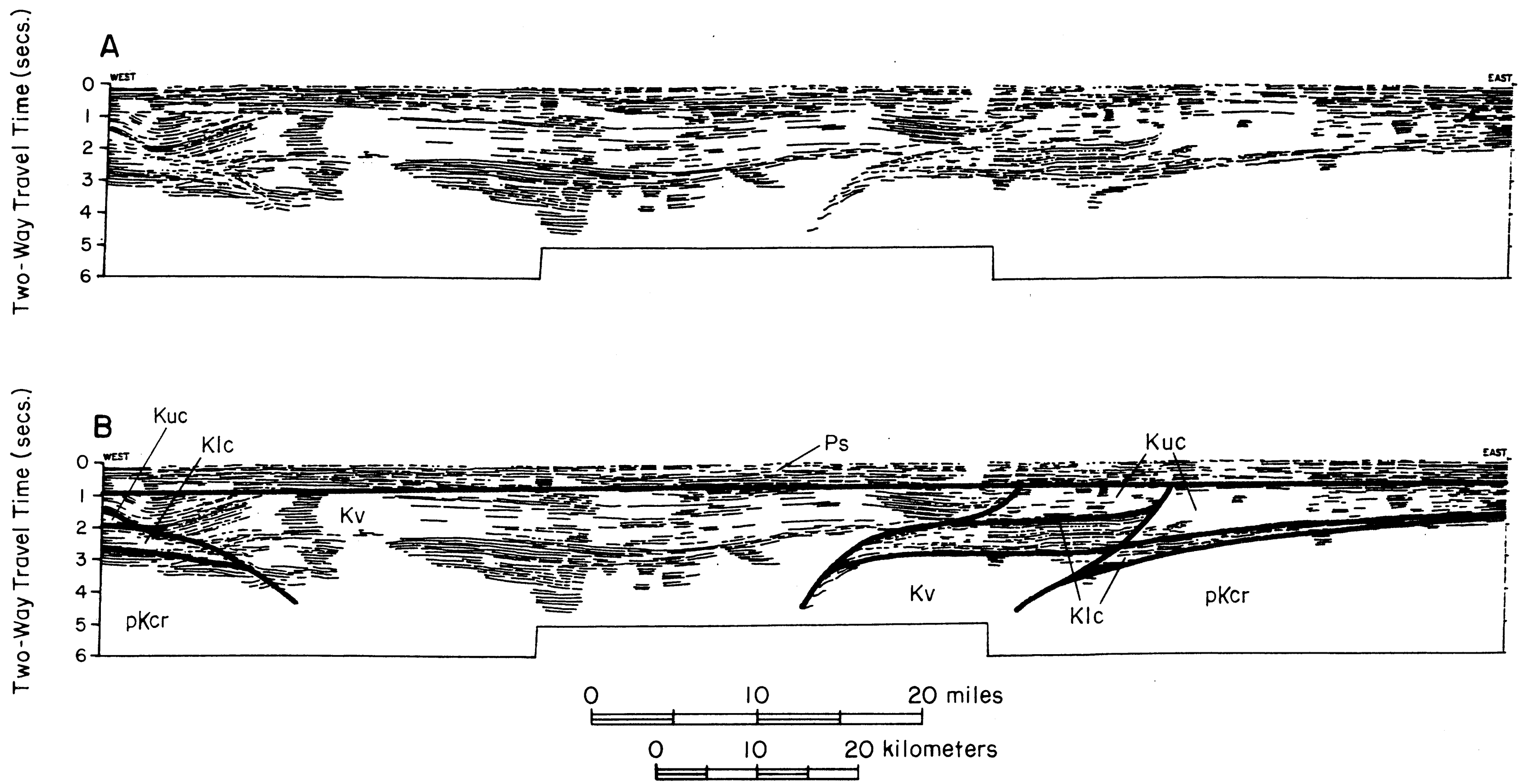

Figure 4. Uninterpreted (A) and interpreted (B) line drawings of reflection seismic profile 11. Seismic data courtesy of Halliburton Geophysical Services, Inc. Ps=Paleozoic sediments; Kv=Keweenawan volcanics; Kuc=Keweenawan Upper "Red Clastic" Sequence; Klc=Keweenawan Lower "Red Clastic" Sequence; pKcr=pre-Keweenawan crystalline rocks.

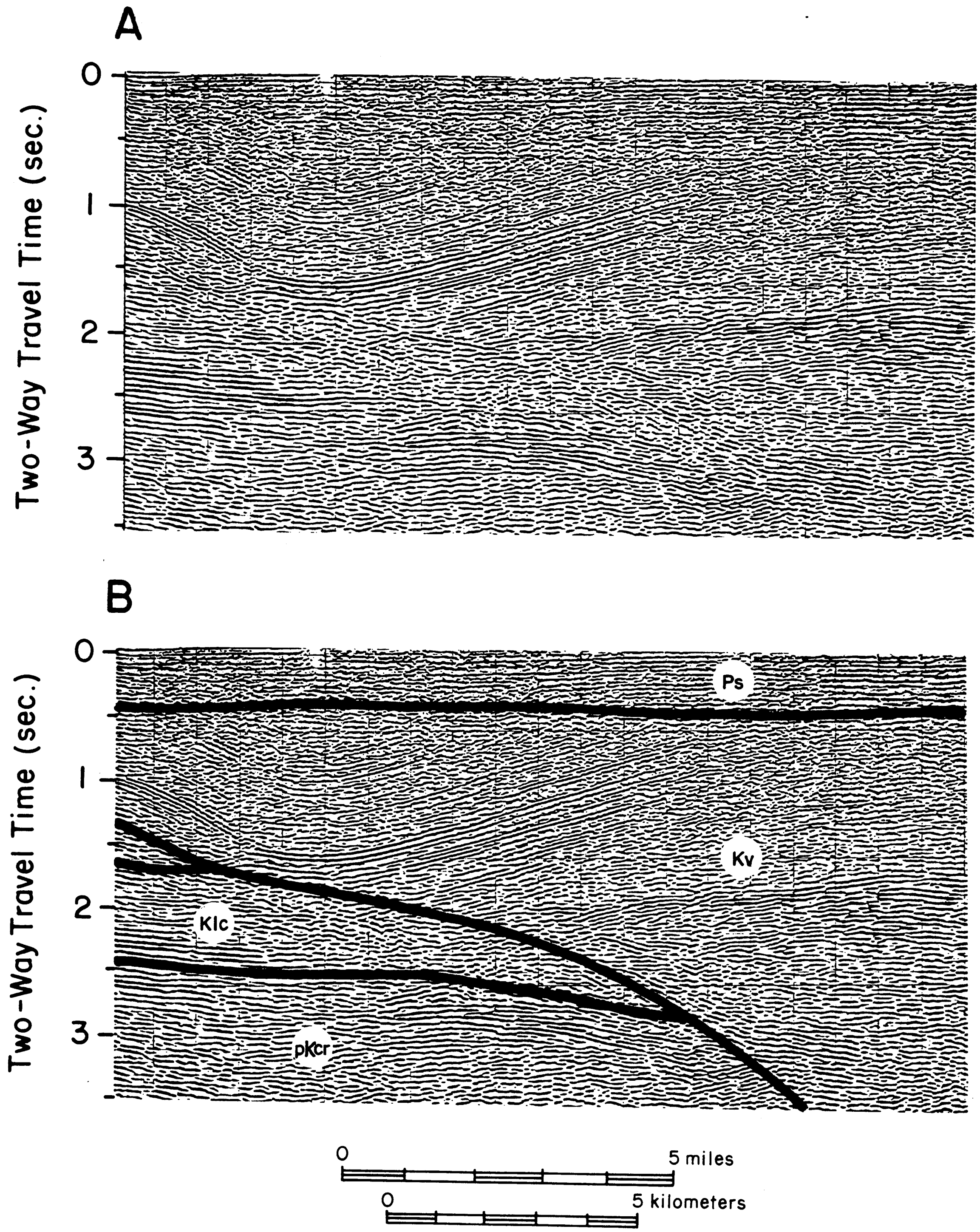

Figure 5. Uninterpreted (A) and interpreted (B) migrated reflection seismic data from western area of profile 11. Seismic data courtesy of Halliburton Geophysical Services, Inc. Ps=Paleozoic sediments; Klc=Keweenawan Lower "Red Clastic" Sequence; Kv=Keweenawan volcanics; pKcr=pre-Keweenawan cryatalline rocks.

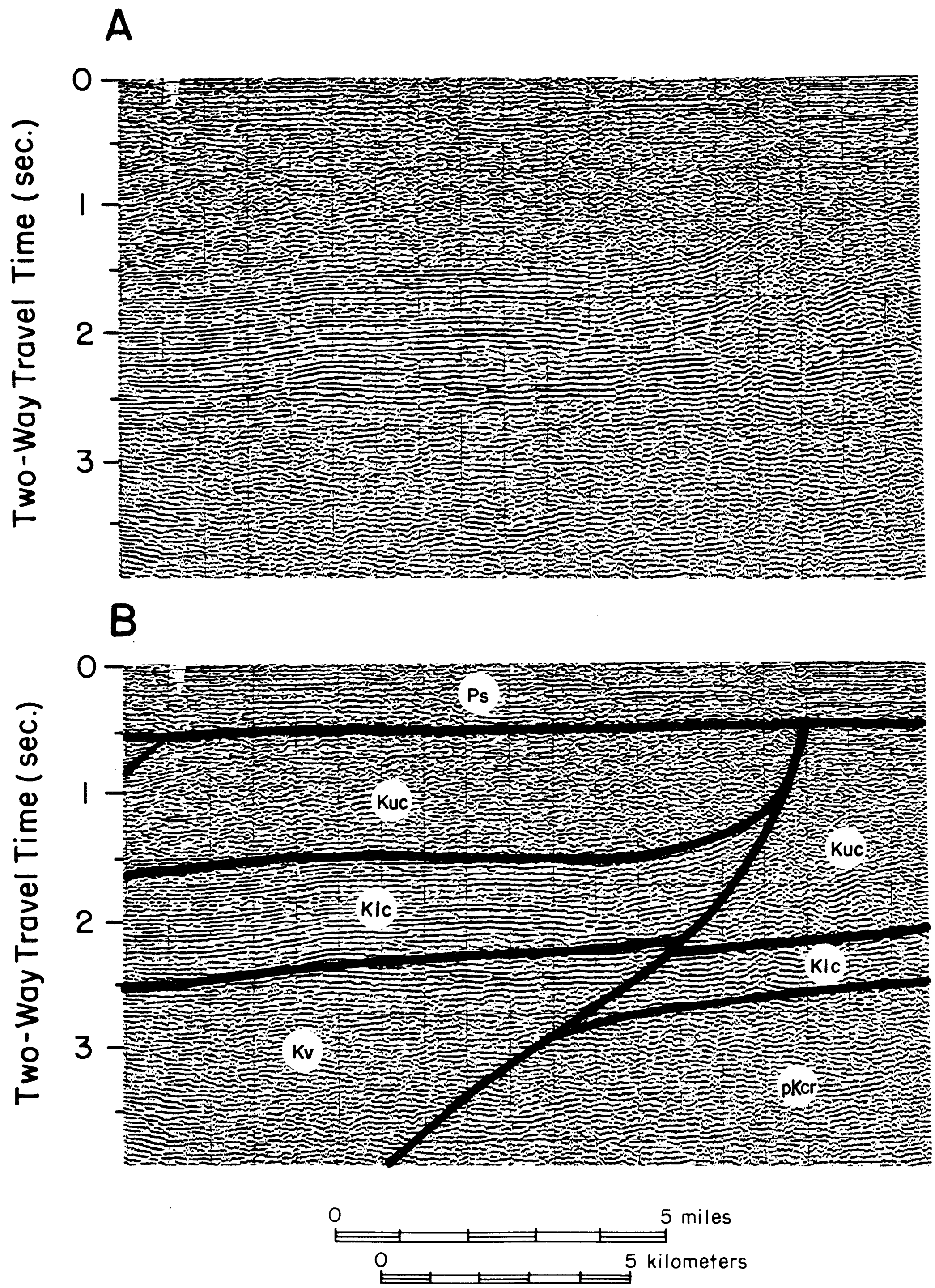

Figure 6. Uninterpreted (A) and interpreted (B) migrated reflection seismic data from central area of profile 11. Seismic data courtesy of Halliburton Geophysical Services, Inc. Ps=Paleozoicsediments; Kv=Keweenawan volcanic rocks; Kuc=Keweenawan Upper "Red Clastic" Sequence; Klc=Keweenawan Lower "Red Clastic" Sequence; pKcr=pre-Keweenawan crystalline rocks.

Table 1. Densities and seismic velocities used in modelling.

LITHOLOGIC UNIT	VELOCITY (ft/sec)	DENSITY (g/cc)
Phanerozoic sediments	9,000	2.44
upper Keweenawan clastics	13,200	2.40-2.45
lower Keweenawan clastics	15,800	2.70-2.75
Keweenawan volcanics		
upper crust	19,800	2.90
middle crust	----	2.97
zone of dikes	----	3.00
granitic plutons		
upper crust	----	2.67-2.68
middle crust	----	2.79
pre-rift crystalline basement		
upper crust	----	2.74-2.78
middle crust	----	2.81-2.85
lower crust	----	2.88

documented by Shanabrook, Ciolek, and Locher from equations developed by Talwani and Worzel, 1959). GRAVMAG was modified to run on IBM-compatible personal computers, use a batch file input, and produce an output product that displays the model and both calculated and observed gravity amomalies. GRAVMAG was written by Tom Vujovich, John Schmidt, Joost Korpel, and C. D. Hall of the Data Processing Bureau of the Iowa Department of Natural Resources for the Geological Survey Bureau.

The good fit of the gravity anomaly calculated from the seismic-based model along profile 11 to the observed gravity anomaly (Fig. 7) indicates that the interpretations from the seismic data are compatible with gravity data. Additionally, the limits of the horst as modelled are in agreement with interpretations of the magnetic maps and with Eischeid well data.

From the modelling it appears that the Eischeid well was drilled on the flank of a slight basement high that appears as positive deflection of the isogals that define the Defiance Basin on the Bouguer Gravity Map of Iowa (Fig. 1) and may relate to a low relief positive magnetic anomaly that can be observed on the magnetic maps of Iowa. The thicknesses of the upper and lower clastic sequences modelled on the gravity profile are similar to the thicknesses of the Upper and Lower "Red Clastic" sequences observed in studies of samples from the Eischeid well (see Witzke, this volume). The velocities and densities used to identify the upper and lower clastic sequences in the gravity model are within the range of those measured from rocks in the Lake Superior outcrop region and used by Chandler and others (1989) in their modelling, suggesting a petrophysical correlation of the Upper and Lower "Red Clastic" sequences with the Bayfield and Oronto groups of northern Wisconsin.

The modelling also suggests that MRS volcanic rocks on the Iowa Horst may continue to a depth of 15 miles (24 km) and that the horst may be underlain by a zone of dense feeder dikes (Fig. 7).

CONCLUSIONS

Interpretations of gravity, magnetic and reflection seismic data over the MRS in the vicinity of the Amoco M.G. Eischeid #1 well in western Carroll County, Iowa indicate that the rift is characterized by an axial horst (Iowa Horst) about 48 miles (77 km) wide that is dominated by mafic volcanic rocks and is flanked by clastic-filled basins which reach depths in excess of 25,000 feet (7700 m). The Eischeid well was drilled in the northeastern end of one of these basins, the Defiance Basin, about 5 miles (8 km) west of the western edge of the Iowa Horst. The Defiance Basin reaches a maximum model depth of about 25,000 feet (7700 m) about 25 miles (40 km) southwest of the Eischeid site. These interpretations, controlled by scant available drill data including the Eischeid well, suggest the presence of two clastic sequences, a less dense upper sequence and a denser lower sequence that

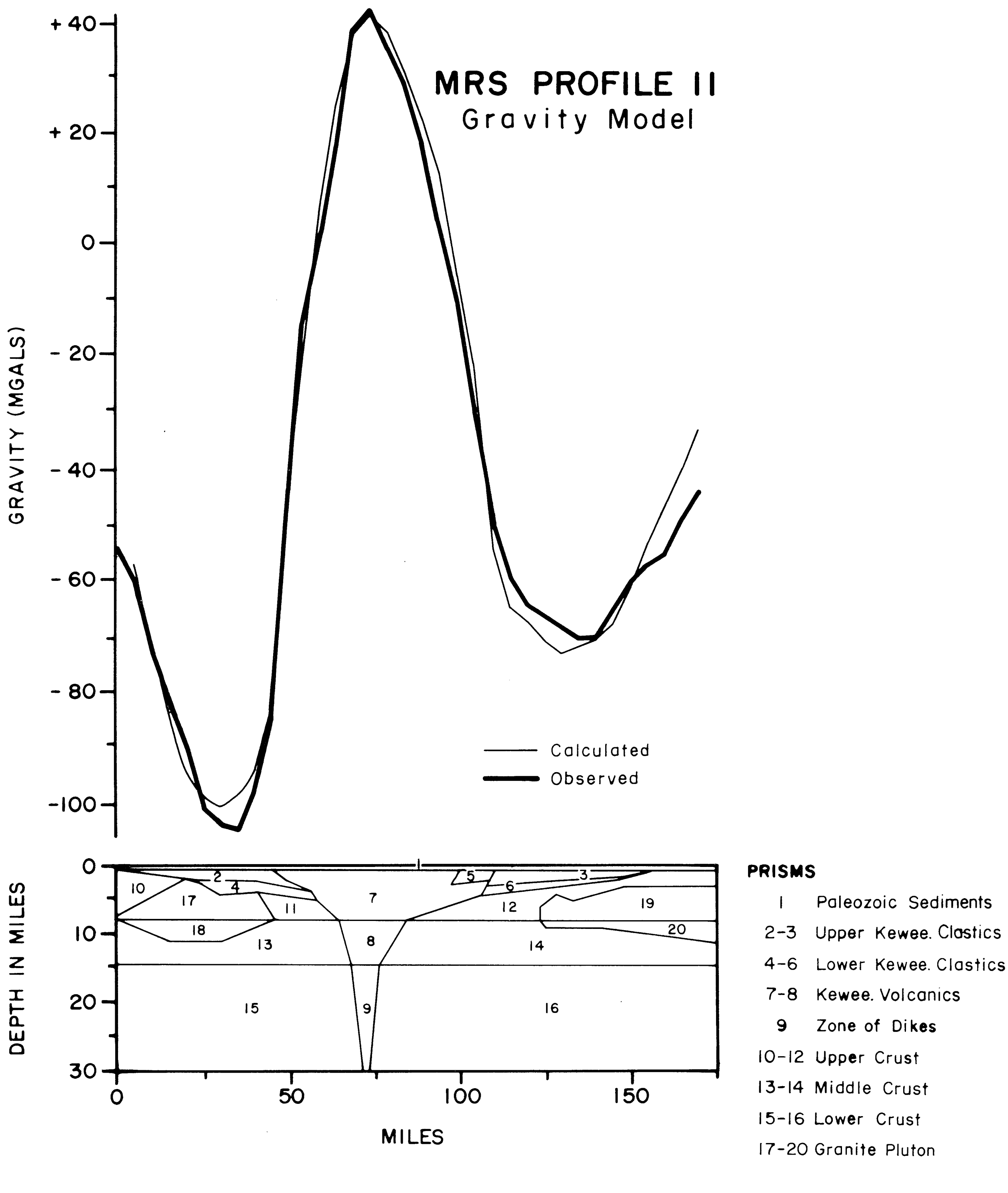

Figure 7. Gravity model of profile 11.

are correlative to the Upper and Lower "Red Clastic" sequences identified in the Eischeid well. They are lithologically similar to the Bayfield and Oronto groups, two groups of clastic rocks associated with the MRS in its Lake Superior outcrop belt.

The Iowa Horst is thrust over the clastic rocks in the flanking basin along reverse faults with angles ranging from about 15 to 70 degrees, and with total vertical displacements in excess of 25,000 feet (7700 m). The original displacement of these faults is not known since the thickness of rocks that have been erosionally removed from the top of the horst is not known. Interpretations of reflection seismic profile 11 and 2-D gravity modelling along an extension of that profile that passes near the Eischeid well suggest that the vertical displacement of the horst over the clastic rocks in that area is about 18,000 feet (5500 m) along a reverse fault that dips approximately 26 degrees.

ACKNOWLEDGEMENTS

The preparation of this article involved the efforts of a number of individuals whose work is gratefully acknowledged. Editorial comments by Dr. Robert Carmichael (University of Iowa Department of Geology) and Greg Ludvigson, Brian Witzke, Paul VanDorpe, and Art Bettis (Iowa Department of Natural Resources [IDNR]) were very helpful. I would also like to thank Bill Bunker, Mary Pat Heitman, Kay Irelan, and Pat Lohmann (IDNR) for their assistance in preparing this manuscript for publication.

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GENERAL STRATIGRAPHY OF THE PHANEROZOIC AND KEWEENAWAN SEQUENCE, M.G. EISCHEID #1 DRILLHOLE, CARROLL CO., IOWA

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ABSTRACT

Amoco's M.G. Eischeid No. 1 drillhole penetrates a sequence of Phanerozoic and Keweenawan sedimentary rocks, providing an exceptional look at the stratigraphic succession within a flanking basin of the Midcontinent Rift System in Iowa. The Phanerozoic sequence is consistent with the general stratigraphic succession in western Iowa. An interval of poorly-consolidated coarse-grained quartzose to feldspathic sandstone (Unit H) underlies the standard Phanerozoic sequence and overlies finer-grained and more consolidated Keweenawan strata; correlation of this unit is tentative, but it may represent a uppermost Keweenawan interval. The upper half of the lithified Keweenawan sequence (informally labelled Upper "Red Clastic" Sequence) is dominated by feldspathic sandstones interbedded with red-brown siltstones and shales; this succession resembles in a gross sense that seen in the Bayfield Group of the Lake Superior area, although compositional differences are apparent. The lower half of the Keweenawan sequence (Lower "Red Clastic" Sequence) contains sandstones, siltstones, and shales, dominantly red-brown but including significant amounts of reduced gray to black shales and mudstones in some units. The Lower Sequence displays a succession similar to that seen in the Oronto Group of the Lake Superior area, although compositional differences suggest contrasting sediment sources and/or structural-depositional setting between the two regions. Black shales are common to abundant in the Eischeid well from depths of about 15,000 to 16,400 feet (Unit C), in facies similar to those of the Nonesuch Formation (Oronto Group). The Keweenawan sedimentary sequence overlies a pre-Keweenawan mafic intrusion (1280 Ma) at the bottom of the hole.

INTRODUCTION

Samples and geophysical logs derived from Amoco's M.G. Eischeid No. 1 well, drilled near Halbur, Carroll County, Iowa, in 1987, have provided a unique opportunity to define a complete sequence of Phanerozoic and Keweenawan sedimentary rocks found within Iowa's portion of the Midcontinent Rift System (MRS) (Fig. 1). The following descriptions present a generalized lithostratigraphic framework for subsequent discussions in this volume. Stratigraphic units are subdivided based primarily on information derived from well cuttings (Exlog mudlog and grain-mount petrographic investigations of Ludvigson and others, this volume) as well as additional information from the suite of Schlumberger geophysical logs. The Exlog mudlog of well cuttings generally agrees with general observations made by the staff of the Iowa Department of Natural Resources Geological Survey Bureau, with only minor discrepencies noted. However, the relatively coarse sampling interval of well cuttings (typically 20-30 feet) has made resolution of some stratigraphic boundaries in the Phanerozoic sequence difficult. Please note that all depths mentioned for the Eischeid well are measured from Kelly bushing and not from ground level (see Preface).

QUATERNARY

The absence of geophysical logs above 360 feet depth and the general unsatisfactory nature of well cuttings descriptions in the top 300 feet (no sample 0-120 feet) have precluded an accurate assessment of the Quaternary and Cretaceous sequence in the upper part of the drillhole. Fortunately, a detailed description of this interval is available from the W. Eischeid water well (W22467; SW SW SW SE sec. 6, T83N, R35W) drilled in 1969 and located only one-half mile south of Amoco's M.G. Eischeid #1

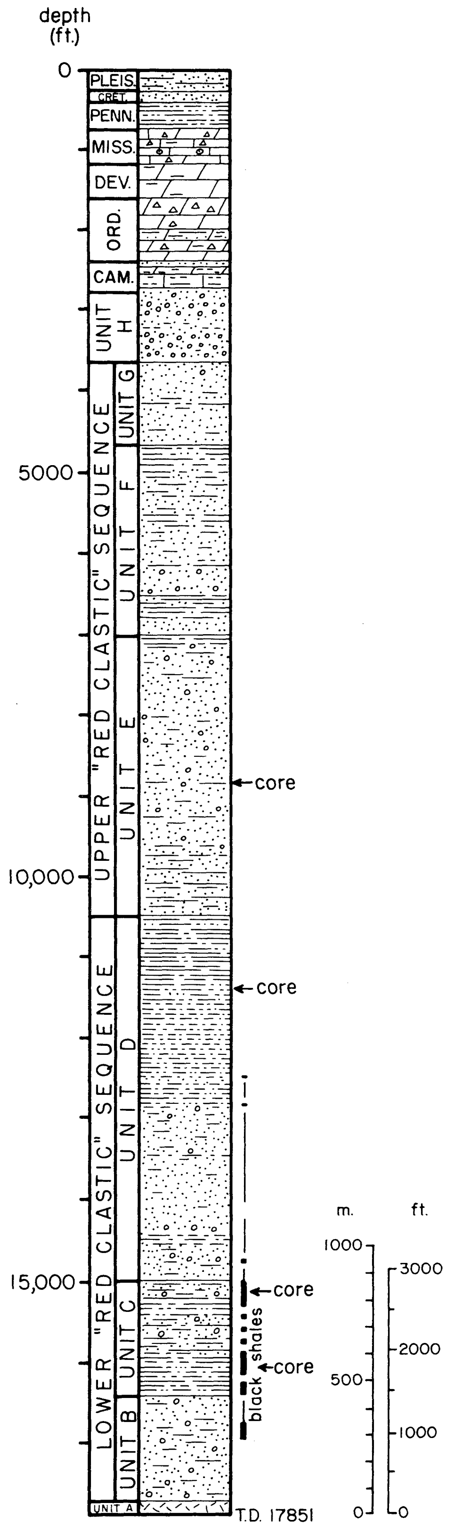

Figure 1. General stratigraphic sequence in the M.G. Eischeid #1 drillhole #1 drillhole, Carrol Co., Iowa. Lithologic symbols as in Figure 2.

drillhole. The W. Eischeid well displays a 235-foot Quaternary sequence dominated by glacial til (poorly-sorted, clay-rich sediments with silt, sand, a gravel clasts); till units are separated by thin inter- (intra-till coarse-grained sands. Three or more till u are present; the upper two are dominated by unoxi(till, but are oxidized in their upper parts. The basal unit is thinner and entirely oxidized.

Amoco's M.G. Eischeid #1 drillhole lies onl 5.5 miles southwest of the margin of the De Moines Lobe, which encompasses the younges (Wisconsinan) glacial tills in Iowa. As such Wisconsinan glacial tills are not present in th Eischeid well. Wisconsinan or earliest Holocen aeolian silts (loess), with modern soils developed a the top, cap the Quaternary sequence in the area o the Eischeid wells, but loess is characteristicall absent on the Des Moines Lobe. Illinoian till units are absent in western Iowa, and the entire till sequence in the W. Eischeid well is of pre-Illinoian age (that is, early or middle Pleistocene)

If the base of the Quaternary sequence is at similar elevations in both the W. Eischeid and M.G. Eischeid wells, it should occur at a depth of about 282 feet in the Amoco well. However, no tills were recorded in the upper part of the Amoco well on the Exlog mudlog, which notes a "sandstone"-dominated interval, with chert, limestone, shale, siltstone, and "lignite." Subsequent re-examination of the well cuttings by M. J. Bounk of the Geological Survey Bureau likewise failed to disclose any glacial till (sand and gravel only, with limestone grains). It would be regionally anomalous for glacial tills to be absent at the Amoco well site, and it is suggested that drilling fluids washed out the clay-fraction of the till leaving only the more resistant sand and gravel fraction (including limestone and chert clasts) in the cuttings.

CRETACEOUS

The interval from about 280-410 feet in the Amoco well is assigned to the Dakota Formation, a widespread mid-Cretaceous rock unit in western Iowa and adjacent states (Witzke et al., 1983). The Dakota Formation is preserved beneath the Quaternary sequence in the nearby W. Eischeid well (15 feet penetrated), and reaches thicknesses in excess of 145 feet in adjacent townships. The Dakota Formation is represented in numerous well penetrations in the Carroll County area where the sandstone-dominated lower Dakota sequence (Nishnabotna Member) forms a productive aquifer. Upper Dakota mudrock dominated strata have been erosionally bevelled beneath Quaternary sediments in the Carroll County area. In both the W. Eischeid and M.G. Eischeid wells the preserved lower Dakota interval is characterized by poorly consolidated sandstone, fine- to medium-grained. It is dominated by quartzarenites.

PENNSYLVANIAN

A sharp lithologic change to shale domination occurs beneath the Dakota Formation in the Eischeid drillhole, and the interval from about 410-760 feet is assigned to the Middle Pennsylvanian (Atokan-Des Moinesian) Cherokee Group (Fig. 2). This interval is dominated by medium to dark gray shales and mudstones, with very fine to fine-grained sandstones noteworthy from 490-670 feet (dominant in part). Argillaceous limestones (at 450, 550 feet), siltstones, black shales (420, 590, 650, 740 feet), and coal (430, 530, 600 feet) occur in the sequence. The Cherokee Group is the main coal-bearing interval in Iowa, and is dominantly a nonmarine sequence. However, cyclic marine transgressive units punctuate the sequence with marine shales and limestones; prominent gamma-log spikes are noted at 426 and 517 feet, which correspond to widely traceable black shales of the Oakley Member and Upper Floris Formation, respectively (Ravn et al., 1984). The Cherokee Group unconformably overlies Mississippian carbonate strata regionally; this erosional boundary separates the Absaroka (Pennsylvanian) and Kaskaskia (Middle Devonian-Mississippian) Sequences in the Iowa area.

MISSISSIPPIAN

"St. Louis" Formation

The upper part of the Mississippian sequence (760-810 feet) is assigned to the Meramecian "St. Louis" Formation; the unit is informally labelled in quotes to reflect uncertainty in correlations with type St. Louis strata in Missouri (see McKay et al., 1987). This interval in the Eischeid drillhole is dominated by limestone (dolomitic and sandy in part) and dolomite (cherty in part). Very fine grained sandstone and shale occurs in the lower part of the unit. The "St. Louis" disconformably overlies strata of the Keokuk and Warsaw formations regionally.

"Keokuk-Burlington" Undifferentiated

Osagean strata are subdivided into three formations in southeast Iowa (Burlington, Keokuk, Warsaw), but these units are difficult to differentiate across much of western Iowa and eastern Nebraska where the interval is informally labelled the "Keokuk-Burlington" undifferentiated. The Warsaw Shale is recognized at the top of the sequence in southeastern Iowa, but this upper shale interval grades into carbonate-dominated facies across portions of central and western Iowa. Neither cuttings nor gamma logs differentiate the Warsaw Shale in the Eischeid drillhole. The "Keokuk-Burlington" interval (810-1010 feet) in the Eischeid well (Fig. 2) is characterized by limestone and dolomitic limestone, cherty to very cherty and argillaceous in part, with scattered to abundant fossil fragments; the carbonates are interbedded with gray calcareous shales, especially in the lower and upper parts.

Gilmore City Formation

The Gilmore City Formation is recognized in the Eischeid drillhole (about 1010-1090 feet) by characteristic oolitic limestone lithologies. The upper part contains peloidal microcrystalline limestone and dolomite.

Maynes Creek-Chapin Formations

The basal interval of Mississippian strata in the Eischeid drillhole (about 1090-1200 feet) is dominated by limestone and dolomite, cherty and argillaceous in part, assigned to the Maynes Creek Formation. The basal 20 feet or so of this interval includes oolitic limestones assigned to the Chapin Formation. Although not seen in cuttings, geophysical logs suggest the presence of a siltstone near the base (1196 feet), possibly a thin Prospect Hill Formation. Mississippian strata unconformably overlie Upper Devonian shales and carbonates regionally.

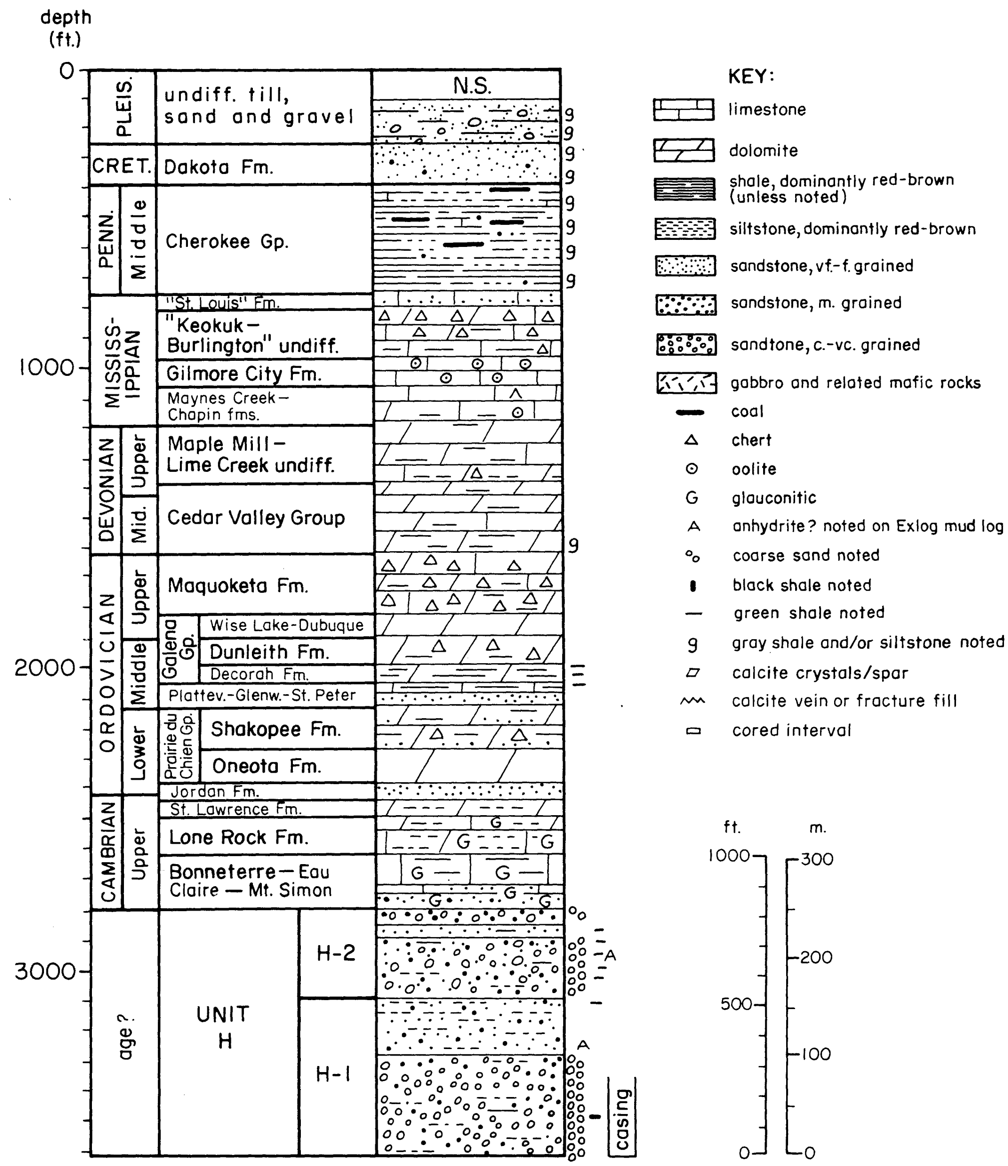

Figure 2. Phanerozoic stratigraphic sequence in the M.G. Eischeid #1 drillhole, Carrol Co., Iowa. Correlation of Unit H is unclear, but it may be an upper Keweenawan interval.

DEVONIAN

Maple Mill-Lime Creek Formations

Upper Devonian (late Frasnian, Famennian) strata in central and western Iowa are dominated by a thick carbonate-dominated interval assigned to the Lime Creek Formation (late Frasnian) which is disconformably capped by a relatively thin shale interval tentatively included in the Maple Mill Formation (Famennian) (see Metzger, 1989). The upper shale interval is locally absent (either erosionally removed or replaced by carbonate facies), and has not been recognized in the Eischeid drillhole (neither well cuttings or geophysical logs). The interval from about 1200-1350 feet is dominated by dolomite with subordinate limestone; this interval primarily, if not entirely, includes strata characteristic of the Lime Creek Formation. The interval is argillaceous in part, sandy to cherty in the lower part, and includes scattered oolitic carbonate lithologies in the top 60 feet. The Lime Creek unconformably overlies late Givetian and early Frasnian strata of the Cedar Valley Group regionally.

Cedar Valley Group

Middle and lower Upper Devonian strata (late Givetian-early Frasnian) of the Cedar Valley Group underlie Lime Creek strata regionally. The Cedar Valley Group is divided into four formations corresponding to four major transgressive-regressive sedimentary cycles, each marked by open-marine carbonate facies in the lower part and by restricted-marine to evaporitic facies in the upper part (Witzke et al., 1988). The interval from about 1350 to 1630 feet in the Eischeid drillhole is assigned to the Cedar Valley Group (Fig. 2), although the basal contact is uncertain and may lie slightly deeper. This interval is dominated by dolomite and dolomitic limestone, in part argillaceous (minor chert). Microcrystalline limestones, sandy to silty carbonates, and green-gray shales and siltstones also occur within the interval; these lithologies are characteristic of the shallowing phases of sedimentation within individual sedimentary cycles. The Cedar Valley Group unconformably overlies bevelled Ordovician strata across large areas of northern and western Iowa. Older Middle Devonian strata of the Wapsipinicon Group are absent in the Eischeid well and across western Iowa.

ORDOVICIAN

Maquoketa Formation

Although shale-dominated in eastern Iowa, the Upper Ordovician Maquoketa Formation in western Iowa is a carbonate-dominated facies. The formation in the Eischeid drillhole (approximately 1630-1840 feet) is characterized by dolomite and dolomitic limestones, fossiliferous, vuggy and argillaceous in part. The interval is cherty to very cherty through much of the interval; cherty carbonates characterize much of the formation across western Iowa. Where buried beneath Silurian rocks in southwestern Iowa, the Maquoketa Formation reaches thicknesses in excess of 325 feet, but the formation is erosionally bevelled beneath Devonian rocks northward in western Iowa. The preserved interval of the Maquoketa Formation in the Eischeid drillhole (Fig. 2) encompasses the lower to middle parts of the formation. Maquoketa strata conformably overlie carbonate rocks of the Galena Group in western Iowa.

Galena Group

The Galena Group is a Middle Ordovician to lower Upper Ordovician carbonate and cherty carbonate-dominated sequence with basal shaley strata across large areas of the midcontinental United States. It spans the interval from about 1840-2060 feet in the Eischeid drillhole (Fig. 2). The upper Galena Group (Wise Lake and Dubuque formations; 1840-1900 feet) is characterized by generally non-cherty fossiliferous dolomite, although minor cherts are present. The middle Galena Group (Dunleith Formation; about 1900-2000 feet) is dominated by cherty to very cherty fossiliferous dolomite; it becomes slightly argillaceous in its lower part. The basal Galena Group (Decorah Formation; about 2000-2060 feet) is dominated by fossiliferous dolomitic limestone (dolomite in the upper part) interbedded with prominent green-gray calcareous shales. The Galena Group overlies, probably conformably, the Middle Ordovician Platteville Formation.

Basal Middle Ordovician Strata

The Platteville Formation in the Eischeid drillhole (about 2060-2080 feet) is characterized by fossiliferous dolomitic limestone, silty to argillaceous in part. The Platteville regionally overlies a thin gray-green shale interval, the Glenwood Formation; although not apparent from cuttings, a prominent gamma spike at 2080 feet is probably the Glenwood Shale. The basal part of the Middle Ordovician interval across most of the midwestern United States is assigned to the St. Peter Sandstone. In the Eischeid drillhole (about 2080-2128 feet), the St. Peter is characterized by poorly consolidated fine-grained quartz sandstone (Fig. 2). The St. Peter regionally overlies an eroded surface of Lower Ordovician or older rocks; the sub-St. Peter erosional episode separates underlying Sauk Sequence (Cambrian-Lower Ordovician) deposition from that of the Tippecanoe Sequence (Middle Ordovician-Silurian).

Prairie du Chien Group

The Lower Ordovician Prairie du Chien Group (2128-2390 feet) can be subdivided into two formations (Fig. 2). The upper Shakopee Formation (2128-2280 feet) is dominated by cherty to very cherty dolomite, sandy to oolitic in part, with minor interbedded green-gray shale and fine- to medium-grained quartz sandstone (sandstone best developed at base, the New Richmond Member). The Shakopee sharply overlies the Oneota Formation (2280-2390 feet), an interval of relatively pure dolomite (minor argillaceous content). The Oneota conformably overlies, and is gradational with, the Jordan Sandstone.

CAMBRIAN

Jordan Sandstone

The Jordan Sandstone is a regionally persistent sandstone that is known to straddle the Cambrian-Ordovician boundary in its outcrop belt in the Upper Mississippi Valley area. The Jordan Sandstone in the Eischeid drillhole (about 2390-2440 feet) is characterized by very fine- to fine-grained sandstone with minor dolomitic cement (Fig. 2).

St. Lawrence Formation

The St. Lawrence Formation (Upper Cambria lower Trempealeauan) is characterized regiona by silty to argillaceous dolomite above glauconi strata of the Lone Rock Formation. The S Lawrence is tentatively identified in the Eische drillhole from about 2440-2500 feet, where silty argillaceous dolomites occur; this interval is sligh glauconitic in its lower part.

Lone Rock Formation

Franconian-aged (Upper Cambrian) strata a highly glauconitic across large areas of th midwestern United States. Franconian strata eastern Iowa include a sequence of greensan siltstone and shale with minor carbonate assigne to the Lone Rock Formation. The interval fro about 2500-2620 feet in the Eischeid drillhole tentatively included within the Lone Roc Formation (Fig. 2); it is dominated by ve glauconitic carbonates (silty dolomites in uppe part, limestone in lower part) interbedded wit glauconitic siltstones (most abundant in lower part Strata immediately underlying this interval lac siltstones and dolomite and are slightly les glauconitic; the boundary separating these interval is provisionally used to mark the base of the Lon Rock.

Bonneterre-Eau Claire Interval

The interval from about 2620-2782 feet i dominated by very glauconitic slightly argillaceou limestone, but the lower 60-70 feet is characterize by a fining-upward highly glauconiti sandstone-dominated interval (very fine- t medium-grained). The limestones, in part wit echinoderm grains, interbed with green-gra calcareous shales, which form about 10% of the interval. The limestones in this interval are lithologically similar, and occupy a simila stratigraphic position, to the Bonneterre Formation of Missouri. The glauconitic sandstones in the lower part resemble those described by McKay (1988) from the Eau Claire Formation of eastern Iowa. The Bonneterre and Eau Claire formations are both of Dresbachian (Upper Cambrian) age. The interval in the Eischeid well overlies, apparently conformably, coarser-grained non-glauconitic sandstones of the Mt. Simon

Sandstone.

Mt. Simon Sandstone

The Mt. Simon Sandstone has been used as a formational term to encompass the basal Cambrian sandstones above the Precambrian basement (and below younger Dresbachian strata) across a large portion of the midwestern United States (Wisconsin, Minnesota, Illinois, Michigan, Indiana, Ohio, Iowa, Nebraska). This sandstone interval reaches thicknesses in excess of 1000 feet in portions of Indiana, Michigan, eastern Iowa, and Illinois (to 2600 feet). The Mt. Simon thins regionally to the north and west; it is commonly less than 100 feet thick over granites or gneisses in much of western Iowa. Along the central horst of the MRS in Iowa, the Mt. Simon commonly ranges from about 50 to 150 feet in thickness but is locally absent where younger Cambrian rocks overlie the Precambrian. Mt. Simon thicknesses have been more difficult to interpret in the flanking basins of the MRS in Iowa, where the formation overlies Keweenawan or other pre-Mt. Simon sedimentary rocks.

Previously, lithic criteria that would reliably serve to distinguish Mt. Simon from other Cambrian and Precambrian sandstones have not been clearly delineated. However, McKay (this volume) proposes a lithologic definition of the Mt. Simon that generally excludes stratigraphic units with coarse-grained detrital feldspars from the formation. He recognizes the presence of rounded K-feldspars in the Mt. Simon dominantly in the silt to fine-sand size fraction (with common authigenic overgrowths), a feature seen in many other Cambrian cratonic sandstone formations as well. These K-feldspar characteristics can serve to distinguish Mt. Simon lithologies in the type area of Wisconsin and Minnesota (and southward to eastern Iowa and northern Illinois) from most coarse-grained Keweenawan sandstones in the MRS. However, it should be noted that strata previously assigned to the Mt. Simon in other regions are known to contain intervals with coarse detrital feldspars (e.g. Illinois Basin--Hoholick et al., 1984; Ohio--Heald and Baker, 1977). Likewise, lateral equivalents of the Mt. Simon in Missouri (Lamotte Sandstone) also contain intervals with coarse feldspars or rhyolite grains (Houseknecht and Ethridge, 1978). If the general absence of coarse feldspar grains is used to characterize a lithologic definition of the Mt. Simon, basal Cambrian sandstone strata in some areas may need to be removed from the formation and alternative nomenclature proposed. Lateral compositional variations in basal Cambrian sheet sandstones in the cratonic interior of the United States would be a natural response to geographic variations in source terranes, climate, and tectonic setting.

The age of the Mt. Simon, even in its type area, is not actually known. It underlies strata of the Eau Claire Formation with *Cedaria* Zone faunas, the lowest zone of the Upper Cambrian, but the Mt. Simon does not contain faunas useful for age determination. Considering that the Mt. Simon is regionally covered by units of this age, it seems unusual for thick Mt. Simon sequences (1000-2600 feet) to still be included within this zone at its base when *all* remaining zones of the Upper Cambrian span only 300-800 feet of total section in the Iowa area. Unless Mt. Simon deposition was characterized by unprecendented cratonic sedimentation rates, it seems unavoidable that thick Mt. Simon sections are, at least in part, of pre-Dresbachian age (i.e. Middle or possibly Lower Cambrian).

Following McKay's suggestions (this volume), the Mt. Simon is limited to a thin interval in the Eischeid drillhole (2782-2802 feet). The cuttings sample (2770-2800 feet) that encompasses this interval includes fine to very coarse quartz sand grains and quartzose sandstone, with a significant component of apparent cavings from up-hole. The presence of coarse feldspar grains in the sample is anomalous with respect to typical Mt. Simon lithologies. The thin Mt. Simon interval in the Eischeid drillhole overlies a thick, poorly consolidated sandstone interval (2802-3615 feet) herein termed Unit H. The stratigraphic relations between the two units are not known.

UNIT H

Unit H is defined in the Eischeid drillhole from a depth of about 2802 to 3615 feet (Fig. 2) forming an interval greater than 800 feet in thickness. It is dominated by pale gray (clear) to red-brown poorly consolidated to friable sandstone; coarse to very coarse quartz and feldspar grains (angular to subrounded) occur through most of the sequence. However, intervals within the sequence display finer textures including fine-grained and fine- to medium-grained sandstone with interbedded red-brown (minor green) siltstone to shale. However, medium to coarse and very coarse-grained sandstone (angular to subrounded grains) dominates most of the Unit H sequence, and scattered granules are noted (2800-2860, 2900-3100 feet). Red-brown argillaceous siltstones and micaceous shales, with minor green shale, interbed with the sandstones through most of Unit H, and form between a trace and about 20% of the samples in the coarse-grained intervals. Calcite and dolomite cements are noted in some of the sandstones and mudstones, but Unit H is primarily poorly consolidated. Unit H is subdivided into two intervals (Fig. 2); the lower interval, H-1 (3100-3615 feet), forms a large-scale fining-upward sequence with coarse-grained lithologies in the lower part and finer-grained sandstones, siltstones and shales above (3100-3290 feet). The upper interval, H-2 (2802-3100 feet) contains coarse-grained lithologies through most, with a thin interval of fine-grained sandstone in the upper part (2860-2900 feet).

The general modal composition of Unit H sandstones is not decidedly different from that noted in underlying Keweenawan units (Ludvigson et al., this volume), and both intervals probably were sourced from similar cratonic terranes. The relatively coarse and texturally immature fabrics in Unit H suggest alluvial sedimentation without significant sediment reworking. The proposed boundary between Units H and G was selected at a position where changes in grain size and cementation are apparent, although the suite of geophysical logs was of little apparent utility in identifying this contact. However, a noteworthy change in the caliper log occurs at a depth of about 3615 feet that undoubtedly reflects changes in hardness and cementation in the sandstones. The sequence above is primarily poorly consolidated (abundant loose quartz and feldspar grains), whereas sandstones below are predominantly well consolidated (see percent cuttings figure in Ludvigson et al., this volume). In addition, the mudlog identifies medium to coarse-grained sand dominant above this point, whereas fine to medium-grained sandstone dominates below (especially below 3700 feet); the proposed lower boundary of Unit H, therefore, further corresponds to a significant change in grain size. Minor compositional differences may also contrast intervals above and below the proposed boundary; Unit H apparently lacks plagioclase and has low percentages of lithic fragments (1-2%), whereas underlying Unit G contains minor plagioclase and displays higher percentages of lithic fragments (6-9%)(see Ludvigson et al., this volume). Amoco's placement of steel casing (seated at 3682 feet) a short distance below the base of Unit H (Fig. 2) was certainly a reflection of the change from dominantly poorly consolidated sands above to more consolidated sands below, and further underscores the general contrasts between Unit H and underlying strata.

What is Unit H, and how does it fit into the stratigraphic sequence of Proterzoic and Cambrian sandstone units? The overall modal composition of Unit H is comparable in a general sense to that seen in some underlying units, suggesting possible relations with the Keweenawan Supergroup. Nevertheless, significant contrasts in average grain size and relative cementation serve to distinguish Unit H from all underlying Keweenawan units. On the other hand, the poorly consolidated nature and coarse-grained fabrics resemble features seen in some basal Cambrian sandstone intervals in the midwestern U.S. Although contrasted with typical Mt. Simon lithologies, Unit H resembles some coarse feldspathic facies seen in the "Mt. Simon" or Lamotte sandstones in other areas (Illinois, Indiana, Ohio, Missouri; see previous section).

Poorly consolidated coarse quartzose and feldspathic sandstone facies similar to those seen in Unit H in the Eischeid well have also been noted in flanking basins along the MRS in Page and Butler Counties, Iowa, where they have been variably assigned to the "red clastic series" or "Mt. Simon sandstone." These occurrences are tentatively correlated herein with Unit H. If Unit H is restricted within the MRS in Iowa, possible comparisons with other poorly cemented sandstone intervals within the MRS in Minnesota and the Lake Superior area may be warranted. Three units are considered: 1) the Hinckley Sandstone of Minnesota, 2) the Jacobsville Sandstone of upper Michigan, and 3) the Fond du Lac Formation of Minnesota. The Hinckley and Jacobsville are both overlain by Cambrian sandstones (Mt. Simon or Munising sandstones), and the Fond du Lac is variably overlain by the Hinckley or Mt. Simon Sandstone.

The Jacobsville Sandstone of upper Michigan is a fine- to coarse-grained feldspathic to quartzose sandstone, poorly consolidated in some beds, and containing minor pebbly conglomerates, shales, and siltstones (Kalliokoski, 1982). Although stratigraphic relationships are not clear, recent workers suggest partial correlation of Jacobsville and Bayfield Group strata (e.g. Ojakangas and Morey, 1982). Unit H in Iowa resembles the Jacobsville in general composition and maturity, although Unit H is apparently less consolidated than most Jacobsville strata. Unlike Unit H, which overlies a thick "red clastic" sequence, the Jacobsville overlies Keweenawan volcanic or older Precambrian igneous and metamorphic rocks.

The Fond du Lac Formation of Minnesota is characterized by an interbedded sequence of red shale, poorly consolidated fine- to coarse-grained arkosic sandstone, and conglomerate (Morey, 1972). It resembles Unit H in gross lithologic character, although the Fond du Lac typically displays finer-scale alterations of shale and sandstone than seen in Unit H. Unlike the Fond du Lac, Unit H apparently lacks plagioclase and displays significantly lower percentages of lithic grains (<1% vs. 10%). The Hinckley Sandstone overlies the Fond du Lac Formation with apparent conformity, and is a fine- to coarse-grained sandstone characterized by relatively high textural and compositional maturity (average $Q_{96}F_{2}L_{2}$) with varying amounts of silica cement; minor feldspathic sandstone (feldspar to 12%) and volcanic pebble conglomerates also occur (Tryhorn and Ojakangas, 1972; Morey and Ojakangas, 1982). Unit H in Iowa does not compare lithically with the Hinckley Sandstone, as Unit H is more texturally and compositionally immature.

The unique lithologic character (especially its poor consolidation) and stratigraphic position (coarse sandstone above lithified "red clastics") of Unit H does not permit direct comparisions with upper Keweenawan stratigraphic units in the Lake Superior area. As noted by Ojakangas and Morey (1982, p. 163), correlation of sedimentary units in the Lake Superior area is fraught with problems; ". . . detailed comparative petrographic studies may provide useful information, but even this approach may be of limited value because of factors such as local variation in source areas and in the amount of local reworking." Such problems are amplified when inter-regional comparisons are made.

Correlation of Unit H in the Eischeid drillhole with other stratigraphic units in the MRS is not attempted here, and the age of the unit is left in an unassigned positon between the more lithified "red clastic" sequence below and the Cambrian sequence above (Figs. 1,2). Nevertheless, three possible correlations of Unit H are briefly considered. 1) Unit H may conceivably represent a coarse feldspathic facies correlative in part with thick Mt. Simon sequences in eastern Iowa-northern Illinois (where Mt. Simon thicknesses range from 1000-2600 feet). Although typical Mt. Simon sequences lack coarse feldspar grains, correlative intervals south of the Upper Mississippi Valley area (Illinois Basin, Ohio, Missouri) are known to contain such facies (see earlier discussion). 2) Another alternative might place Unit H unconformably between Unit G and Mt. Simon strata in a post-Keweenawan and pre-Dresbachian position. Such an interpretation would separate Unit H from the standard sequence of Keweenawan sedimentary events and suggest a Late Proterozoic and/or Early-Middle Cambrian age. 3) A third alternative would make Unit H an extension of the Upper "Red Clastic" Sequence conformably above Unit G. This interpretation would make Unit H the least consolidated and coarsest-grained facies recognized in the Keweenawan sequence in Iowa. This third alternative probably represents the simplest stratigraphic solution.

Regardless of the actual correlation, deposition of Unit H was marked by a significant shift to more coarse-grained sedimentation, probably alluvial, over that seen in underlying Keweenawan units. Coarser-grained sedimentation probably reflects an increase in stream competency, possibly a response to increased subsidence in the flanking basins of the MRS in Iowa. Unit H sediments were probably sourced from Precambrian "granitic" terranes outside the MRS; the coarse feldspars and common angular to subangular grains suggest that Unit H is dominantly a first-cycle sandstone. The poorly consolidated character of Unit H further suggests a differing diagenetic history than underlying Keweenawan units.

KEWEENAWAN UPPER "RED CLASTIC" SEQUENCE

Introduction

The Keweenawan sedimentary sequence in Iowa has been informally termed the "red clastic series" by various geologists and well drillers in the area since it was first encountered in drillholes in the 1920s, and this traditional label is retained pending further study. Reddish-colored siliciclastic rocks dominate the sequence, and the term has an informal but descriptive meaning. The thick sequence of Keweenawan sedimentary rocks in the Eischeid drillhole is informally divided into two large-scale intervals. These intervals can be regarded as being of group rank, and each is further subdivided into a series of informal units given lettered designations (Fig. 1). The upper interval is labelled the Upper "Red Clastic" Sequence, which shares overall similarities with the Bayfield Group and Fond du Lac Formation in the Lake Superior area. Correlation with these units seems likely, although compositional variations and lithostratigraphic uncertainties necessitate the use of an informal nomenclature in the Iowa sequence pending further study. In general, the Upper "Red Clastic" Sequence in the Eischeid drillhole is compositionally more immature than much of the Bayfield Group. The Upper "Red Clastic" Sequence is compositionally similar to much of the Fond du Lac Formation, although a higher percentage of finer-grained sandstones and an absence of conglomerates in the Eischeid sequence contrast with facies described for the Fond du Lac Formation (Morey, 1972). Mature quartzarenites have not been identified in the Upper "Red Clastic" Sequence, and facies equivalents of the Hinckley and Devils Island sandstones (both are mature quartzose sandstones) have not been recognized in the Eischeid drillhole. Units E, F, and G are delineated within the Upper "Red Clastic" Sequence based on relative abundances of sandstone vs siltstone-shale.

Unit G

Unit G forms the upper part of the Upper "Red Clastic" Sequence in the Eischeid drillhole and encompasses the interval from about 3615 to 4690 feet (Fig. 3). Unit G is dominated by fine to medium-grained sandstone, with minor traces of coarse sandstone in the middle and upper parts. The sandstones are pale gray (clear) to red-brown in color and are generally well consolidated; however, loose sand grains increase in abundance upward in the upper half, possibly reflecting the presence of poorly consolidated intervals within upper Unit G or, alternatively, the loose grains represent cavings from Unit H. The sandstones average about 10-15% feldspar and contain relatively high proportions of volcanic lithic grains (Ludvigson et al., this volume). The sandston interbed throughout Unit G with red-brow siltstones and shales (minor green shale), in pa micaceous to slightly calcareous. Siltstones a most abundant in the interval from abo 4000-4185, where they comprise 30-80% of th samples. The Exlog mudlog notes traces anhydrite in Unit G, but this has not been verifie by recent studies (this volume).

Unit F

Unit F is a shale and siltstone-rich unit fro about 4690-7020 feet which is subdivided into thre generally fining-upward sequences labelled F- through F-3 (Fig. 3). Each of these sequences i dominated by very fine to fine-grained sandstone in their lower parts, with minor medium t coarse-grained textures noted. The sandstones ar consolidated and red-brown and pale gray (clear to gray in color, with some light brown to brown they average about 20-25% feldspar content, an display a relative increase in plagioclase over tha noted in Unit G (Ludvigson et al., this volume) Sandstone dominated intervals interbed wit red-brown shales and siltstones. The upper part o each fining-upward sequence (F-1 through F-3) i dominated by red-brown to red shale and siltstone with shale most abundant in the uppermost portion these interbed with sandstones to varying degrees The shales and siltstones are mottled light green t green-gray, in part, and some dark brown siltstone are present (around 5150 feet). Some siltstone and sandstone is calcite cemented. Trace amounts o anhydrite were noted associated with the reddish mudstones on the Exlog mudlog, but these occurrences have not been substantiated for this article.

Interval F-3 (about 4690-5510 feet) is the most mud-rich of the three fining-upward sequences delineated, and is shale or siltstone dominated through much of the interval (to 5300 feet). Interval F-2 (5510-6525 feet) is more sandstone dominated and contains the highest proportion of medium to coarse grained sandstones; shale-siltstone dominated units are present in the middle to upper parts (5510-5640, 6120-6150 feet). Interval F-1 (about 6525-7020 feet) forms the basal fining-upward sequence of Unit F; its base is drawn above a relatively thin shale dominated interval at the top of Unit E. Unit E is closely similar in many respects to Unit F, but contains proportionately

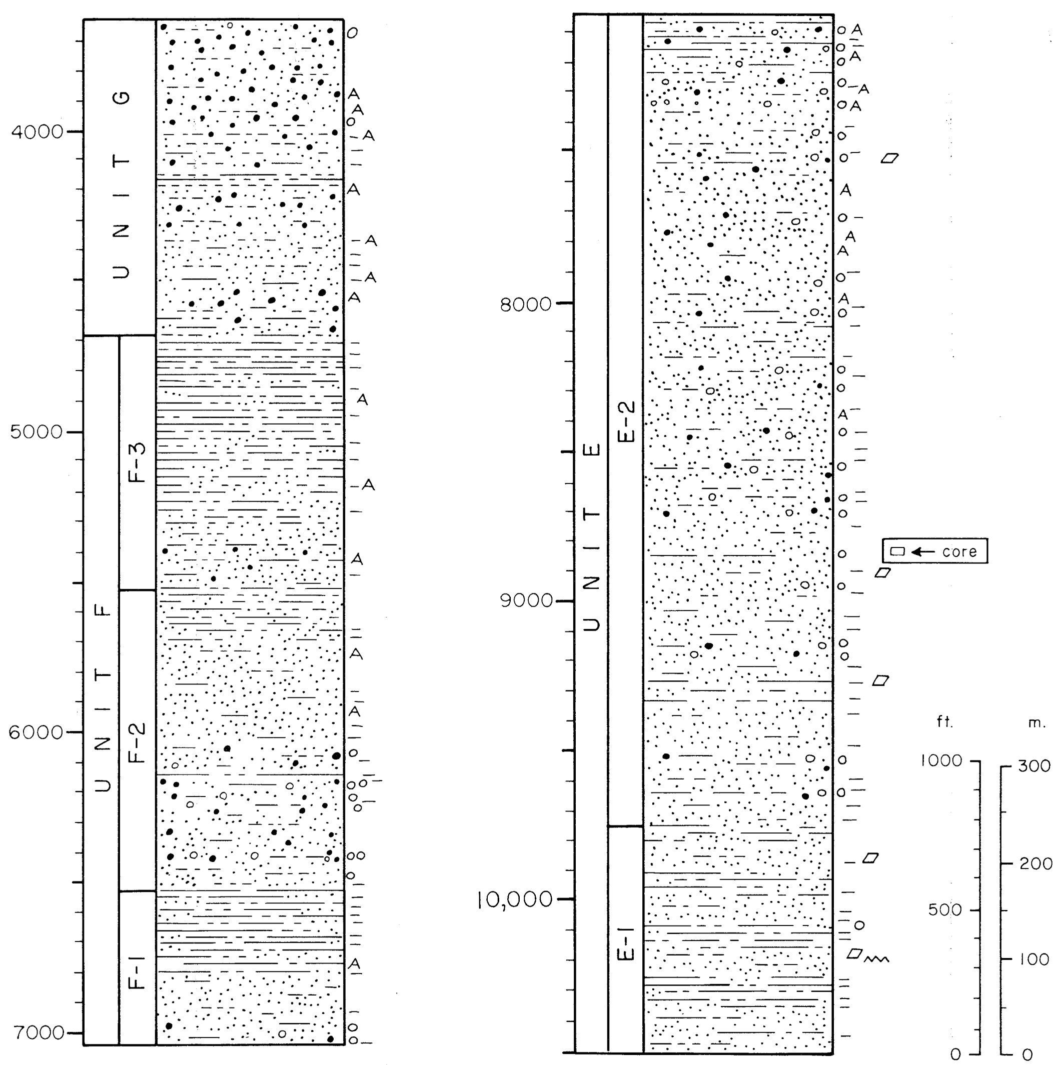

Figure 3. Graphic stratigraphic column of Upper "Red Clastic" Sequence (Keweenawan), M.G. Eischeid #1 drillhole, Carroll Co., Iowa. Lithologic symbols as in Figure 2.

more sandstone.

Unit E

Unit E is a thick sandstone-dominated interval (7020-10510 feet; Fig. 3). Feldspar content in the sandstones is relatively high but variable (8-31%; avg about 20-25%), and lithic grains achieve their greatest abundance (7-19%; avg about 10-15%) in the Keweenawan sequence within Unit E (Ludvigson et al., this volume). Unit E is subdivided into two descriptive intervals, E-1 and E-2. Interval E-2 (7020-9740 feet) is dominated by red to red-brown and light to dark brown sandstones, primarily very fine to fine grained but containing some medium to coarse and very coarse-grained lithologies. Red and red-brown to brown shales and siltstones (some mottled greenish-gray) interbed with the sandstone sequence, and are most abundant in relatively thin intervals (7020-7170, 8060-8100, 9210-9340 feet). The Exlog mudlog notes traces of anhydrite associated with the reddish mudrocks, but these occurrences have not been substantiated in this study. A small portion of interval E-2 was cored (8834-8844 feet), which displays horizontally-bedded sandstone with horizontal laminations and low-angle cross-laminations; small intraclasts of shale and mudstone occur along some laminae.

Interval E-1 (9740-10510 feet; Fig. 3) contains proportionately more shale than interval E-2, and is characterized by four relatively thin fining-upward sequences (9740-9900, 9900-10,080, 10,080-10,230, 10,230-10,510 feet). Each of these sequences is dominated by shale with lesser siltstone in the upper part, with some interbedded sandstone; the shales and siltstones are red to red-brown and dark brown (with minor green-gray). The lower part of each fining-upward sequence is dominated by red-brown, brown, and pale gray, very fine- to fine-grained sandstone; medium- to coarse-grained sandstone occurs near the base of the upper two sequences, and medium-grained sandstone is noted near the base of the lowest sequence. The boundary between the Upper and Lower "Red Clastic" Sequences is drawn at the base of Unit E, where Unit E sandstones contrast with the thick shale-dominated interval in upper Unit D. This boundary is probably the lithostratigraphic equivalent of the contact between the Bayfield and Oronto groups in the Lake Superior area. The nature of this contact, whether conformable or not, is not apparent from the data available for this study, although the contact may be complicated by faulting (see below).

KEWEENAWAN LOWER "RED CLASTIC" SEQUENCE

Introduction

The Lower "Red Clastic" Sequence in the Eischeid drillhole (Figs. 1, 4) is divided into three informal units (Units B, C, D) that are remarkably similar to the general stratigraphic sequence described from the Oronto Group in the Lake Superior area. Lithologies in the Lower "Red Clastic" Sequence are similar in a general sense to those noted in the upper sequence. However, reduced gray to black shales and siltstones occur in all units of the lower sequence in varying abundance (Fig. 4), whereas such lithologies are absent in the upper sequence. In addition, sandstones in the lower sequence display a lower average percentage of lithic grains than seen in the upper sequence, and, excluding the basal portions, volcanic grains are proportionately less abundant in the lower sequence (Ludvigson et al., this volume).

The increased abundance of calcite vein and fracture fill in the uppermost portions of the Lower "Red Clastic" Sequence (interval D-4; see Fig. 4) as well as a marked increase in angular deviation of the drillhole through upper Unit D suggest that a structural discordance may be present. The upper shale-dominated portion of the lower sequence may have formed a detachment surface for faulting, and, as such, the general boundary between the upper and lower sequences may be marked by a subsidiary fault. The degree of structural deformation further serves to contrast the Upper and Lower "Red Clastic" Sequences in the Eischeid drillhole; in general, all of the upper sequence is apparently a stacked package of essentially horizontally-bedded strata, whereas the lower sequence contains both horizontally-bedded and steeply-dipping strata, disrupted in part by faulting (e.g., core in lower Unit C). Similar differences in the degree of structural deformation contrast the Oronto and Bayfield groups in the Lake Superior area.

Unit D

Unit D forms the upper part of the Lower "Red Clastic" Sequence (about 10,510-14,980 feet; Fig.

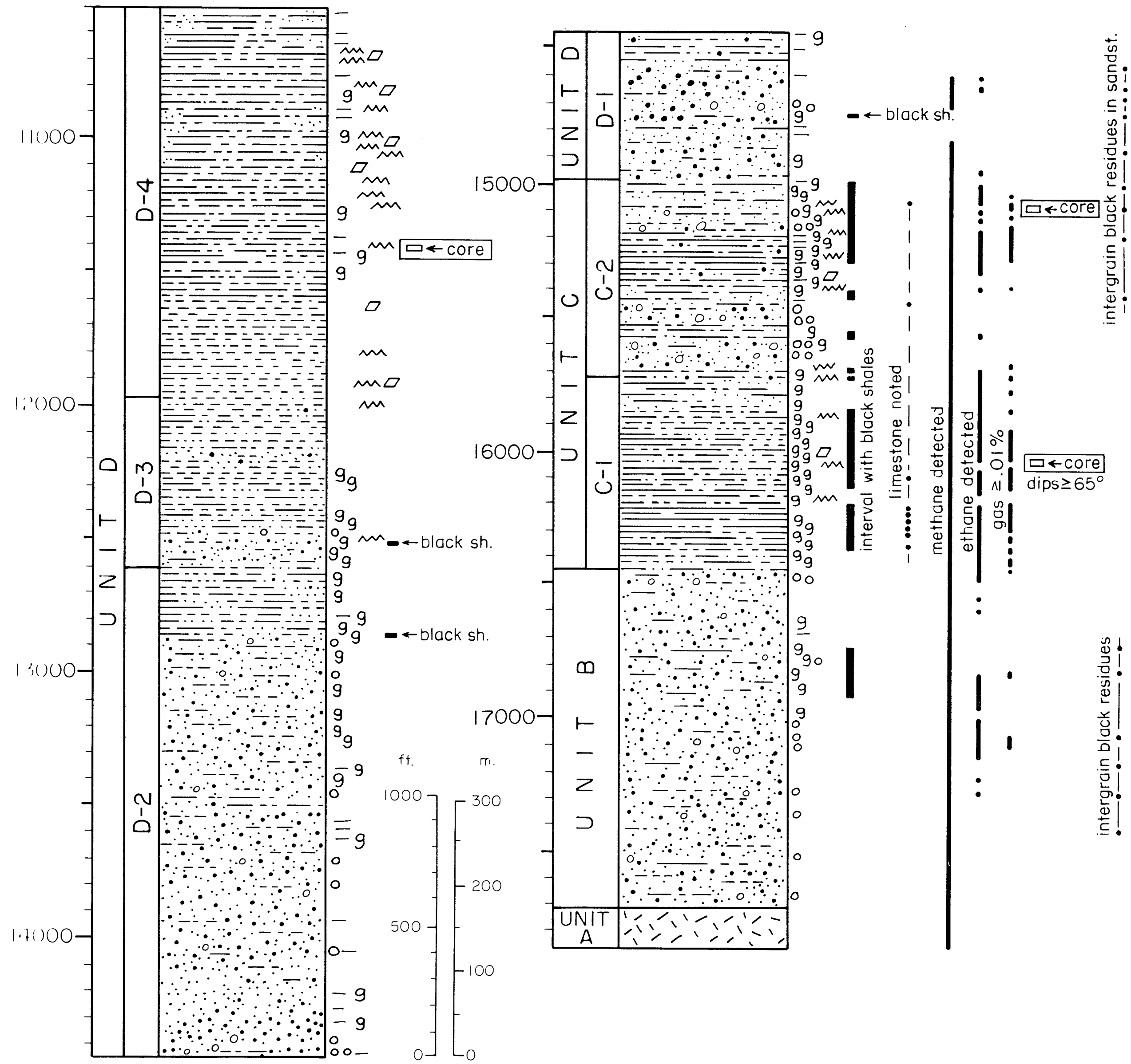

Figure 4. Graphic stratigraphic column of Lower "Red Clastic" Sequence (Keweenawan) above pre-Keweenawan mafic igneous rock, M.G. Eischeid #1 drillhole, Carroll Co., Iowa. Lithologic symbols as in Figure 2.

4). In a gross sense, Unit D forms a thick fining-upward sequence, sandstone-dominated in the lower half (including coarse sandstones) and siltstone to shale-dominated in the upper half. It is subdivided into four intervals based on overall composition (D-1 through D-4). Like other Keweenawan units in the Eischeid drillhole, Unit D sediments are primarily consolidated (lithified). However, a marked increase in loose quartz and feldspar grains in samples from the lower part (D-1, D-2) suggests that some lithologies are in part poorly lithified.

The upper interval (D-4; 10,510-11,960 feet) is dominated by red-brown to brown shales through the upper half, with minor light green and light gray shales present; the shales are micaceous in part. The shales are interbedded with red-brown siltstones through much of the sequence, and interval D-4 becomes siltstone-dominated in the lower half. Minor very fine-grained red-brown sandstones are noted within the interval. A short core segment from the lower half of interval D-4 (11,381-11,395 feet) is an interlayered siltstone and very fine micaceous sandstone sequence displaying horizontal laminations and small-scale cross-stratification; small mudstone and shale intraclasts are present. The core is generally horizontally-bedded, but fault-related deformation is well-displayed in the the lower part (see Ludvigson et al. and Ludvigson and Spry, this volume).

Interval D-3 (11,960-12,600 feet) is siltstone -dominated, but differs from interval D-4 in containing proportionately more sandstone and in displaying coarser grain sizes. Interbedded siltstones and shales are similar to those in interval D-4, although an influx of light to medium gray shales and siltstones is noted at 12,420-12,450 feet; some dark gray lithologies and minor traces of black carbonaceous specks also occur at that position. In addition, gray to black siltstones are present in the lower part (12470-12535 feet). Such "Red Clastics" reduced lithologies recur in the Lower "Red Clastic" Sequence, but are unknown in the Upper Sequence. Interval D-3 is sandstone-dominated in the lower 180 feet, where pale to light gray fine- to medium-grained sandstones interbed with shale and siltstone; some coarse-grained sandstone is present.

Interval D-2 (12,600-14,450 feet) is sandstone -dominated through most. However, the upper 250 feet is siltstone-dominated, where the shales and siltstones are variably colored red-brown to brown, light to dark gray, and minor green-gray. Some of the gray siltstones display dark gray to black shaley laminations, pyritic in part (at about 12,840 feet). The remainder of interval D-2 contains abundant sandstone, interbedded in part with minor siltstone and shale (primarily red-brown with some light to medium gray and green-gray). Shales and siltstone are scarce to absent from 14,100-14,400 feet. The sandstones vary from red-brown to medium gray in color and range from very fine to fine, fine to medium, and fine to coarse-grained. Coarse grains are most abundant in the lower 100 feet, but occur scattered in other portions of the interval.

Interval D-1 (14,450-14,980 feet) is also a sandstone -dominated unit, but is separated from interval D-2 by a shale and siltstone dominated package in the top 110 feet. This upper package contains shales and siltstones of variable color including red-brown, brown, green, purple, and medium to dark gray. The bulk of interval D-1 is characterized by pale to light gray and red-brown sandstone, fine to medium-grained (minor coarse grains). The sandstones interbed with shale and siltstone as above, although traces of black shale are noted (about 14,740 feet). Of particular note is the presence of intergrain black residues in some sandstone samples (Fig. 4), possibly relict hydrocarbons sourced from Unit C. In addition, on-site chromatograph analysis shows traces of methane and ethane in interval D-1 (Exlog).

The general lithologic sequence in Unit D is closely similar to that noted in the Freda Formation (upper Oronto Group) of Wisconsin-upper Michigan and part of the Solor Church Formation in Minnesota. The Freda is characterized as a general fining-upward sequence with coarsest facies present in the lowest one-third of the formation and shales most abundant in the upper part (Daniels, 1982, p. 123). The Freda is dominated by red-brown lithologies, but unoxidized beds are present, as in Unit D. The Solor Church Formation, although composed of numerous small-scale fining-upward sequences (as is the Freda), likewise displays a general upward increase in mudstone and shale content and an overall decrease in maximum grain size (Morey, 1972, p. 444-445). Both the Freda and Solor Church formations were interpreted (ibid.) to have been deposited primarily in alluvial plain environments, and Unit D by inference presumably shared a similar depositional setting. Morey (1972) suggested that scattered semi-permanent bodies of water were present on the alluvial plain and interpreted some lithologies in the Solor Church as being of lacustrine origin. The common presence of reduced gray mudstones (and rare black shales) in portions of Unit D may indicate that lacustrine sedimentation (e.g. oxbows) was locally a feature of Unit D deposition, although, alternatively, reduced sediments may have accumulated in fluvial channel-fill or overbank settings. However, the similarity of some lithologies in Unit D with probable lacustrine facies in Unit C suggests some degree of overlap in sedimentary environments between the two units.

Unit C

Unit C (14,980-16,450 feet; Fig. 4) contrasts with all other Keweenawan units by the general abundance of gray to black shales and siltstones. In addition, calcite cements and calcite vein fills reach their highest abundances in Unit C, probably a reflection of fracture-filling associated with structural deformation and faulting within the unit. As in interval D-4, shales and mudstones in Unit C may have formed surfaces for structural detachment and faulting. Structural complexity may further be reflected by the high degree of angular deviation of the drillhole in Unit C (up to 19°; Exlog mudlog). Because of structural complexities and drillhole deviation, the actual thickness of Unit C may not be accurately recorded by drillhole depths. Unit C is subdivided into two intervals based on the relative abundance and grain size of the contained sandstones. A notable shift on the dual induction log occurs at the base of Unit C.

Interval C-2 (14,980-15,700 feet; Fig. 4) is characterized by an interbedded sequence of shale, siltstone, and sandstone. It contrasts with interval C-1 in containing coarse-grained lithologies and a significantly higher proportion of sandstone. Gray to black shales and siltstones, in part with disseminated pyrite, occur through portions of interval C-2 (see Fig. 4), and are most abundant in the upper half. Shales and siltstones are dominantly red-brown in the lower half (with some gray to black laminations), and traces of red-brown, light brown, and green-gray shales and siltstones are scattered in the upper half. Sandstones vary from white to medium gray in color and are dominantly medium- and fine- to very coarse-grained (some granules); some very fine-to fine-grained sandstones are present in the uppermost part. Intergrain black residues are noted in some sandstones in the upper half of interval C-2 (Fig. 4), and may represent relict hydrocarbons sourced from the interbedded carbonaceous shales. Traces of chalcopyrite or native copper were noted on the Exlog mudlog at about 15,440 feet. A core in the upper part of interval C-2 (15,096-15,120 feet) displays an interlayered sequence of light to dark gray shale, siltstone, and sandstone (variably very fine to very coarse-grained and granular, some shale intraclasts); the core is disrupted by numerous calcite veinlets. Of particular note is the presence of detrital limestone grains in the sandstones, including aggregate and coated carbonate grains and ooids (Barnes, this volume).

By contrast, interval C-1 (15,700-16,450 feet) is dominated by siltstone and shale through most of the interval. These are dominantly light to dark gray in color; black shaley interlaminations are noted through much of the interval, and dark brown to black shales are present in the lower half. Subordinate very fine- to fine-grained sandstone interstratifies with the sequence in the upper half (dominates 15,800-15,840 feet). Calcite cements, spar, and veinlets are common in interval C-1. An additional carbonate rock type, identified as limestone on the mudlog, occurs in the lower half of interval C-1 (and scattered in C-2; see Fig. 4); samples are microcrystalline to very fine-crystalline, argillaceous to very argillaceous, in part with shaley interlaminations (see discussion in Ludvigson et al., this volume). A segment of interval C-1 was cored (16,043-16,058 feet) which displays an interlayered sequence of medium to dark gray and black shale and siltstone; it is steeply dipping (>65°, in part overturned) and contains evidence of reverse faulting (see Ludvigson and Spry, this volume).

The on-site chromatograph detected methane throughout Unit C, and ethane was detected through much of the unit as well (Fig. 4). However, gas concentrations are low, varying from less than 0.01% to about 0.15%. These are clearly not commercial quantities of gas, but the presence of gaseous hydrocarbons within the Keweenawan sequence indicates that potential may exist within the MRS for hydrocarbon production, if appropriate traps and migration pathways can be identified. The occurrence of intergranular black residues within Unit C (as well as units B and D-1) warrants additional study. If these prove to be relict hydrocarbon residues, they may help constrain the movement and thermal history of liquid hydrocarbon migration within the system. The dark gray and black shales and mudstones within Unit C still retain organic carbon; core samples examined by Palacas and others (this volume) reach total organic carbon values to 1.4% (average 0.6%). As evidenced by the common occurrence of dark-colored organic-rich rocks, Unit C clearly forms the primary target for source-bed evaluation.

Unit C in the Eischeid drillhole forms a sequence that is closely comparable to the Nonesuch Formation (Oronto Group) in the Lake Superior area (northern Wisconsin, upper Michigan). The Nonesuch is a sequence dominated by interlayered medium gray to black siltstones and shales, in part forming rhythmites; minor sandstones and conglomerates also occur (Daniels, 1982). Like Unit C, it is in part steeply dipping to locally overturned. Detrital sediments of the Nonesuch Formation are more compositionally mature than overlying and underlying strata in the Oronto Group (ibid.). By contrast, Unit C contains the most feldspathic lithologies noted in the Keweenawan sequence of the Eischeid drillhole (maximum to about 30%; see Ludvigson et al., this volume), suggesting differences in detrital sources between Iowa and the Lake Superior area. Shales of the Nonesuch Formation are petroliferous in part, and are the source of the world's oldest known liquid hydrocarbons near White Pine, Michigan. The Nonesuch also contains diagenetic limestone nodules scattered within the shaley intervals (ibid.), and the presence of argillaceous limestones within Unit C in the Eischeid drillhole suggests similarities (see Ludvigson et al., this volume).

The Nonesuch Formation is generally interpreted to have been deposited in lacustrine environments, in a standing body of water with restricted bottom circulation. Possible episodic marine or marginal marine connections with the lake basins cannot be ruled out as yet. Lobate sandstone bodies and channel-fills are suggestive of deltaic systems that prograded into the lacustrine environments; stratigraphic relations indicate that the lake systems were contemporaneous with fluvial deposition marginally (ibid.). Unit C can reasonably be interpreted to have been deposited in a similar environmental setting. This suggests that a series of similar lake systems were developed locally within the MRS from Michigan to Iowa, perhaps in a manner analogous to the lake systems of the modern East African Rift System. The presence of detrital limestone grains (including coated grains and ooids) in interval C-2 sandstones indicates that additional facies contributed material to the reduced lacustrine sediments. The lower Oronto Group in the Lake Superior area (Daniels, 1982) and the Solor Church Formation of Minnesota (Morey, 1972) contain subsidiary limestone facies (with stromatolitic, oolitic, and intraclastic lithologies) which probably were deposited in localized carbonate environments within ephemeral lakes or lagoons on the aggrading alluvial plain. Fluvial reworking of similar facies in the Iowa area may account for the transportation of detrital carbonates into the lacustrine facies of Unit C.

Unit B

Unit B forms the basal portion of the Keweenawan sedimentary sequence in the Eischeid drillhole (approximately 16,450-17,700 feet; Fig. 4). Samples are generally sandstone-dominated, although a variety of shale and siltstone lithologies are noted that may represent, in part, cavings from up-hole. Sandstones are primarily white to light medium gray and red-brown (lower part), and olive green to orange speckles are noted. The sandstones vary between very fine- to fine-grained and very fine- to medium-grained, although coarse to very coarse grains are scattered through the unit, particularly in the upper part. Intergrain black residues, like those seen in Units C and D-1, are seen in some sandstones. The sandstones are interbedded with shale and siltstone in varying proportions, ranging between red-brown and gray to black in color. Some of the gray to black shales may represent cavings from Unit C, although a notable influx of black shale at about 16,830 feet may suggest that black shales similar to those in Unit C are also present in the upper part of Unit B. Trace quantities of methane were noted throughout the interval by the on-site chromatograph, and ethane was detected in the middle and upper parts (Fig. 4).

The sedimentary interval below the Nonesuch Formation in the Lake Superior area is termed the Copper Harbor Conglomerate, an interval dominated by red-brown conglomerates and medium to coarse-grained sandstones with only minor mudstone (Daniels, 1982). Sandstones of the Copper Harbor are the most compositionally immature of the Keweenawan sedimentary sequence, and are further characterized by an abundance of volcanic rock fragments (24-74%; ibid.). Although Unit B apparently occupies a similar stratigraphic position to the Copper Harbor Conglomerate, it is compositionally and texturally dissimilar. Petrographic data (Ludvigson et al., this volume) shows the most quartz-rich sandstones in the Keweenawan sequence within Unit B, as well as the lowest percentages of lithic grains. In addition, conglomeratic textures have not been noted in samples from Unit B, and coarse-grained sandstones are subordinate to the finer-grained lithologies. These features suggest significant differences in source terranes and/or environmental-tectonic setting between most of the Copper Harbor Conglomerate and Unit B. The upper part of the Copper Harbor locally is dominated by fine- to medium-grained micaceous sandstones (the "red facies"; up to 700 feet thick), probably deposited distally from the coarse-grained alluvial facies around the basin margins (ibid.; White and Wright, 1960). Perhaps the finer-grained facies of Unit B were deposited in a similar setting. Unit B was probably deposited primarily in alluvial environments, although the presence of black shales in the upper part suggests that lacustrine environments similar to those of Unit C may have been developed during the closing phases of Unit B deposition.

BASAL PRECAMBRIAN BASEMENT ROCKS -- UNIT A

The basal interval in the Eischeid drillhole, Unit A (about 17,700-17,851 feet; Fig. 4), is a slightly metamorphosed mafic intrusive rock (gabbro), light to dark green in color. Although not available for this article, a portion of the interval was cored (17,733-17,742 feet; for description, see Van Schmus, this volume). The presence of chlorite and epidote in some cuttings indicates low-grade metamorphism; serpentine, fibrous in part, suggests hydrothermal alteration. Although the position of these mafic rocks beneath probable correlates of the lower Oronto Group (i.e. Unit B) invites comparison with the Duluth Complex or other Keweenawan mafic intrusives in the Lake Superior area, the radiometric age of these rocks is considerably older (ca. 1281 Ma; Van Schmus, this volume). Low-grade metamorphism of Unit A may be related to later Keweenawan igneous activity within the MRS.

CONCLUSIONS

The Phanerozoic sequence in the Eischeid drillhole is consistent with the known stratigraphic sequence in western Iowa, and Quaternary, Cretaceous, and Paleozoic units are recognized. However, a sub-Mt. Simon Sandstone interval (Unit H), characterized by coarse-grained poorly-consolidated coarse feldspathic sandstones, has proven difficult to correlate and differs from typical basal Cambrian and characteristic upper Keweenawan sandstones.

The Eischeid drillhole provides the first look at a complete stratigraphic sequence of Keweenawan sedimentary rocks available at any single site within the Midcontinent Rift System. The succession of Keweenawan sedimentary rocks is generally comparable to that seen in outcrops in the Lake Superior area. The Lower "Red Clastic" Sequence in the Eischeid well resembles the general sequence seen in the Oronto Group: 1) sandstone-dominated Unit B compared to the sandstones and conglomerates of the Copper Harbor Conglomerate; 2) gray to black shales and siltstones of Unit C compared to the Nonesuch Formation; 3) the upward-fining sequence of red-brown sandstones, siltstones, and shales in Unit D compared to the Freda Formation. Strata in the Lower "Red Clastic" Sequence of Iowa and the Oronto Group likewise display similar structural complexities, and steeply-dipping units and significant faulting characterizes both areas. The sandstones and interbedded shales-siltstones seen in the Upper "Red Clastic" Sequence in the Eischeid drillhole is similar in a gross sense to the sequence seen in the Bayfield Group of the Lake Superior area, although quartzarenites are not recognized in the Iowa sequence.

Although the sequence of gross lithologic types in the Eischeid drillhole is similar to the Keweenawan sedimentary sequence in the Lake Superior area, important compositional differences contrast the rocks in the two areas. The lower Oronto Group in the Lake Superior area contains the most compositionally immature lithologies and the highest percentages of lithic grains in the Keweenawan sequence, whereas the basal parts of the Lower "Red Clastic" Sequence in Iowa display the most compositionally mature lithologies and the lowest percentages of lithic grains in the Precambrian sequence. In addition, the Bayfield Group in the Lake Superior area contains the most compositionally mature lithologies in the Keweenawan sequence (including quartzarenites), while the Upper "Red Clastic" Sequence in Iowa is feldspathic throughout and contains the highest percentages of volcanic grains. Contrasting compositions suggest that differences in source terranes and/or tectonic-depositional settings need to be considered in evaluating sedimentation along the entire trend of the MRS.

Evidence from the Eischeid drillhole and samples provides a degree of encouragement for potential hydrocarbon development within the MRS. Although commercial quantities of hydrocarbons were not present at the Eischeid site, the presence of methane and ethane in the Lower "Red Clastic" Sequence indicates that gaseous hydrocarbons occur within the flanking basins. Provided that suitable pathways and traps are available, the potential for gas accumulations within the MRS cannot as yet be discounted. In addition, the Eischeid well clearly demonstrates that gray to black shales containing organic material (like those of the Nonesuch Formation) are present within the MRS in Iowa, which enhances the likelihood that potential source rocks occur at other localities within the MRS. Although thermal maturation studies of organic material from Unit C indicate that liquid hydrocarbons have been expunged, having passed through the dry-gas "window" (Palacas et al., this volume), the fate of such mobilized liquid hydrocarbons in the Keweenawan basins remains unknown. If the black intergrain residues seen in sandstones of Units B, C, and D of the Eischeid well prove to be solid hydrocarbon residues, then it would be likely that the lighter hydrocarbon fractions have been lost (inspissated) from the system.

Amoco's pioneering efforts in drilling the Eischeid No. 1 well have helped significantly to advance our understanding of the deep sedimentary basins associated with the MRS, and have inspired groups of geologists to further study. The identification of organic-rich rocks and trace quantities of gas in folded and faulted Keweenawan strata in the Eischeid well offer a degree of optimism concerning hydrocarbon development in the MRS, although the thermal history of the organic material suggests that liquid hydrocarbons may have been expelled during the Late Precambrian. Could hydrocarbon traps survive intact for 800 to 1000 million years? Further exploration is needed to unravel the answer to this and countless other questions concerning th history and development of the MRS.

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REGIONAL ASPECTS OF THE MT. SIMON FORMATION AND THE PLACEMENT OF THE MT. SIMON - PRE-MT. SIMON SEDIMENTARY CONTACT IN THE AMOCO M. G. EISCHEID #1 DRILLHOLE

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INTRODUCTION

The Mt. Simon Formation (or Mt. Simon Sandstone) is widely recognized across the northern midcontinent, U.S. (Ohio to Nebraska), as a basal Phanerozoic sandstone, of Cambrian age, which rests unconformably on a wide variety of Precambrian terranes and grades conformably upward into the Eau Claire Formation or Bonneterrre Formation of Dresbachian age. The formation derives its name from a large sandstone bluff (Mt. Simon) along the Chippewa River in the town of Eau Claire, Wisconsin. The Mt. Simon's outcrop area is limited to a portion of west-central Wisconsin, and throughout the remainder of the northern midcontinent the unit is recognized and mapped from subsurface data. Across most of the region, the basal boundary of the formation currently is consistently placed at the contact between poorly to moderately cemented sandstone above and metamorphic to igneous rock types of Precambrian age below.

The basal Mt. Simon contact is picked with less certainty in the vicinity of the Midcontinent Rift System, where sandstone of the Mt. Simon overlies pre-Mt. Simon rift-associated sedimentary rocks. This uncertainty over placement of the basal Mt. Simon contact in the Midcontinent Rift region has been expressed by several workers in Minnesota and Wisconsin (Stauffer and Thiel, 1941; Ostrom, 1967; Morey, 1972 and 1977), and in Iowa (Bunker, 1981; and Bunker, et al., 1988).

Uncertainty amongst staff members of the Iowa Department of Natural Resources Geological Survey Bureau (GSB) staff, has also been experienced regarding the placement of the basal Mt. Simon contact in the Amoco M. G. Eischeid #1 drillhole, and this article discusses the criteria that can be applied to the placement of the Mt. Simon/pre-Mt. Simon contact in Iowa and the Eischeid #1 drillhole. These criteria are an outgrowth of ongoing GSB studies which are a part of the U. S. Geological Survey sponsored Strategic and Critical Minerals Studies Project.

CHARACTERISTICS OF THE MT. SIMON IN THE TYPE AREA AND THE NORTHERN MIDCONTINENT REGION

Type Area

Recent stratigraphic, petrologic, and sedimentologic studies of Ostrom (1966, 1970), Asthana (1969), Odom (1975) and Driese and others (1981) serve best to define the lithic character of the Mt. Simon in its type area of west-central Wisconsin. In this geographic region, the Mt. Simon ranges in thickness from 0 to 250 feet thick; it regionally thins to zero feet onto the Wisconsin dome and thins more locally over paleotopographic knobs on the Precambrian crystalline surface. Much of the formation is a submature to mature, quartz arenite, but some lithofacies contain significant amounts of submature to mature, feldspathic to highly feldspathic arenites (textural maturity usage of Folk, 1974; mineralogic classification of Odom, 1975). Grain size and sorting within the arenites is highly variable from bed to bed, and grain size throughout ranges from very fine to pebbly. Almost all the feldspar is K-feldspar; plagioclase is extremely rare. The detrital K-feldspar is restricted to the coarse silt to fine sand-size fraction although minor amounts of medium sand-size K-feldspar is present. Detrital K-feldspar grains are mostly subround to round. K-feldspar grains commonly display well defined low temperature, high K_2O feldspar overgrowths (Odom, 1975). Micaceous and feldspathic to highly feldspathic siltstone and shale comprise less than five percent of the formation in the type area. The occurrence of body fossils (molds or shells) is limited to the upper twenty feet, but trace fossils occur sporadically throughout the entire section. Asthana (1969) and

Odom (1975) provided important mineralogic and textural data on the Mt. Simon. Odom (1975) documented the nearly linear increase of feldspar abundance to the increase in volume of detrital grains in the coarse silt to fine sand size fraction. Similar feldspar-grain size relations were observed and noted by Driese and others (1981) during sedimentologic study of the Mt. Simon in the outcrop area. Driese and others (ibid) also noted that there is little to no evidence to suggest that the basement rocks contributed significant amounts of lithic detritus (lithic rock fragments) to the Mt. Simon except in close proximity to positive paleotopographic features.

The age assigned to the Mt. Simon in Wisconsin is Upper Cambrian; this is based on its gradational upper contact with the Dresbachian-age Eau Claire Formation. It is noteworthy that demonstrable Upper Cambrian fossils are absent from the formation except in the uppermost portion. These studies which document the facies and lithic character of the Mt. Simon in the outcrop region, serve as a benchmark for comparison with subsurface data which in general are of lower quality (well cuttings) or remotely sensed (wireline logs).

Subsurface of the Northern Midcontinent

Lithostratigraphic correlation of the Mt. Simon from the Wisconsin outcrop area into the subsurface of Wisconsin and neighboring states, was fully achieved by the first half of the twentieth century through the study of drill cuttings from deep water wells and oil tests. Most of these studies placed the entire sandstone interval between the crystalline basement and the fine-grained, dolomitic and glauconitic Eau Claire Formation in the Mt. Simon. However, several workers (Thwaites, 1923; Templeton, 1950; Raasch, 1950; and Logan, 1926) suggested correlation of the lower portion of this sandstone interval with Keweenawan formations of the lake Superior region (Hinckley, Fond du Lac, and Jacobsville formations, and Bayfield Group units). Some of these authors (Templeton and Raasch) also considered the nonfossiliferous lower Mt. Simon and the nonfossiliferous aforementioned Keweenawan units to be of Middle or possibly Early Cambrian age.

Since these early investigations, more recent subsurface studies, using an enlarged data base (additional drillholes and limited core), hav contributed to a refined understanding of the Mt Simon (Becker et al, 1978; Janssens, 197: Buschbach, 1964; Buschbach, 1975; Collinson et al 1988; Fisher et al., 1988; Catacosinos, 197: Carlson, 1969; Austin, 1970 and 1972; Mossle: 1983; Hoholick et al., 1984; Heald and Baker, 197 Duffin, 1989; and Flurkey, 1976). These studie assign all siliciclastic strata beneath the Eau Clair Formation or Cambrian carbonates and abov Precambrian metamorphic or igneous rocks to th Mt. Simon Formation, and designate their age a Upper Cambrian. In a small part of the regior however, the Mt. Simon overlies pre-Mt. Simo siliciclastic strata and the contact between the tw units as well as the age assignment of the olde strata is uncertain (Beaver Island, Michigan Catacosinos, 1973; and Fisher et al., 198 Midcontinent Rift, southern Minnesota, More 1977; and Midcontinent Rift, central and souther Iowa, Bunker, 1981; and Bunker et al., 1988).

The thickness of the subsurface interva assigned to the Mt. Simon varies substantiall across the region from zero feet ove paleotopographic positive features to greater tha 1000 feet across portions of Iowa, Illinois, Indian and Michigan. Maximum thicknesses are reporte from depocenters in northeastern Illinois (260 feet, Buschbach, 1964), central Michigan Basi (1500 feet, Fischer et al., 1988), Rough Cree Graben, western Kentucky (>1000 feet, Collinso et al., 1988) and southwest to central Iow (1000-1400 feet, Bunker, 1981, and Bunker et al 1988). The interval thins substantially over much c Wisconsin, Minnesota, Iowa, and Nebraska t thicknesses consistently less than 300 feet, an commonly less than 100 feet, especially throug portions of central and western Iowa, southwes Minnesota, and eastern Nebraska.

Most published descriptions of the Mt. Simo interval tend to be brief and generalized. Moda analyses and detailed mineralogic composition documentation is rarely supplied. The formation i dominantly sandstone, but micaceous shale an siltstone are present in intervals ranging i thickness from less than 1 inch to 60 feet. Less tha five percent of the formation is shale or siltstone Grain size and sorting within the dominan sandstone portion varies substantially from bed t bed. Throughout the entire formation grain siz ranges from very fine to very coarse sand, bu intervals containing granules and pebbles are als present. There is a general vertical grain size and sorting trend across the region. The lower part consists of fine to very coarse-grained and pebbly more poorly sorted sandstone which grades upward to better sorted, fine to coarse-grained sandstone in the upper part. A distinct poorly sorted, pebbly basal conglomerate, found in portions of the outcrop area, has not been recovered in the subsurface. Sandstone color varies from white to clear to yellow and red. Shale colors include hues of green, red, purple, and gray.

Cementation and Mineralogy

Induration of the Mt. Simon varies from poor to good across the region. The more deeply buried portions are generally the more highly cemented. The dominant cements are quartz and potassium feldspar overgrowths, and subhedral to euhedral pore-filling K-feldspar crystals, with lesser amounts of hematite, kaolinite, chlorite, microquartz, anhydrite, and carbonate (Heald and Baker, 1977; Hoholick et al., 1984; Anderson, 1990). Porosity ranges from 5 to 35% at depths less than 1000 feet to 1 to 2% at depths of 14,900 feet (Hoholick et al., 1984).

The sandstone framework grain mineralogy of the Mt. Simon in the subsurface apparently is similar to that of the outcrop belt, but few detailed petrologic studies are available for comparison. The majority of the formation is reported to consist of submature to mature quartz arenites with lesser amounts of feldspathic to arkosic arenites; lithic arenites are not reported. Hoholick and others (1984) reported a gradual downward increase in feldspar content in the Illinois subsurface from approximately 90% quartz and 5% feldspar to about 75% quartz and 20% feldspar. However, a gradual downward increase in feldspar content was not observed by Duffin (1989), Kersting (1980) or McKay (in progress) during their petrologic studies of several thick (>800 feet) Mt. Simon sections in northern Illinois. Thick and thin (>500 feet and <300 feet) Mt. Simon sections in eastern and western Iowa are dominantly quartz arenites with subordinate amounts of feldspathic arenite (Flurkey, 1976; and Anderson, 1990). Quartz arenites are also reported to dominate the formation in the subsurface of Minnesota (Mossler, 1983), Indiana (Becker et al., 1978), Michigan (Catacosinos, 1973) and Nebraska (Carlson, 1969), but Heald and Baker (1977) report that the Mt. Simon is dominantly a feldspathic arenite in southeast Ohio and northwest West Virginia. Arkose locally dominates the base of the Mt. Simon in parts of Indiana (Becker et al., 1978), Illinois (Templeton, 1950; Buschbach, 1964) and Michigan (Fisher et al., 1988).

Feldspar in the Mt. Simon subsurface is similar to feldspar in the outcrop area in composition, shape, size, and occurrence. Almost all feldspar is potassium feldspar; plagioclase is extremely rare to absent. Detrital feldspars are dominantly subround to round and usually limited to the coarse silt to fine size fractions. Minor medium and coarse sand size K-feldspar is present at the base of the formation locally (Odom, 1975; Buschbach, 1964; Hoholick et al., 1984). Subsurface detrital K-feldspars commonly exhibit subhedral to euhedral authigenic K-feldspar overgrowths which are very similar to those in the outcrop region. As in the outcrop region, the percentage of K-feldspar in subsurface samples tends to increase with decreasing arenite average grain size (Flurkey, 1976; Heald and Baker, 1977; Hoholick et al, 1984; Duffin, 1989; Anderson, 1990; and Mossler, 1990, personal communication). Heald and Baker (1977) and Hoholick and others (1984) report that K-feldspar is a dominant constituent in the fine-grained fraction, but that minor amounts of medium and coarse K-feldspar are also present. The similarity of Mt. Simon feldspar characteristics across such a large region may serve as a lithostratigraphic discriminator in the subsurface within an interval apparently lacking potential for biostratigraphic correlation.

Detrital grains, other than quartz and feldspar, are rare in the Mt. Simon. Grains of glauconite, iron-ooids, and inarticulate brachiopod fragments occur in the upper portion of the formation where it is gradational to the overlying Eau Claire Formation. Lithic detrital grains (aphanitic rock fragments) are very rare in the Mt. Simon except in the basal few feet where it immediately overlies the Precambrian crystalline basement.

To summarize, the principal distinguishing lithic characteristics of the Mt. Simon Formation in the outcrop area and northern midcontinent subsurface are as follows: 1) the formation is dominated by sandstone with less than 5% shale and siltstone; 2) formational thickness varies from zero to 2600 feet 3) sandstone composition is dominated by quartz arenite with subordinate amounts of feldspathic arenite; 4) detrital feldspars are subround to round K-feldspars and predominantly confined to the coarse silt to fine sand size fractions, with minor amounts of medium and coarse sand-size feldspar; 5) dominant cements are composed of quartz and K-feldspar overgrowths with lesser amounts of hematite, kaolinite and chlorite; 6) body fossils are restricted to inarticulate brachiopods in the uppermost twenty feet and trace fossils occur in the uppermost few hundred feet; and 7) apparent absence of fossils throughout the middle and lower parts of the formation where its thickness approaches or exceeds 1000 feet.

PLACEMENT OF UPPER AND LOWER MT. SIMON CONTACTS IN THE EISCHEID DRILLHOLE

The placement of the upper and lower Mt. Simon contacts in the Eischeid drillhole is based upon evaluation of the following data set: 1) Schlumberger wireline logs (Fig. 1); 2) Exlog mudlog; 3) thin sections of cuttings from three sample intervals (2800-2830 feet, 3000-3010 feet, and 3500-3510 feet); and 4) binocular microscopic examination of selected sample cuttings from 2740-3100 feet. Qualitative analysis of the caliper, gamma ray, photoelectric absorption cross section index, litho-density, and compensated neutron porosity log traces in conjunction with the examination of well cuttings suggests that the Mt. Simon is confined to the 2782-2802 feet depth interval.

Upper Mt. Simon Contact

The upper Mt. Simon in Iowa usually is gradational into the overlying Eau Claire (fine sandstone- to shale-dominated) or Bonneterre (dolostone- to sandy dolostone-dominated) formations. In western Iowa, this gradational interval typically is 5 to 20 feet thick and composed of interstratified coarser- and finer-grained glauconitic and dolomitic sandstone and sandy, glauconitic dolostone. Log traces and samples indicate sandy and glauconitic dolostone (calcareous in part) from 2736 to 2760 feet. Sparse ($<5\%$), loose iron oxide pellets and iron oxide pellets in a dolomite matrix are present in the 2740-2770 feet interval (30 feet samples). An increase in bulk density and Pe (photoelectric absorption cross section index) and a decrease in gamma ray intensity in the 2756-2760 feet interval suggests that this depth interval is the source of the iron oxide pellets. Iron oxide pellets and ooids are commonly present at or near the Eau Claire - Mt Simon contact in northern and western Iowa.

Log traces from 2760 to 2782 feet indicate downhole decreases in bulk density (from 2.43 gm/cm^3 to 2.30 gm/cm^3), Pe (from 2.7 to 1.9) and drill-time (1.5 min/ft to 0.6 min/ft), and moderately steady gamma ray values (45-65 units from 2760 to 2778 feet, and 65-95 units from 2778 to 2782 feet). Cuttings samples through this depth range (30 foot samples; 2740-2770 feet, and 2770--2800 feet) indicate the interval is dominated by very fine- to medium- grained, glauconitic and dolomitic sandstone with lesser amounts of grey-green micaceous shale; sparse phosphatic inarticulate brachiopod fragments are also present. These rock types are typical of the lowermost Eau Claire - Bonneterre strata in western Iowa.

The top of the Mt. Simon appears as an abrupt shift in the log traces at 2782 feet. Bulk density values through the Mt. Simon interval (2782-2802 feet) are stable, ranging between 2.27 and 2.32 gm/cm^3. Pe values range between 1.8 and 2.0, and gamma ray intensity varies between 20 and 75 units (averages 35 units). Drill-time decreased from the overlying strata, and was uniform through the interval at 0.4 min/feet. The neutron porosity trace is in close agreement with the density trace and indicates porosity of about 20%. The low Pe values and similarity of neutron porosity and bulk density values indicate the presence of a relatively clean (quartz-rich) sandstone.

The cuttings sample which encompasses the interval (30 foot sample, 2770-2800 feet) is dominated by very light grey and light red, fine- to coarse-grained sandstone and loose individual grains of medium-to very coarse-grained quartz. Approximately 30 to 40% of the cuttings are very fine- to medium-grained glauconitic sandstone. These along with trace amounts of iron oxide pellets and green micaceous shale are interpreted to be sourced from above the Mt. Simon. The grey to red sandstone is moderately hard to friable, quartzose to feldspathic, and indurated by siliceous cement. The loose quartz grains are subround to well-rounded and frosted.

Trace amounts of loose, pinkish red, medium-to coarse-grained, subangular feldspar also occur in the cuttings sample. Coarse feldspar is rarely found in the Mt. Simon in Iowa, and the first occurrence of it in this sample interval may be interpreted several ways. The feldspar may have been drilled

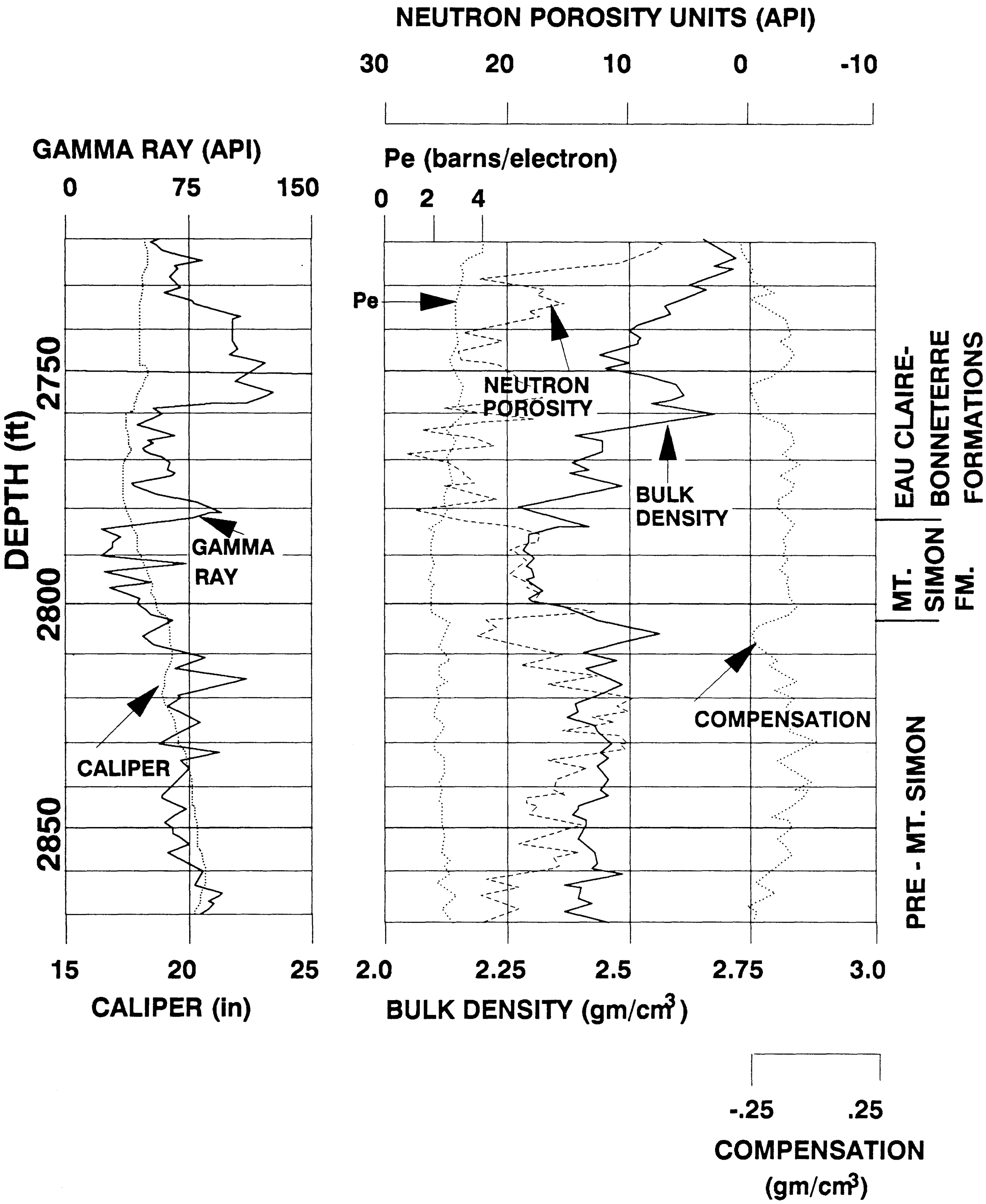

Figure 1. Segment of the Schlumberger Litho-Density/Compensated Neutron/Gamma Ray Log between 2720 and 2870 feet showing interpreted upper and lower Mt. Simon Formation contacts in the Eischeid drillhole.

from underlying pre-Mt. Simon arkosic sandstone and inadvertently caught and included by the mudlogger in the 2770-2800 feet sample. Fast drilling through the Mt. Simon interval (0.4 min/ft) would result in very little lag-time separation of cuttings from basal Mt. Simon and uppermost pre-Mt. Simon strata. Thus the coarse feldspar may not really be from the Mt. Simon, but instead from the underlying uppermost pre-Mt. Simon subarkose. Another explanation is that the coarse feldspar is indeed present in the basal few feet of the Mt. Simon where the Mt. Simon overlies pre-Mt. Simon, fine- to coarse-grained arkose.

Mt. Simon - Pre-Mt. Simon Contact

The top of the pre-Mt. Simon sedimentary section is marked by an abrupt shift in log traces and a distinct change in sample cuttings. Bulk density increases 0.12 gm/cm^3 to average values of 2.43 gm/cm^3. Pe values increase from an average of 1.9 in the Mt. Simon to 2.3 in the pre-Mt. Simon. This indicates higher clay mineral, feldspar and/or carbonate cement content. Gamma ray intensity increases across the contact an average of 35 units to values averaging 70 units. Neutron porosity values decrease from the overlying Mt. Simon and range between 10 and 22 porosity units. Some of the apparent porosity values are elevated due to the presence of shaley siltstone. Drill-time increases downhole across the contact from 0.4 min/ft in the Mt. Simon to average values of 1.9 min/ft through the upper 300 feet of the pre-Mt. Simon. All these traces reflect a downhole change to a denser, harder, less porous rock stratum which contains significantly greater quantities of minerals with Pe values greater than 2.0 (e.g., clay, feldspar, carbonate).

The two rock types that are representative of the upper 300 feet of pre-Mt. Simon strata are: 1) 80% to 90% clear to light reddish brown, fine- to medium, and fine- to very coarse-grained subarkosic sandstone; and 2) 10 to 20% reddish brown, micaceous, and shaley to sandy siltstone. The sandstones are poorly to moderately indurated; much of this interval drilled up as loose individual grains. Sandstone grain shape is angular to subround. Rock types which contaminate upper pre-Mt. Simon samples include: fine-grained glauconitic sandstone, sandy dolostone and iron oxide pellets and ooids. These are sourced from the lower Eau Claire-Bonneterre interval.

Average QFL modal composition of the upper 300 feet of sandstone is $Q_{82}F_{17.5}L_{0.5}$ (2 samples; see Ludvigson et al., this volume; tables 1 and 2). This QFL distribution is not decidely different from typical Mt. Simon Formation feldspathic arenites, but fine-to very coarse-grained Mt. Simon in central Iowa is typically a quartz arenite, although feldspathic arenites may be present in subordinate amounts. The absence of quartz arenite in this sandstone dominated interval is one line of evidence to suggest that these sandstones are different from typical Mt. Simon sandstones.

Additional compositional and textural evidence also suggests that sandstones below 2802 feet are different from typical Mt. Simon sandstone in Iowa. Detrital feldspar is all K-feldspar (2802-3100 feet) and much of it is coarse- to very coarse-grained and angular to subangular. This is noticeably different from typical Mt. Simon K-feldspar which is dominantly very fine-to fine-grained (rarely medium and coarse) and subround to round. Trace amounts of aphanitic volcanic rock fragments in the upper 300 feet of the pre-Mt. Simon section also suggests compositional variance from the Mt. Simon (Ludvigson, et al., this volume, table 2).

The significant compositional and textural variation of the interpreted pre-Mt. Smion sandstone from typical Mt. Simon sandstone also can be considered within the context of overall formational thickness. Throughout much of the northern midcontinent (excepting southeast Ohio), including all of Iowa, the Mt. Simon is dominated by quartz arenites. Quartz arenite domination occurs in sections which vary in thickness from less than 100 feet to greater than 1000 feet. Arkosic to subarkosic sandstones appear to dominate the unit only locally, and only in the basal 50 to 300 feet in sections where the entire formation attains thicknesses in excess of 1000 feet. This local basal arkosic domination is quite different from what is seen in the Eicheid drillhole. The Eischeid drillhole contains an interpreted 20 feet of quartzose Mt. Simon sandstone underlain by approximately 800 feet of poorly indurated subarkosic to arkosic arenite and lesser siltstone. If this thick, poorly indurated arkosic arenite interval were to be included within the Mt. Simon, it would represent a significant combined compositional and thickness deviation from any known Mt. Simon sequence.

One last line of evidence which supports separation of the Mt. Simon from the pre-Mt.

Simon at a depth of 2802 feet comes from the presence of microbrecciated sandstone cuttings in the pre-Mt. Simon interval. Trace amounts of microbrecciated sandstone fragments were seen in thin sections in the upper 700 feet of the poorly indurated pre-Mt. Simon interval. These microbrecciated sandstone fragments appear to be similar to microbreccias found downhole throughout a large portion of the pre-Mt. Simon sedimentary section. The presence of the microbreccia chips may imply that the uppermost preserved portion of the pre-Mt. Simon section was affected by structual movements similar to those that created tectonized fabrics throughout much of the Eischeid drillhole sequence (Ludvigson, et al., this volume). These structural movements on the Iowa Horst are presumably Late Keweenawan in age (Anderson, this volume) and thus may place a minimum age of Late Keweenawan on the uppermost pre-Mt. Simon sedimentary section. However, only cursory examination of these microbreccias has been conducted, and a more detailed investigation of these and downhole microbreccia chips and tectonized cored intervals is warranted before firm age constraints can be established.

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AGE RELATIONSHIPS FOR GABBRO FROM THE AMOCO M.G. EISCHEID #1 WELL

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ABSTRACT

Core recovered from 17,733 to 17,742 feet in the Amoco M. G. Eischeid #1 well, Carroll County, Iowa is a medium-grained, undeformed gabbro. U-Pb analyses of two slightly discordant, sub-milligram fractions of zircon from the gabbro yield an age of 1281 ±50 Ma, significantly older than U-Pb ages (1086 to 1108 Ma) of Keweenawan volcanic and plutonic rocks in the Lake Superior region. Common Pb compositions from the gabbro are distinctly different from those of basalt and gabbro at known Midcontinent Rift (MCR) locations. Therefore, we conclude that the gabbro is from the pre-Keweenawan basement. The primary mineralogy is altered, but the undeformed nature of the rock and its age show that it is not part of the regional Early Proterozoic basement.

Ages of Middle Proterozoic mafic units in the Canadian shield show several major magmatic events at 1250 to 1270 Ma. The gabbro underlying sedimentary units of the Amoco well is most likely a dike, sill, or pluton intruded into the older basement during 1270 Ma mafic igneous activity and exposed by erosion prior to deposition in the flanking basin of the MCR. This gabbro does not bear on the age of magmatism in the rift, but it confirms that the well was drilled through the sedimentary fill of the basin.

INTRODUCTION

The Midcontinent Rift (MCR) system is one of the major geological and geophysical features of North America, but only the portion of the rift in the Lake Superior region is exposed. Although much has been learned about the structure, petrology, geochemistry, and geochronology of the MCR in the Lake Superior region, the paucity of samples from the buried portion has obscurred its properties. Deep drill holes that penetrate the buried portion of the rift provide samples for analysis. A few such opportunites have developed in the past ten years, notably the McClure Sparks #1-8 well in Michigan (Sleep and Sloss, 1978) and the Texaco Poersch #1 well in Kansas (Berendsen et al., 1988).

Some of the major data needed for the buried portion of the rift are precise and accurate isotopic ages which, with ages from the Lake Superior region, will allow evaluation of the timing of rift development. Samples from wells drilled prior to the Eischeid #1 well have not yet yielded such ages, due largely to lack of suitable rock types. For example, several K-Ar ages obtained from the Texaco Poersch #1 well in Kansas ranged from 800 Ma to 1,000 Ma (Berendsen et al., 1988); because of the ease with which radiogenic argon can be lost during burial and alteration, they probably represent minimum ages that may be up to 30 percent too young.

Samples from the Eischeid #1 well were provided for us to attempt precise and accurate age determination. The only method capable of yielding such ages for altered mafic rocks is U-Pb dating of zircon or some other suitable trace mineral (e.g. baddeleyite; Krogh et al., 1987). We were able to find zircon in gabbro core provided from the lower part of the hole (17,733 to 17,742 feet deep; Project Upper Crust No. IACA-001) and to obtain an age of 1,281 ±50 Ma. These results and their interpretation are described below.

REGIONAL SETTING

The drill hole is located west of the main

Table 1. Chemical analysis for metagabbro (IACA-001; 17,738 feet), Amoco M.G. Eischeid #1 well, Carroll Co., Iowa.

Major Elements (%)		Trace Elements			Normative Analysis (%)	
SiO_2	49.21	Rb	73	ppm	Quartz	1.4
TiO_2	1.03	Sr	233	ppm	Orthoclase	6.9
Al_2O_3	16.57	Ba	333	ppm	Albite	18.8
FeO	9.50	Ni	107	ppm	Anorthite	31.8
Fe_2O_3	1.93	Co	67	ppm	Diopside	4.1
MnO	0.18	Cr	86	ppm	Hypersthene	27.5
MgO	6.05	Mo	<1	ppm	Magnetite	2.8
CaO	8.13	W	20	ppm	Ilmenite	2.0
Na_2O	2.22	Zn	151	ppm	Apatite	0.3
K_2O	1.77	Pb	4	ppm	Calcite	1.0
F	0.05	Bi	6	ppm	Water	3.0
H_2O	3.04	Cd	0.5	ppm		99.6
CO_2	0.45	V	236	ppm		
S	0.11	Cu	169	ppb	An/(Ab+An) = 0.63	
P_2O_5	0.11	Au	8	ppb		
Total	99.75	Pt	15	ppb		
		Pd	16	ppb		

Analysed at Institute for the Study of Mineral Deposits, South Dakota School of Mines and Technology, Rapid City, SD.

geophysical anomaly of the MCR in Iowa (Anderson, "Interpretation of Geophysical...," this volume) and penetrated clastic rocks of the western flanking basin. The sedimentary units could be underlain by early MCR flood basalts or by pre-Keweenawan basement. There is sparse subsurface control on the nature of the pre-rift basement in this part of Iowa, but regional studies (Van Schmus et al., 1987; Wallin and Van Schmus, 1988; and Van Schmus et al., 1989) indicate that this basement is either part of the 1,850 Ma Penokean Orogen (Sims et al., 1989) or the older portion (1,750-1,780 Ma) of the Central Plains Orogen (Sims and Peterman, 1986; Bickford et al; 1986; Wallin and Van Schmus, 1988). In either case the older basement represents juvenile orogenic crust accreted to the older craton of the Canadian Shield during the Early Proterozoic (see Hoffman, 1988; Van Schmus et al., 1989).

The older basement is generally tectonically deformed and metamorphosed, as shown by drill hole and outcrop samples (Yaghubpur, 1979; Denison et al., 1984; Sims and Peterman, 1986; Van Schmus et al., 1987). It was subsequently intruded by numerous granitic plutons, emplaced during one or both of the 1400 to 1500 Ma and 1300 to 1400 Ma anorogenic felsic igneous events known in the midcontinent region (e.g., Thomas et al., 1984; Bickford and Van Schmus, 1985). These plutons are typically massive and undeformed, indicating that little regional deformation occurred after 1,500 Ma. No igneous events in the interval between 1,300 Ma and 1,100 Ma had been reported from the western part of the midcontinent region prior to this study.

PETROGRAPHY

The core from the 17,733 to 17,742 foot depth of the Eischeid #1 well is medium-grained metagabbro, consisting of relatively fresh augite, altered plagioclase, lesser amounts of hypersthene partially altered to chlorite or serpentine, and minor amounts of opaque minerals. The bulk chemistry and corresponding normative mineral composition (Table 1) are consistent with classification of this rock as tholeiitic gabbro. Microbeam analyses of augite and plagioclase grains and serpentine pseudomorphs from this core are given in Table 2. The best preserved major

Table 2. Chemical data for minerals in the metagabbro from the Amoco M.G. Eischeid #1 well, Carroll Co., Iowa; 17,738 foot depth.

Oxide %	Clinopyroxene crystals			Serpentine pseudomorphs		Plagioclase crystals			
SiO_2	51.18	51.22	52.66	28.93	30.17	54.65	58.16	51.50	51.95
TiO_2	0.51	0.52	0.39	0.05	0.07	nd	nd	nd	nd
Al_2O_3	2.80	3.04	1.64	15.52	14.51	27.49	25.76	29.41	29.45
FeO*	11.52	10.93	11.42	29.44	29.51	1.01	0.50	0.20	0.80
MnO	0.25	0.28	0.35	0.22	0.45	nd	nd	nd	nd
MgO	15.00	16.20	16.55	13.42	13.24	nd	nd	nd	nd
CaO	18.82	18.25	17.11	0.36	0.44	11.57	9.08	13.66	13.80
Na_2O	0.31	0.27	0.21	0.04	0.00	5.05	6.55	3.46	3.72
K_2O	0.00	0.00	0.00	0.01	0.00	0.21	0.46	0.65	0.17
Total	100.39	100.71	100.33	87.99	88.39	99.98	100.51	98.88	99.89
Wo	38.5	36.9	34.7		An	55.3	42.3	67.9	66.7
En	42.7	45.5	46.7		Ab	43.6	55.2	31.0	32.4
Fs	18.8	17.6	18.6		Or	1.2	2.6	1.1	0.9
Mg#	69.4	72.1	71.5		An/(An+Ab)	55.9	43.4	68.7	67.3

nd = not determined. * Total Fe reported as FeO. Mg# = Magnesium number (Fe/Fe+Mg).
Analysed at Institute for the Study of Mineral Deposits, South Dakota School of Mines and Technology, Rapid City, SD.

mineral is augite, with a magnesium number (Mg/[Mg+Fe]) of about 70; plagioclase is moderately altered, although relict domains exist which indicate that the primary composition was in the range An_{45}-An_{65}, consistent with the normative composition.

The gabbro is virtually undeformed, indicating that alteration of the primary mineral assemblage took place in the absence of penetrative deformation, perhaps as a result of deep burial or circulating hydrothermal fluids. This rock clearly does not resemble amphibolites, gneisses, and schists derived from mafic rocks of the subsurface Central Plains Orogen or of metavolcanic units that crop out in Wisconsin and Colorado.

GEOCHRONOLOGIC ANALYSES

Substantial amounts of gabbro core from the 17,733 to 17,742 foot depth were provided for analysis (our number IACA-001). After a pilot study on a small portion yielded trace amounts of zircon, most of our sample (representing about half of the total core) was processed to obtain enough zircon for analysis. The total yield of zircon was less than 1 mg, from which two fractions were picked out by hand; baddeleyite was not seen in the heavy mineral concentrate. Because of the small zircon yield we did not attempt air abrasion of the zircon to improve concordancy (Krogh, 1982).

Sample analysis included micro-analytical dissolution (Parrish, 1987), mixed ^{205}Pb-^{235}U tracer, and HBr media for ion exchange separation of Pb; U was separated from the HBr wash using HCl ion exchange separation. Analytical blanks at the time of these analyses were less than 100 picograms total Pb and less than 10 picograms total U. Although Pb blanks represent about half (or less) of the non-radiogenic Pb, both samples were sufficiently radiogenic that little uncertainty is introduced for radiogenic Pb or for U (Table 3). The original common Pb correction was calculated on the basis of 1300 Ma old lead, using the Stacey and Kramers (1975) model.

The two fractions yield slightly discordant results and plot close to one another on a concordia diagram (Fig. 1). Regression of a chord through the data (Ludwig, 1983) yields an upper intercept on concordia of 1,281 Ma ±50 Ma (two-sigma) based on analytical errors of ±0.2% for radiogenic

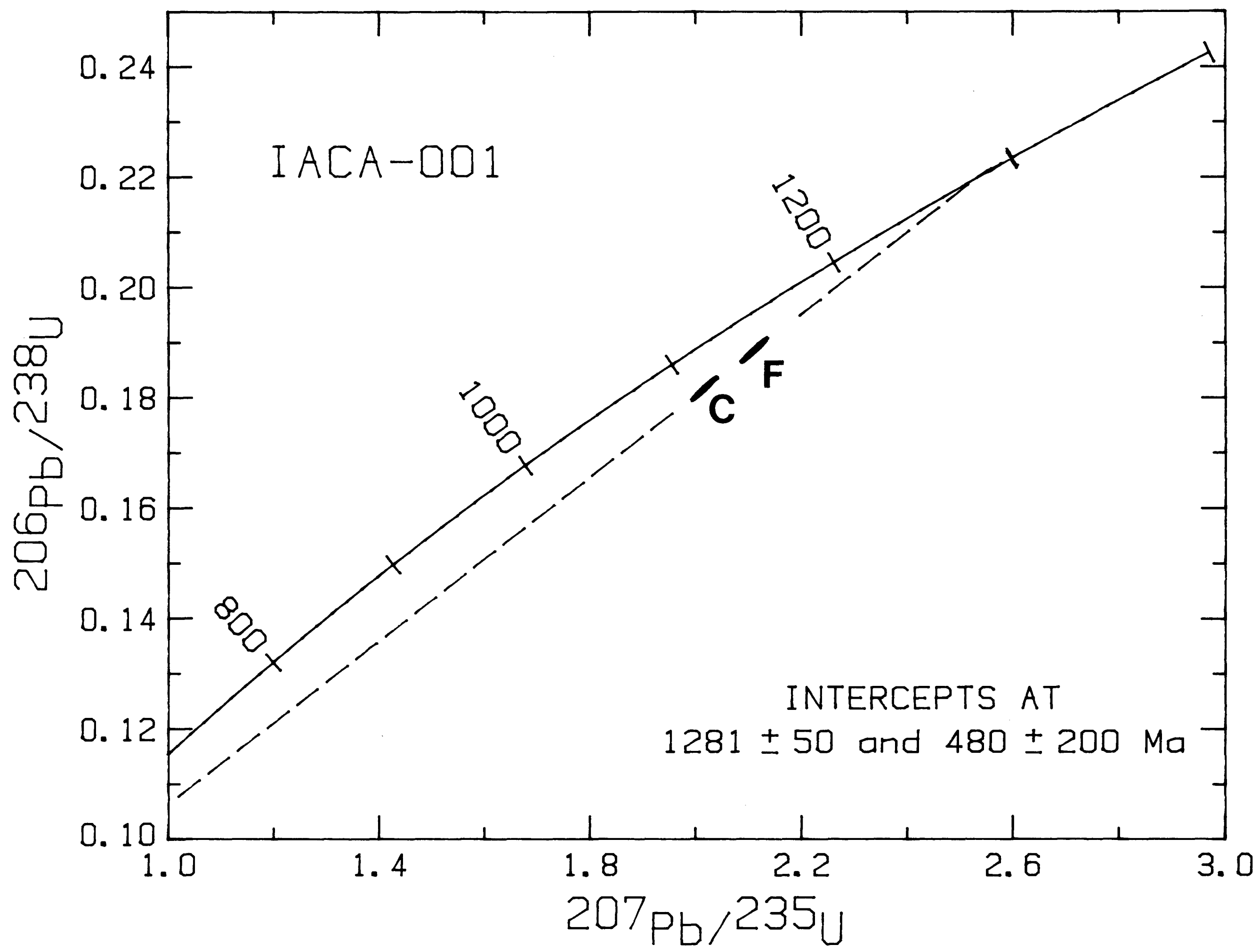

Figure 1. Plot of U-Pb data for two zircon fractions from gabbro at the bottom of the Amoco M.G. Eischeid #1 well (17,733-17,742 feet). No geologic significance is attributed to the apparent age of the lower intercept. Solid ellipses represent 2-sigma errors, C and F refer to size fractions from Table 3.

Table 3. Analytical data for zircons from metagabbro at 17,738 foot depth in Amoco M.G. Eischeid #1 well.

				Observed[3]	Radiogenic Ratios[4]				Ages[5]		
	Weight	U^2	Pb^2	Pb-206	Pb-207	Pb-208	Pb-206	Pb-207	Pb-206	Pb-207	Pb-207
Fraction[1]	(mg)	(ppm)	(ppm)	Pb-204	Pb-206	Pb-206	U-238	U-235	U-238	U-235	Pb-206
C (+200)	0.195	169.7	31.7	1,477	0.080444	0.07238	0.18159	2.0147	1,076	1,121	1,208
F (-200)	0.053	264.1	52.8	758	0.081061	0.07967	0.18869	2.1105	1,114	1,152	1,223

Regression: U.I. = 1,281 ±50 Ma; L.I. = 480 ±200 Ma

Notes:
1. Numbers refer to mesh size; both samples hand-picked; C = coarse, F = fine.
2. Total U and Pb, corrected for analytical blank.
3. Measured ratio, corrected for spike, but not for blank or non-radiogenic Pb (see text).
4. Pb corrected for spike, blank and non-radiogenic Pb; U corrected for blank (see text).
5. Ages given in Ma; decay constants according to Steiger and Jaeger (1977).

Table 4. Pb data for fractions of gabbro from the Eischeid #1 drill hole.

		Pb Isotopic Composition		
Sample	Subsample[1]	206/204	207/204	208/204
IACA-001	A:(M@0.2),L2	18.073	15.574	27.483
	A:(M@0.2),L3	18.208	15.618	37.690
	B:(M@0.3),L2	18.070	15.565	37.529
	C:(M@0.4),L2	18.633	15.650	38.231
	D:(M@0.5),L2	18.406	15.611	37.822
	H:(M@0.9),L2	18.350	15.605	37.928
	H:(M@0.9),L3	17.661	15.550	37.091
	J:(NM@1.0),L2	18.920	15.647	38.250
	J:(NM@1.0),L3	18.667	15.688	37.394

1. Subsamples refer to magnetic fractions (e.g., M@0.2 = magnetic at 0.2 amps current), L2 and L3 refer to leach fractions.

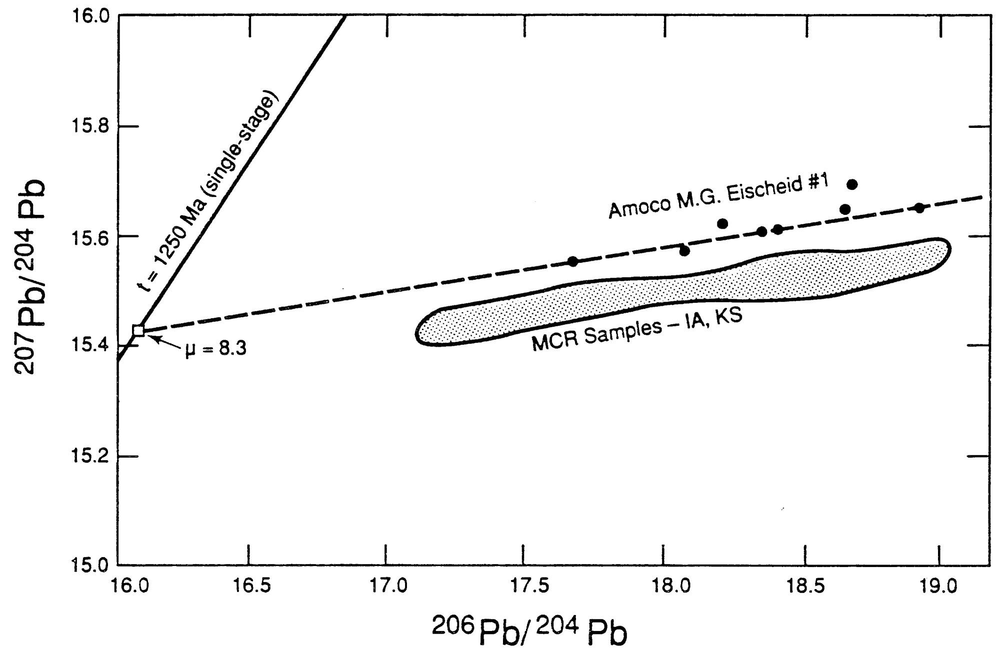

Figure 2. Plot of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ data for magnetic fractions from the Eischeid #1 gabbro (IACA-001, Table 4) plus data for samples of MCR basalt and gabbro in Guthrie Co., Iowa, Riley Co., Kansas, and Washington Co., Kansas (Van Schmus, unpublished). Note that data from IACA-001 plot distinctly above those from the MCR. Assuming a single-stage lead evolution model, $^{238}U/^{204}Pb$ for IACA-001 Pb evolution is approximately 8.3; that for Pb from MCR samples is 8.2. Also, shown is a 1250 Ma geochron for single-stage Pb evolution.

$^{207}Pb/^{206}Pb$, ±1% for Pb/U, and a correlation coefficient of 0.98. A minimum age is given by the $^{207}Pb/^{206}$ Pb age of 1,223 ±5 Ma for the -200 fraction. There was insufficient zircon to prepare an air-abraded, non-magnetic, more concordant fraction; thus, 1281 ±50 Ma is the best estimate of the age of the sample. The option of obtaining a larger sample is not possible without unreasonable cost (e.g., another drill hole)!

We also analysed IACA-001 for its common Pb. Because the limited core available did not produce a significant range of U/Pb ratios, we separated the -60 to +100 mesh portion of ground core into several fractions with the Franz Isodynamic Separator. These separations essentially produced mineralogic fractions, with augite concentrated in more magnetic fractions and feldspar concentrated in less magnetic fractions. Alteration and fine grain size precluded obtaining pure mineral fractions, but the fractions that were obtained could be expected to consititute a mixing array colinear with data obtained from pure mineral fractions, provided there has been no disturbance of the U-Pb isotopic system since the rock formed.

Each magnetic fraction was first treated with a cold HCl wash to remove loosely-bound Pb (leach-1), then subjected to two HF leaches (leach-2, leach-3) to extract Pb from HF-soluble phases (feldspar, pyroxene, etc.); the insoluble residue was not processed further. Pb was extracted from the solutions using HBr ion-exchange methods. The combination of magnetic splits and leaches yielded Pb compositional data (Table 4) that have a significant range in values, with a moderate, but significant linear correlation (Fig. 2). Even though the trend from IACA-001 is sub-parallel to that for mafic rocks from known MCR sample sites in Kansas and Iowa (Fig. 2), it apparently has a significantly higher inferred single-stage $^{238}U/^{204}Pb$ value, supporting our contention that IACA-001 is not a MCR gabbro.

REGIONAL INTERPRETATION

Several U-Pb ages of zircon and baddeleyite have recently been reported from Keweenawan igneous rocks of the Lake Superior region (Table 5). These define a narrow interval between 1087 and 1109 Ma, consistent with previous estimates of

Table 5. Ages from Selected Middle Proterozoic Mafic Units.

Unit	Age (Ma)	Method*	Reference
A. Keweenawan Igneous Units, Lake Superior Region.			
Michipicoten Island Formation (rhyolite)	1,087 ±3	U-Pb (Z)	P1
Copper Harbor Conglomerate (andesite)	1,087 ±2	U-Pb (Z)	D1
Various volcanic and plutonic units	1,089 ±15	Rb-Sr (WR)	V2
Portage Lake Volcanics (basalt)	1,094 ±2	U-Pb (ZB)	D1
Portage Lake Volcanics (basalt)	1,096 ±2	U-Pb (ZB)	D1
Osler Group (rhyolite)	1,098 ±4	U-Pb (Z)	D2
Osler Group (porphyry)	1,108 ±4	U-Pb (Z)	D2
Coldwell Complex (gabbro, syenite)	1,108 ±1	U-Pb (ZB)	H1
Logan Sills (diabase)	1,109 ±4	U-Pb (ZB)	D2
Various volcanic and plutonic units	1,110 ±10	U-Pb (Z)	S1
B. Central Metasedimentary Belt, Grenville Province			
Rhyolite, Tudor Township	1,279 ±3	U-Pb (Z)	H2
Rhyolite, Belmont Township	1,287 ±10	U-Pb (Z)	H2
Volcanism and plutonism	1,290-1,250	U-Pb	L2
C. Other Mafic Units in the Candadian Shield.			
Great Abitibi Dike, Timmins, Ontario	1,141 ±2	U-Pb (ZB)	K1
Sudbury dike (diabase)	1,238 ±4	U-Pb (B)	K1
Sudbury dikes (diabase)	1,250 ±50	Various	V1
Mackenzie dikes (diabase)	1,267 ±2	U-Pb (B)	L1
Muskox Intrusion (pyroxenite)	1,270 ±4	U-Pb (B)	L1

*: B = baddeleyite, Z = zircon, WR = whole-rock

D1: Davis and Paces, 1990.
D2: Davis and Sutcliffe, 1985.
H1: Heamon and Machado, 1987.
H2: Heamon et al., 1987.
K1: Krogh et al., 1987.
V2: Van Schmus et al., 1982.
L1: LeCheminant and Heaman, in press.
L2: Lumbers et al., 1988.
P1: Palmer and Davis, 1987.
S1: Silver and Green, 1972.
V1: Van Schmus, 1975.

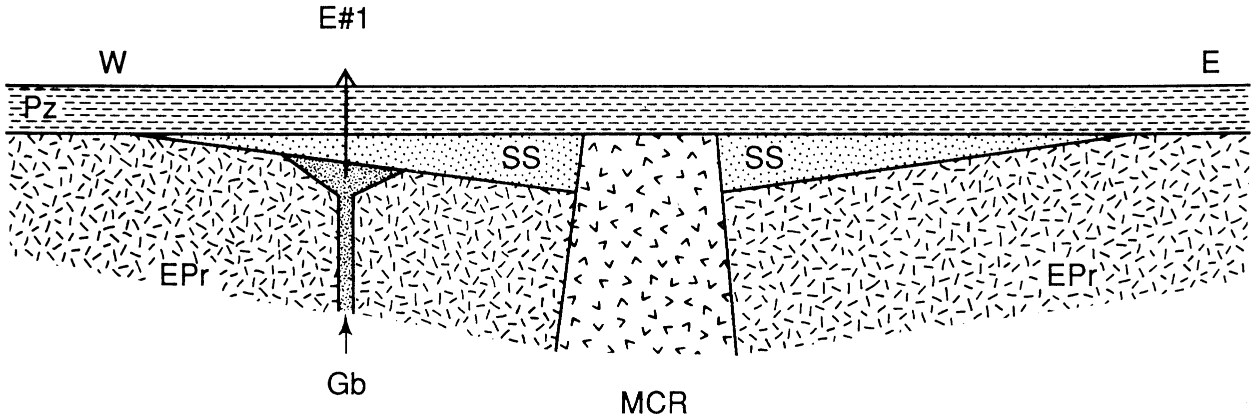

Figure 3. Schematic E-W geologic cross-section across the MCR showing the Precambrian geology inferred for the site of the Amoco M.G. Eischeid #1 well (E#1) on the basis of isotopic data presented in this paper. EPr = Early Proterozoic basement; Gb = gabbro from the Eischeid #1 well; MCR = rocks of the Midcontinent Rift; SS = sandstone and other sedimentary rocks of the flanking rift basins; Pz = Paleozoic and younger cover rocks (not to scale). The essential point is that the gabbro sampled at the bottom of the well is a late intrusive body in the pre-Keweenawan basement and not an early flood basalt of the MCR.

the age and duration of Keweenawan igneous activity (Van Schmus et al., 1982). The age of 1,281 ±50 Ma for IACA-001 is not consistent with interpreting this gabbro as a Keweenawan flood basalt, even allowing for the possibility that rifting was not synchronous throughout the length of the MCR.

The age and petrologic character of IACA-001 are also not consistent with interpreting it either as part of the Early Proterozoic basement or as related to the 1,340 to 1,470 Ma anorogenic plutonism of the midcontinent region. Accordingly, we reviewed ages for Middle Proterozoic igneous units in the Canadian Shield and the buried Proterozoic basement of the United States, focussing on the interval 1,200 to 1,300 Ma. This search was aided by the recent publication of several new, precise U-Pb ages (Table 5).

It is apparent from Table 5 that there was significant igneous activity in North America about 1,250 to 1,280 Ma ago. The most extensive was emplacement of the Muskox layered mafic intrusion and Mackenzie diabase dike swarm 1,267 to 1,270 Ma ago. The other major suite is represented by volcanic rocks and plutons of the Central Metasedimentary Belt in the Grenville Province, which yield precise U-Pb ages of 1,280 to 1,290 Ma with other, less precise results falling in the interval 1,250 to 1,290 Ma. The olivine diabase dikes of the Sudbury area appear to be distinctly younger, with an age of about 1,238 ± 4 Ma.

The age represented by IACA-001 corresponds to very significant igneous activity in North America, although its importance is only now being realized (e.g., LeCheminant and Heaman, 1989). We conclude that the gabbro underlying the Proterozoic sedimentary units in the Eischeid #1 well is most likely a dike, sill, or pluton that was intruded into the older basement (Fig. 3) during the 1250 to 1290 Ma igneous activity. This suggests, in turn, that the thermal and tectonic regime which produced the Muskox intrusion, Mackenzie dike swarm, and volcanic and plutonic rocks of the Central Metasedimentary Belt in the Grenville Province was a continent-wide phenomenon. Future U-Pb dating of zircon and baddeleyite from mafic dikes in Canada and the United States may turn up more representatives of this event.

The gabbro in Carroll Co. must have been exposed by erosion prior to deposition of sediments in the flanking basin of the MCR (Fig. 3). The age of this gabbro therefore has no bearing on the age of magmatism in the Iowa section of the MCR, but it does indicate that the well was drilled completely through the flanking sedimentary basin.

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Landon of Amoco, Inc. for her support of our interest in analysing this sample and deriving as much scientific benefit from this project as was consistent with proprietary concerns. This work was performed as part of Project Upper Crust, whose funding is provided by the National Science Foundation through subcontracts DSC 2-86 and DSC 1-87 from DOSECC, Inc. (EAR 84-16924) and NSF Grant EAR 88-16260 to the University of Kansas Center for Research.

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PETROLOGY OF KEWEENAWAN SEDIMENTARY ROCKS IN THE M.G. EISCHEID #1 DRILLHOLE

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INTRODUCTION

Of the approximately 14,100 feet of Keweenawan sedimentary rocks penetrated in the M.G. Eischeid #1 (MGE) drillhole, a little less than 50 feet of core was recovered. A detailed description of the core is appended to this report, and is briefly discussed below. In addition, Barnes (this volume) discusses the petrology of arenaceous units recovered from cored intervals. The remaining 99.6 % of the Keweenawan sedimentary succession is known only from mudlogs and borehole geophysical logs reposited at the Iowa Department of Natural Resources Geological Survey Bureau (GSB), and drill cuttings (collected at 10 foot intervals) curated at the GSB's rock repository at Oakdale, Iowa.

In order to provide a reasonably complete assessment of the lithic character of the Keweenawan sedimentary rocks in the MGE drillhole, we undertook a reconnaissance petrographic investigation of the drill cuttings. All samples were processed by routine procedures (washed, oven-dried, loaded into standard envelopes and boxes for cataloguing and storage). For our preliminary petrographic investigations, samples were recovered at 500-foot intervals, with selected intervening intervals collected to evaluate uncertain lithologies described in the mudlog. Each sample set of loose cuttings was mounted in a cylindrical polystyrene plug with vaccuum-injected blue-dyed epoxide resin, cut into standard petrographic thin sections, stained for potassium and plagioclase feldspars, and cover slipped. The thin sections were point-counted to determine volume percentages of single-mineral grains and rock chips of various types. Thin sections containing significant volumes of sandstone chips were point-counted a second time in order to quantify the detrital framework modes, evaluate porosity distribution, and describe diagenetic features of the arenaceous rocks.

DESCRIPTION AND DISCUSSION OF THE CORED INTERVALS

Five short intervals of rock were cored in the Eischeid well. The four upper cored intervals are sedimentary rock; the fifth core was taken in medium-crystalline gabbro near the bottom of the hole. Core recovery varied from a low of 36% in core #1 to a high of 98% in core #3. This discussion addresses cores one through four, whereas the igneous rock of core #5 is discussed by Van Schmus and others (this volume).

Sawed portions of cores #1 through #4 were described for rock type, sedimentary fabric and structures, and tectonic structures. Thin sections of sandstone cut from the cores were analyzed and described by Barnes (this volume). Core diameter is four inches and actual core available varied from one-third to two-thirds of a full diameter core. A legend, graphic logs and photographs of rocks slabs from cores #1, #2, and #3 are illustrated in Figures 1, 2, 3, 4, 5, 6, and 7, and a written description of cores #1 through #4 is included in Appendix A.

Core #1 Description

Core #1 was taken from the 8834 to 8844 foot-depth interval. A recovery of 36 percent (8834-8837.6 feet) was the lowest of the five cored intervals. The core consists of red, fine- to coarse-grained sandstone. Red mudstone clasts are common. Sedimentary structures include parallel-horizontal laminae, low-angle cross-strata, and massive unstratified to poorly stratified layers.

The sequence as illustrated in Figure 2 contains two facies: 1) well stratified, fine- to medium-grained, red sandstone with parallel-horizontal laminae, low-angle cross-strata ($< 10°$), and very coarse sand-size, red mudstone clasts; and 2) massive, nonstratified, fine- to coarse-grained, red sandstone with red mudstone clasts as large as granule in size.

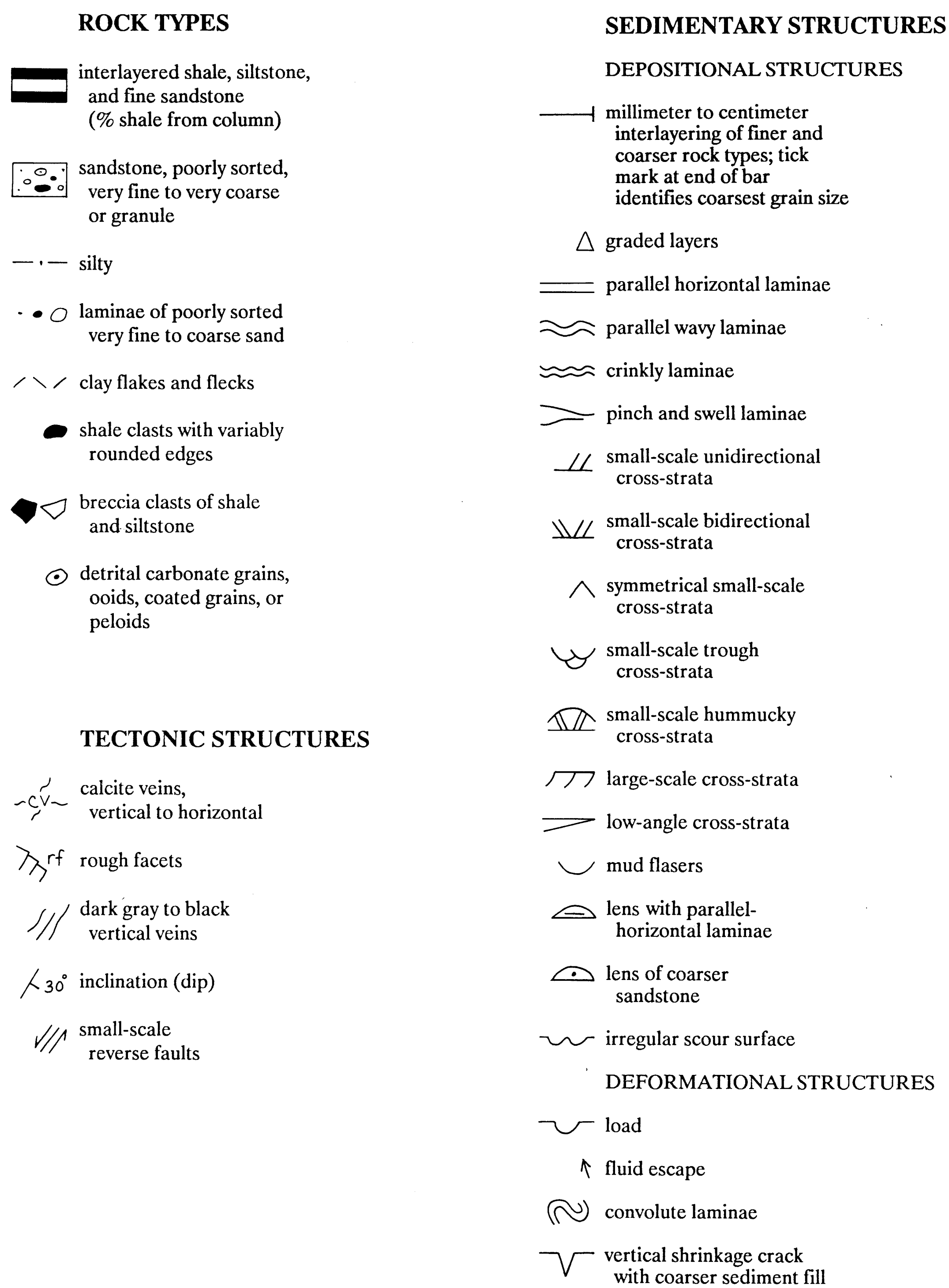

Figure 1. Graphic core log legend for Eischeid test cores (Figs. 2 and 4). See Appendix A for accompanying written description.

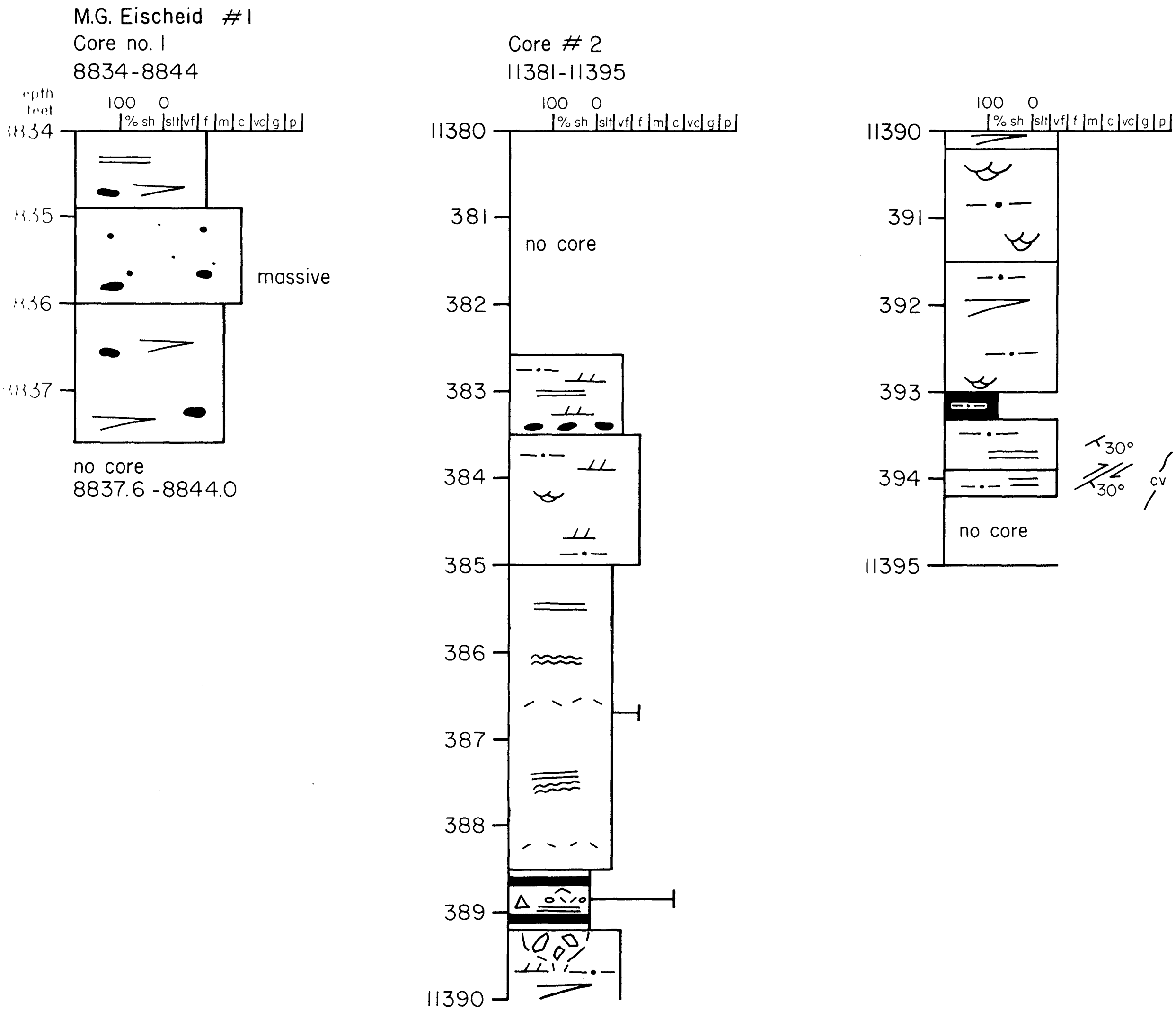

Figure 2. Graphic core log of cores #1 and #2, Eischeid test. Written description in Appendix A.

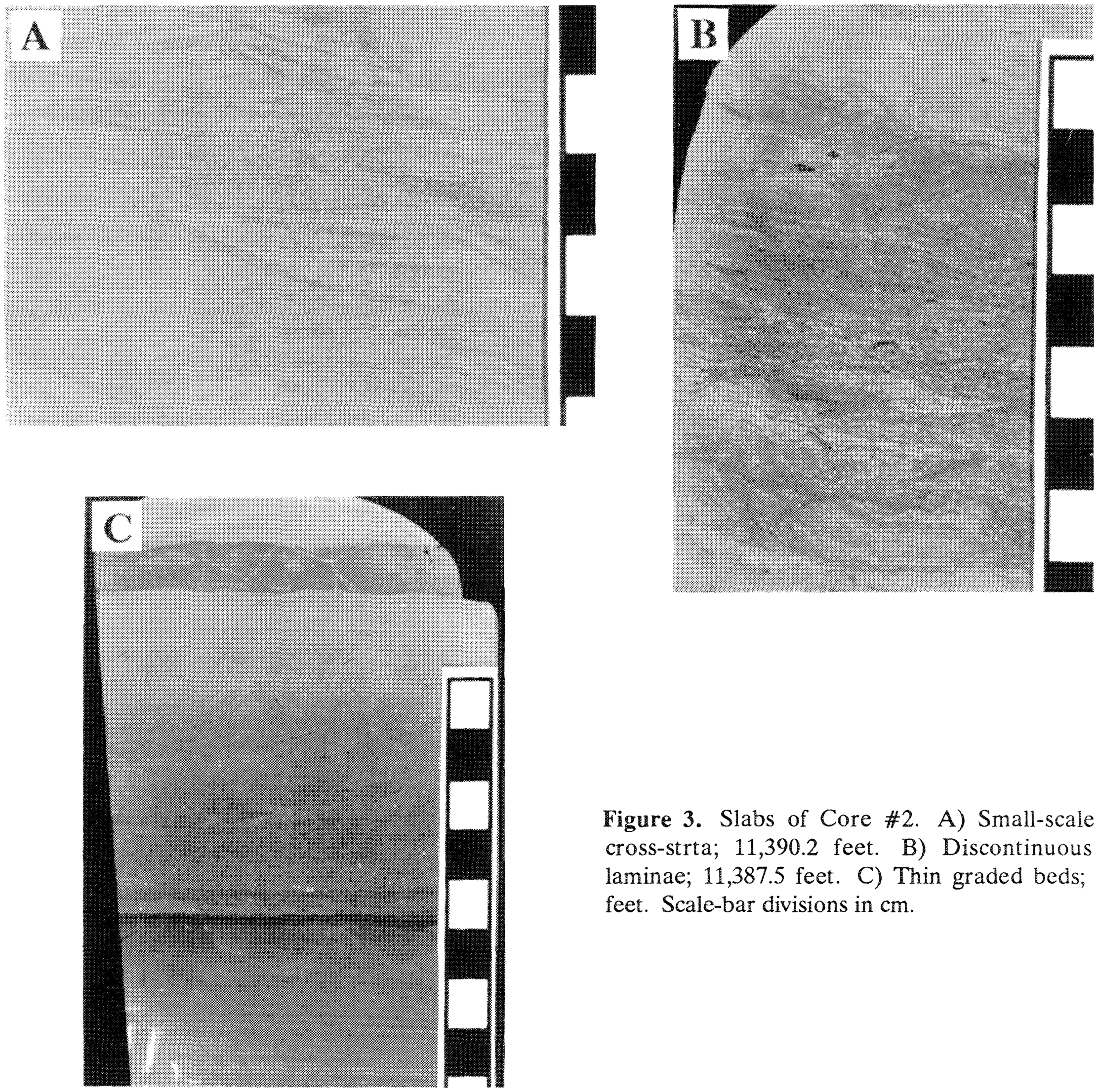

Figure 3. Slabs of Core #2. A) Small-scale troug cross-strta; 11,390.2 feet. B) Discontinuous crinkl laminae; 11,387.5 feet. C) Thin graded beds; 11,389. feet. Scale-bar divisions in cm.

Core #1 Interpretation

Core #1 comes from the middle portion of Unit E-2; it is similar to lower Bayfield Group strata of the Lake Superior region (Witzke, this volume). Both lower Bayfield Group strata and upper Oronto Group strata (Freda Fm.) of the Lake Superior area have been generally interpreted as being the deposits of fluvially dominated processes in the Keweenawan rift sequence (Daniels, 1982; Morey and Ojakangas, 1982). The two red-bed facies present in core #1 can also be readily interpreted to have formed in a fluvial environment.

Two slightly different interpretations of the core seem appropriate. One is that each unit described represents an individual sedimentation event an that three events are recorded. The othe interpretation is that two events are recorded an that the massive, poorly sorted sandstone (middl unit) represents the basal half of a cycle whic ended by deposition of planar laminated sand The poorly sorted sands could represent depositio by traction and rapid suspension fallout from highl sediment-charged waters. The horizontal an low-angle planar-bedded sands may represen deposition under similar upper flow regim conditions, but with lower suspended sedimen concentrations. Low-angle planar-bedded sand cap thick channel sands in the Devonian, Batter Point Sandstone (Cant and Walker, 1976) and ar interpreted as vertical accretion deposits, possibly deposited from powerful floodwaters. Although large cross-stratified bed configurations are absent in core #1, they may exist above or below the core, or they may be non-existant. Daniel's (1982) discussion of sedimentary structures in the Freda Formation emphasizes the rare occurrence of well-defined channel deposits in the Freda and suggests that much of the deposition occurred under shallow water conditions on a braided fluvial plain where water courses were wide and shallow. Sporadic flow events over such terrain could easily produce the core #1 sequence either within or adjacent to a shallow channel.

Core #2 Description

Core #2 was taken from the 11,381 to 11,395-foot depth interval. Eighty-three percent (11.6 feet) of the 14 feet cored was recovered. The core consists of two facies: 1) small- to large-scale cross-stratified very fine- to fine-grained sandstone (7.1 feet) and 2) horizontally stratified very fine-grained sandstone and minor mudstone (4.5 feet). Small-scale thrust faults are present in the basal foot of the core.

The sandstone of the cross-stratified facies is red, very fine- to fine-grained, silty, hard, dense, well-cemented, calcareous, and variably micaceous. The dominant forms of stratification are small-scale unidirectional tabular and trough cross-stratification (Fig. 3A). Larger-scale cross-strata with reactivation surfaces occur at 11,392 feet. Some small-scale tabular cross-strata sets are interstratified with small-scale trough sets. Small, thin and flat red shale or mudstone clasts occur as a lag at the base of one small-scale co-set at 11,383.5 feet. Other intervals such as 11,389.2 to 11,390.2 feet grade from low-angle cross-strata at the base upward to small-scale tabular cross-strata which are topped by brecciated parallel-horizontal laminae.

The horizontally stratified, fine-grained sandstone and mudstone facies is dominated by a 3.5-foot thick unit of horizontal to inclined, parallel-laminated sandstone and mudstone (11,385 to 11,388.5 feet, Fig. 3B). Laminae are generally 1 mm or less in thickness, discontinuous, and crinkly, with maximum amplitudes of 3 to 4 mm. Inclined crinkly laminae intervals dip at angles of 10 to 20 degrees, and contain small (1.0 - 3.0 mm), thin, red mudstone flakes.

Another distinctive sequence within the horizontally stratified facies occurs between 11,388.5 and 11,389.2 feet (Fig. 3C). This interval consists of three thin (8 cm) graded-bed sequences. The basal portions are either horizontal or low-angle laminated sandstone which grade up to a massive poorly sorted, fine- to coarse-grained central portion containing randomly oriented red mudstone flakes. The upper 2 cm consists of horizontally laminated, silty, very fine sandstone with small symmetrical ripples developed in the upper 2 to 3 cm. The top of each graded bed sequence is capped by a red mudstone layer 2 mm to 1 cm thick.

Core #2 Interpretation

Core #2 was taken from the middle portion of Unit D-4. Units D-3 and D-4 represent the fine-grained upper portion of the very thick fining-upward red bed sequence of Unit D (10,510 to 14,980 feet). The sedimentary structures of the core indicates that the interval was deposited in a fluvial environment. The large-scale cross-stratification in the lower portion of the core represents unidirectional bed forms developed during "steady" moderate flow conditions. These strata along with the closely associated small-scale trough cross-strata may represent shallow channel fillings. The breccia zone at the top may represent a reworked subaerial exposure surface which was covered by four feet (11,385 to 11,389.2 feet) of horizontally interlaminated sandstone and mudstone floodplain overbank deposits. Well defined, thin, graded bed sequences in the basal 0.7 feet of this facies represent small "flood" event deposits under rapidly waning flow conditions. The more crinkly and discontinuously interlaminated, fine-grained sandstone and mudstone containing abundant red mudstone flakes probably represent the record of a stacking of many overbank "flood" events and subaerial exposure surfaces outside of a main or subordinate fluvial channel area. The upper three feet, which is dominated by small-scale, unidirectional cross-stratification containing scattered mudstone clasts, represents renewed shallow channel deposition under moderate flow conditions.

Core #3 Description

Core #3 was taken from the 15,096 to 15,120 foot interval. A recovery of 98% was the highest of the five cored intervals. The core consists primarily of millimeter to decimeter thick, layers of medium to dark grey shale and lighter grey siltstone to fine-grained sandstone with a few thicker interbeds of coarse- to very coarse-grained sandstone. Sedimentary structures are abundant, and tectonic structures are also moderately common in the core (Fig. 4 and Appendix A).

Two primary facies are present in the core: 1) thinly interlayered shale and siltstone to fine-grained sandstone, and 2) thicker beds of poorly sorted fine- to very coarse-grained sandstone. All facies are well indurated, and calcite is the dominant cement except in the clay shales which are noncalcareous.

Interlayered Shale and Siltstone to Fine Sandstone Facies

About 90 percent (21.2 feet) of core #3 consists of this facies. Shale comprises approximately 26 percent (5.6 feet) of this facies and 24 percent of the total core. Shale color varies from medium grey to black. Shale intervals are generally laminated, variably silty, pyritic, micaceous, and calcareous; in addition they are dense and well indurated. Palacas and others (this volume) notes that shale samples in this cored interval have total organic carbon values ranging from 0.4 to 1.6 weight percent. Siltstone to fine-grained sandstones with minor coarse-grained sandstone laminae, comprise approximately 73 percent (15.4 feet) of the facies and 66 percent of the total core. Siltstone to fine-grained sandstone is light grey, calcareous, dense, hard, variably pyritic, variably micaceous, and well stratified.

Small-scale sedimentary structures and well developed stratification are abundant in core #3. Normally graded layers with well developed internal stratification are quite common in the sequence (Fig. 5A). Graded layers range in thickness from 1 mm to 1.5 cm, and internally display parallel horizontal to wavy laminae as they grade from siltstone at the base to shale at the top. Alternating millimeter to submillimeter thick laminae of shale and siltstone are also common. The basal laminae of graded layers commonly exhibit overstepping and onlapping geometries over the underlying layer. Erosively scoured basal contacts which truncate several millimeters of underlying laminae are also common.

Siltstone to fine-grained sandstone dominated layers exhibit a wider variety of depositional structures. Parallel horizontal laminae are common, and these typically are partially truncated by sets of small-scale troughs with pinch and swell and draping laminae (Fig. 5B). Horizontally stratified siltstone to fine-grained sandstone intervals may also contain centimeter to subcentimeter thick layers or lenses of poorly sorted, silty to coarse-grained sandstone (Fig. 5C). Variable percentages of medium to very coarse sand grains occur in the finer-grained sandstone associated with these poorly sorted layers.

Cross-stratification within the siltstone to fine sandstone layers is common and well developed. Layers and lenses exhibit small-scale unidirectional, bidirectional, symmetrical, and trough cross-strata (Figs. 5D, 5E). Small-scale amalgamated hummocky cross-strata (microhummocky stratification of Dott and Bourgeois, 1982) is also present in one interval (Fig. 5F).

Sedimentary deformational structures in the interlayered shale and siltstone to fine sandstone facies are limited in occurrence, but are significant for depositional interpretations. Breccia intervals are present at 15,096 and 15,114 feet (Fig. 6A). These thin intervals are composed of angular clasts of shale and siltstone within a generally silty matrix. Small load and flame structures are present beneath coarse-grained sandstone beds (Fig. 6B) and associated with them are disrupted laminae cut by internal sediment fills from possible fluid escape processes. One occurrence of convolute laminae is associated with the small-scale hummocky cross-strata interval at 15,113 feet (Fig. 5F). Compaction deformed layers are prominent where lensatic fine sandstones interlayer with shale (Fig. 5A) and where shales deformed around early-cemented shaley siltstone nodules and early pre-compaction intrastratal pyrite accumulations (Fig. 6C). Compaction has also deformed early vertical calcite veinlets by telescopic breakage (Fig. 6C).

Shrinkage cracks are perhaps the most common sedimentary deformational structure. These occur at a half-dozen positions in the core (Fig. 4 and Fig. 6D). The cracks are generally v-shaped and vertically oriented. Maximum top width is 7 mm and maximum length is 6 cm; some sinuosity may be developed along their length. The cracks cross cut horizontally-laminated shale and siltstone and are filled with poorly sorted siltstone to coarse-grained sandstone. In some occurrences the poorly sorted crack fill is connected to an overlying poorly sorted

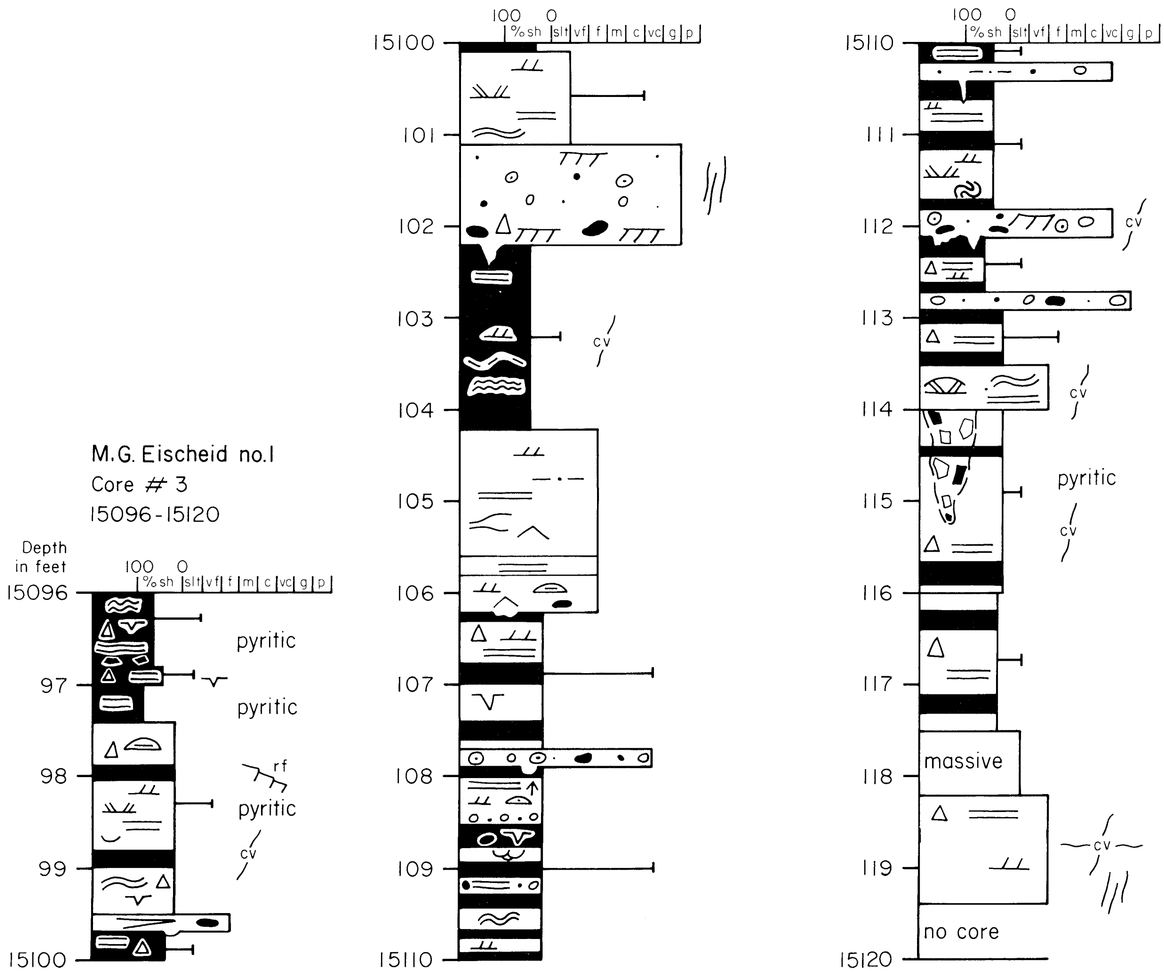

Figure 4. Graphic log of core #3, Eischeid test. Written description in Appendix A.

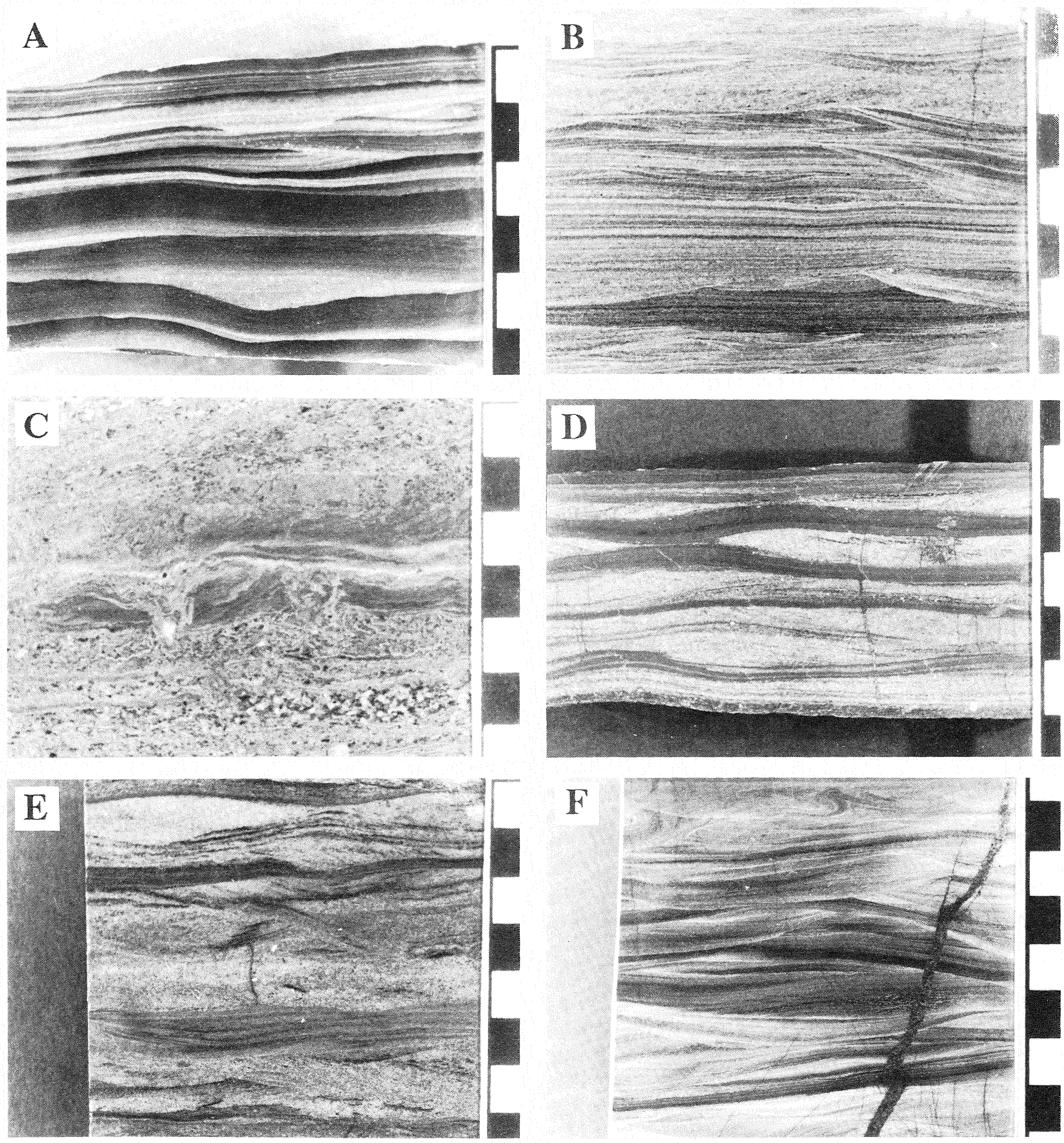

Figure 5. Slabs of Core #3. A) Thin graded layers and truncation surfaces; 15,096.2 feet. B) Parallel horizontal laminae, truncation surfaces and small-scale troughs with pinch and swell laminae; 15,104.4 feet. C) Coarse sand laminae, disrupted shale/siltstone laminae, and shale clasts; 15,108.7 feet. D) Layers and lenses of parallel horizontal to uni- and bi-directional small-scale cross-strata; 15,098.1 feet. E) Bi-directional and symmetrical small-scale cross-strata; 15,106 feet. F) Small-scale amalgamated hummocky cross-strata, convolute laminae at top; 15,113.5 feet. Scale-bar divisions in cm.

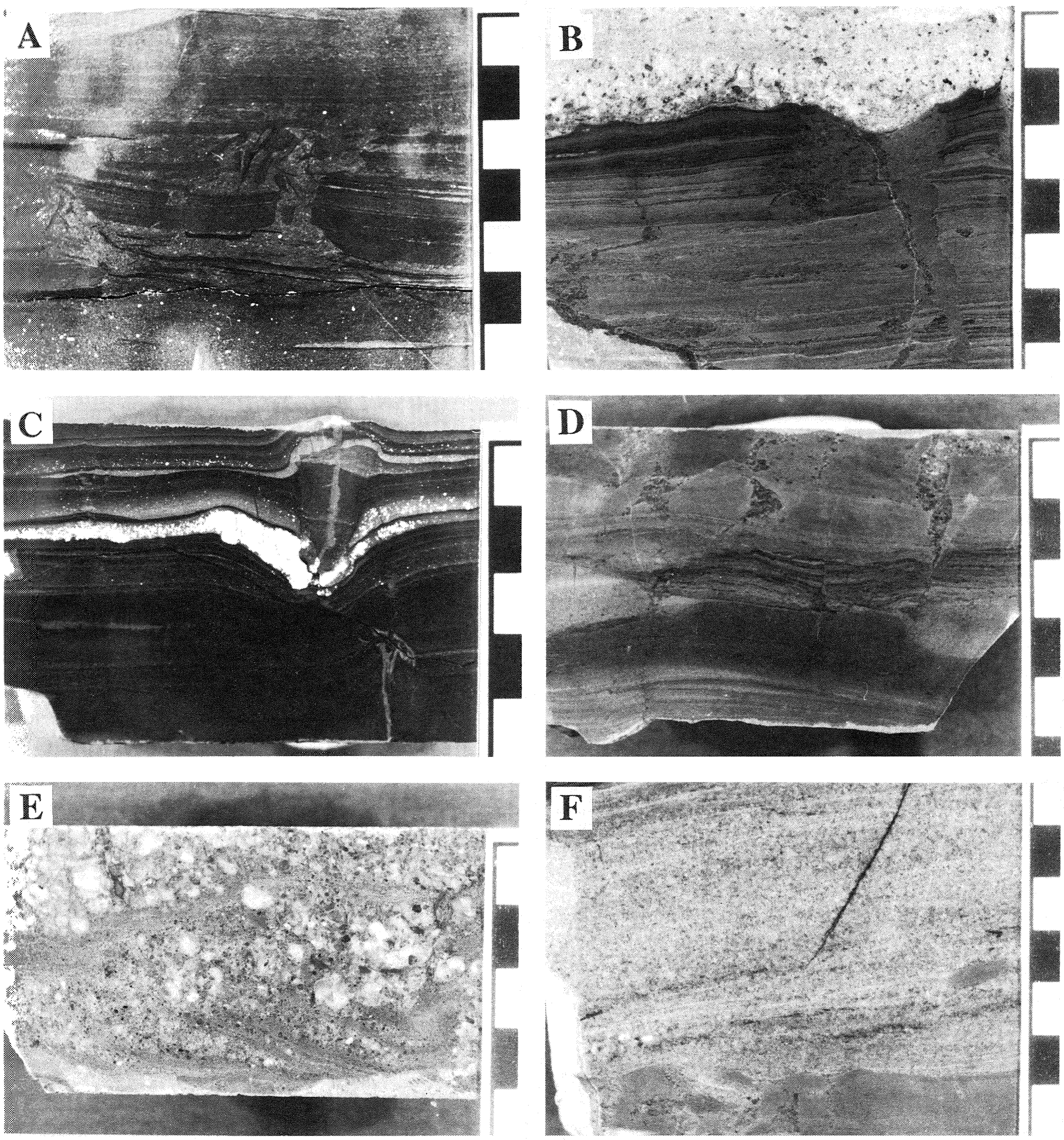

Figure 6. Slabs of Core #3. A) Thin brecciated interval in siltstone and shale; 15,096.7 feet. B) Small flame structures at shale/sandstone contact and possible vertical fluid escape zones of disruption; 15,108.0 feet. C) Compaction deformation of shale layers, early diagenetic pyrite, early vertical calcite veinlets and early cemented siltstone nodule; 15,097.0 feet. D) Vertically oriented shrinkage cracks with poorly sorted coarse sand filling; 15102.1 feet. E) Poorly sorted, very coarse- to granule-grained sandstone; 15,101.0 feet. F) Shale intraclasts and brecciated shale layer beneath sandstone; 15,111.9 feet. Scale-bar divisions in cm.

very fine- to coarse-grained sandstone.

Poorly Sorted Fine- to Very Coarse-Grained Sandstone Facies

About 10 percent (2.4 feet) of core #3 consists of poorly sorted beds of fine- to very coarse-grained sandstone (Fig. 6E). Most of the beds are 5 to 6 cm thick, but one at 15,101 feet is 30 cm thick. Barnes (this volume) elaborated on the framework mineralogy and cement content of these coarser-grained sandstone layers. He characterized them as extensively calcite-cemented subarkoses. The sandstone beds contain some granule-size grains of quartz, and pebble-size shale intraclasts with variably rounded edges are present near the base in almost every interval. Barnes (this volume) noted the presence of intrabasinal detrital carbonate grains in several intervals. These grains include ooids, coated grains and coated aggregate grains, and peloids.

Sandstone beds overlie laminated shale and fine sandstone intervals with sharp contacts. Basal contacts may display load deformation, irregular erosive scours, shrinkage crack infillings, or broken and brecciated shale/siltstone layers (Fig. 6F). Cross-stratification is poorly developed in most intervals although some cross-strata are recognizable. Gradation from coarse-grained at the base to fine-grained at the top is apparent in the thickest sandstone at 15,101 feet.

Tectonic Structures

The three types of tectonic structures visible in core #3 (Figs. 4 and 7) are: 1) slickensides on microfault surfaces with rough facets, 2) calcite veinlets, and 3) vertical sets of dark grey to black vertical veins of unknown composition. Ludvigson and Spry (this volume) discuss the geometry, composition, and origin of the rough facets and the calcite veinlets. The vertical sets of dark grey to black veins have not yet been subjected to further study except to note their occurrence. Dark vein width ranges from <1 mm to 4 mm, and vertically they extend 1 to 8 cms (Figs. 7A and 7B). The boundaries are sharp to diffuse, and the veins are may be linear or sinusoidal in geometry. Further investigation of these veins should be done, particularly with respect to possible organic content.

Core #3 Interpretation

Core #3 comes from the upper portion of Ur C-2, an interval 700 feet thick and composed similar rock types as those in the core (Witzke, th volume). Within the overall "Red Clasti sedimentary sequence, Unit C occupies a equivalent stratigraphic position to the Nonesuc Formation of the Lake Superior area. This is not say that Unit C is correlative with the Nonesuc Formation, but the similarity in stratigraph position of the units is useful, since much more known about the vertical and lateral extent ar composition of the Nonesuch Formation than Unit C.

Although a number of deposition environments (estuarine, deltaic, marine, ar lacustrine) have been proposed by various worke for the Nonesuch, the present general concensus that the formation was deposited in a lacustrir dominated regime which experienced varyir degrees of marginal fluvial-deltaic sedimentatic (summarized in Daniels, 1982). This interpretatic is based on the formation's "ribbon-like rift-confined, linear distribution, and i sedimentary facies and structures. The most rece sedimentological examination of the Nonesuc Formation (Milavec, 1986) concurs with th lacustrine interpretation and subdivides th formation into a number of discret lacustrine-related sedimentary facies.

Gaps in the available data set for Unit C lim our understanding of the unit. Although seismi data has been collected across a portion of th Defiance Basin southwest of the MGE drillhole, w do not have access to it and are not able t comment on the geographic distribution of the un in the basin. However, one can reasonably assun that the unit's original distribution was confined t the rift area in general, but not necessarily solely t the Defiance Basin. Further drilling might reve its presence as an erosional remnant upon th uplifted Iowa Horst and/or its presence in basins i the eastern portion of the Midcontinent Ri System.

The lack of geographic distributional data fc Unit C necessitates increased reliance upon coi and sample data for interpretation of the unit depositional environment. Our study of th available samples, in particular, core #3, sugges that the upper portion of Unit C-2 was deposited i a lake or standing body of water which experience

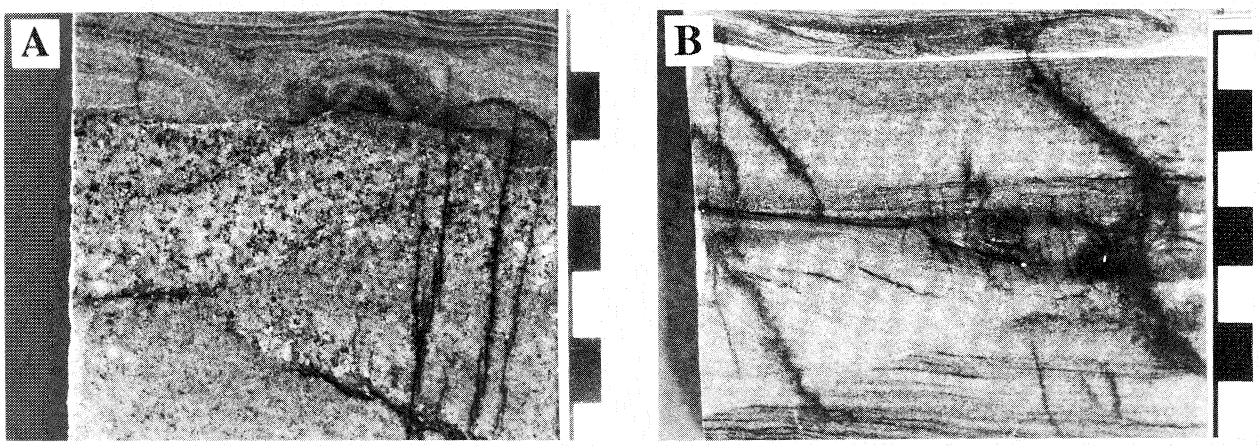

Figure 7. Slabs of Core #3. A) Sets of vertical dark grey to black veins; 15,101.0 feet. B) Diffuse, sinusoidal dark grey veins in sandstones; 15,119.0 feet.

fluctuating water levels and intermittent coarse detrital influx.

A number of the primary sedimentary structures provide direct evidence that a substantial portion of the sedimentation sequence of core #3 was deposited subaqueously in standing water. The thin graded layers which are common throughout the core were deposited by fallout from suspension in a calm water body. However several pre-graded layer scour surfaces document some erosive bottom flows. Preservation of organic carbon, and probable bacterially-reduced sulfur in intrastratal pyrite within the black shales of the graded layers (Palacas et al., this volume; Pollastro and Finn, this volume) records intermittent oxygen-depleted bottom sediment conditions.

The common occurrence of several types of small-scale cross-stratification also support the interpretation of a standing water body. Much of the small-scale cross-stratification is dominated by bidirectional and symmetrical geometries. Pinch-and-swell laminae in lenses and small-scale troughs are common, and minor development of small-scale hummocky cross-strata is noted. These bed and cross-stratal configurations are typically formed by wave-induced oscillatory flows (Newton, 1968; Raaf, et al., 1977; Harms, et al., 1982; Dott and Bourgeois, 1982). Although small-scale unidirectional cross-strata sets are present, they are subordinate in frequency of occurrence to the wave-formed structures, and commonly are interlayered with wave-formed strata. This suggests that these unidirectional sets were formed under asymmetric oscillatory flow or combined flow conditions in a wave-dominated regime.

Water depth during deposition of the core #3 strata can be characterized as shallow due to the presence of intermittent subaerial exposure indicators. The sporadic occurrence of vertical v-shaped shrinkage cracks, filled with coarser sandstone, in interlayered shale and siltstone intervals indicates fluctuating water levels and intermittent subaerial exposure resulting in partial dessication. Brecciated intervals also may have formed during similar periods of exposure. A number of the poorly sorted, fine- to coarse-grained sandstone layers also overlie shrinkage-cracked and slightly brecciated finer sediments, and included shale intraclasts in their basal portions. The shrinkage-cracked intervals probably formed along the margin of the lake and interstratified coarse-grained sandstone layers must have been transported onto the exposed lake margin and into the lake by energetic flow events having minimum flow velocities of approximately 50 cm/sec (Harms, et al., 1982). Minor development of irregular basal scours, small load, flame, and liquification structures in underlying mudstone layers; poorly developed cross-stratification; and crude graded stratification in the sandstone beds (Figs. 4 and 6) support the contention that deposition was rapid. Detrital grains of intrabasinal carbonate (ooids, coated grains, and peloids) within the coarser sandstone layers indicate that proximal sandstone source areas included localized carbonate production sites.

Rare oncolites have been reported from the marginal lacustrine mudstone facies of the Nonesuch Formation in cores from Wisconsin and Michigan (Milavec, 1986); Milavec has suggested that they may have been derived from Copper Harbor Conglomerate stromatolite/carbonate facies similar to those described by Elmore (1983). The carbonate grains found in Unit C-2, core #3 sandstones may have been sourced from a similar environmental setting of ponded, abandoned fluvial/fan channels that were localized sites of carbonate production.

In summary, our study indicates that the upper portion of Unit C-2, as represented in core #3, was deposited in a marginal siliciclastic dominated lacustrine environment. Both subaqueous and subaerial depositional processes are recorded, indicating that the lake level fluctuated intermittently. The shallow lake margin bottom conditions varied from placid to turbulent, and wave-induced turbulent-bottom conditions were common. Intermitent development of anoxic conditions in bottom sediments resulted in preservation of organic matter and the formation of authigenic sedimentary sulfides. Periodic energetic flow events carried coarse, poorly-sorted sand onto the lake margin and into the lake proper. These flows traversed an adjacent fluvial plain which contained localized ponded subenvironments experiencing near contemporaneous coated-grain carbonate production. Minor amounts of these intrabasinal carbonate grains were incorporated into the high energy flows and deposited with the coarse poorly-sorted sands.

Core #4 Description

Core #4 was taken from the 16,043 to 16,058 foot interval. Sixty percent (9.0 feet) of the 15 feet cored was recovered. The entire cored interval has a high angle tectonic dip ranging from a low of 65 degrees to vertical to slightly overturned. Much of the core is broken into golfball- and baseball-sized chunks. It appears that the coring substantially followed near vertical bedding and that the total thickness of the stratigraphic sequence is much less than the recovered footage of nine feet (Appendix A). Representative photos of lithic types from core #4 are included in Ludvigson and Spry (this volume).

The core is composed of 60 percent siltstone and 40 percent shale. Siltstone is light grey, micaceous, dense, well cemented, and calcareous. Shale is medium grey to black, dense, hard, variably silty, and laminated. The entire cored interval is well laminated, interlayered siltstone and shale. Graded layers are present but are not common. Layers range in thickness from 1 mm to 2 cm. A few thin siltstone lenses are present; the lenses exhibit small-scale unidirectional cross-strata. The darkest colored black shales appear to be organic in hand-specimen. Palacas and others (this volume) report on the organic geochemistry of black shales from this core.

Calcite veinlets and slickensided small scale fault surfaces with calcitic rough facets are common. As discussed by Ludvigson and Spry (this volume) these tectonic structures were formed primarily by reverse faulting.

Core #4 Interpretation

Core #4 was taken from the middle portion of Unit C-1. As previously discussed for core #3 and by Witzke (this volume), Unit C of the Eischeid sequence is in a similar stratigraphic position to that of the Nonesuch Formation of the Lake Superior region. Because of the tectonized nature of core #4 (vertical to overturned beds; multiple reverse faults) it is apparent that the true stratigraphic thickness of Unit C cannot be determined from the Eischeid drillhole.

The color, composition, and limited number of primary sedimentary structures in core #4 suggest a depositional environment similar to the lacustrine environment interpreted for the core #3 sequence, with the difference that all of the core #4 sequence was probably deposited in deeper water. The presence of even lamination, graded layers, and sporadic cross-stratified lenses suggests deposition by fallout from suspension under intermittent, weak, bottom flows. The absence of wave-formed structures, coarse-grained sand detritus, and subaerial dessication fabrics suggests deposition was basinward of the lake margin and was not as strongly influenced by lake-level fluctuations and influx of coarse fluvial sediment as the core #3 sequence. The co-occurrence of laminated organic microcrystalline limestones in cored Unit C-1 and the peak drill-cuttings abundance of the limestones in Unit C-1 (see comments in next section) also supports the contention that Unit C-1 was primarily deposited in a deeper and calmer lake environment.

EVALUATION OF DRILL CUTTINGS

Determination of Percent Rock Type by Point-Counting

Each grain-mount thin section was point-counted to determine and quantify the percentage of various lithic types present in the sampled intervals. Approximately 130 to 250 points per sample were classified according to lithic type. Sandstone, siltstone, mudstone, and shale cuttings were most frequently counted, but a number of samples contained significant amounts of single-mineral (loose) grains, primarily quartz and feldspar. Carbonate spar and cataclastic sandstone chips are additional constituents which consistently occur in low percentages. Trace amounts of several other loose grain constituents were also counted. Percentage data derived from percent rock-type point-counting are presented in Table 1 and graphically summarized in Figure 8.

Figure 8 illustrates the large-scale vertical variations in drill-cuttings composition. The highest level examined was from the uppermost pre-Mt. Simon interval at 2800 feet; it contains glauconitic carbonate (40%) which clearly represents contamination of the sample from the overlying Eau Claire-Bonneterre interval (McKay, this volume). Samples from 3000 and 3500 feet contain 80 percent loose grains, primarily quartz and feldspar and lesser amounts of other grain types (Table 1). Intervals, such as this one, which are dominated by loose grains probably indicate sparse or weak cementation, a condition that allowed the drill bit to break off individual detrital grains from sandstones. This interval is termed Unit H (Witzke, this volume) and is of uncertain age.

Loose grain content decreases and cemented-chip content increases substantially in samples from 3790 to 4000 feet, where greater than 50 percent of the samples are cemented chips. The transition in drill-cuttings content across the 3500 to 3790-foot sample intervals, along with other data presented by Witzke (this volume) and McKay (this volume), suggests that Unit H differs from underlying Keweenawan units in terms of compositional and textural maturity, and cementation history.

The 4000 to 10,500-foot interval is dominated by well-cemented chips of very fine- to medium-grained sandstone with subordinate amounts of medium- to coarse-grained sandstone, siltstone, mudstone, shale, and cataclastic sandstone. This interval corresponds to units E, F, and G of the mudlog, as interpreted by Witzke (this volume). Moderate increases in siltstone, mudstone, and shale content at 5000 to 5500, 6500 to 7100, 10,000 to 10,500-foot depths correspond to mudlog subdivisions of units F-3, F-1 and E-1. Chips of cataclastic sandstone and siltstone, displaying a microbrecciated texture, are present in all but one sampled interval in this sequence and they attain a maximum concentration in the 7,000 to 10,000 foot interval (Figs. 9 and 10; Table 1).

A major siltstone, mudstone, and shale package spanning the interval from 10,500 to 12,500 feet corresponds to Witzke's units D-3 and D-4. Associated sandstone is very fine- to fine-grained and cataclastic sandstone content decreases to near zero.

The interval from 12,500 to 15,000 feet (units D-1 and D-2) is a heterogeneous, siliciclastic sequence which contains a large quantity of weakly calcite-cemented sandstone as indicated by the large percentage of loose quartz and feldspar grains (Fig. 8). Sorting and texture of sandstone varies substantially and there is a marked increase in average grain size and a decrease in sorting from units D-3 and D-4 to units D-1 and D-2. Lithic and mineralogic point-count data in this interval (Tables 1 and 2; Figs. 8 and 10) documents slightly greater clay/oxide cements and significantly greater quantities of calcite cements and carbonate spar cuttings chips. This suggests that the loose grains of this interval are probably derived from variably calcite-cemented sandstones.

The interval from 15,000 to 16,500 feet corresponding to Unit C contains abundant calcareous siltstone and shale with lesser quantities of calcareous sandstone. Shale is commonly silty, and shale color ranges from medium grey-green to dark grey to black. Some core in this unit (core #3, 15,096 - 15,120 feet) contains thinly interbedded calcareous sandstone, siltstone, and shale cut by calcite veins displaying abundant multiple sets of intersecting deformational glide twins. Sandstone beds in the cored interval contains extensive calcite spar as intergranular and replacive cements, and detrital intrabasinal carbonate grains (Barnes, this volume) including peloids, ooids, and other types of coated grains. Trace amounts of fine crystalline limestone were noted in the mudlog description of source areas included localized carbonate production sites.

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The color, composition, and limited number of primary sedimentary structures in core #4 suggest a depositional environment similar to the lacustrine environment interpreted for the core #3 sequence, with the difference that all of the core #4 sequence was probably deposited in deeper water. The presence of even lamination, graded layers, and sporadic cross-stratified lenses suggests deposition by fallout from suspension under intermittent, weak, bottom flows. The absence of wave-formed structures, coarse-grained sand detritus, and subaerial dessication fabrics suggests deposition was basinward of the lake margin and was not as strongly influenced by lake-level fluctuations and influx of coarse fluvial sediment as the core #3 sequence. The co-occurrence of laminated organic microcrystalline limestones in cored Unit C-1 and the peak drill-cuttings abundance of the limestones in Unit C-1 (see comments in next section) also supports the contention that Unit C-1 was primarily deposited in a deeper and calmer lake environment.

EVALUATION OF DRILL CUTTINGS

Determination of Percent Rock Type by Point-Counting

Each grain-mount thin section was point-counted to determine and quantify the percentage of various lithic types present in the sampled intervals. Approximately 130 to 250 points per sample were classified according to lithic type. Sandstone, siltstone, mudstone, and shale cuttings were most frequently counted, but a number of samples contained significant amounts of single-mineral (loose) grains, primarily quartz and feldspar. Carbonate spar and cataclastic sandstone chips are additional constituents which consistently occur in low percentages. Trace amounts of several other loose grain constituents were also counted. Percentage data derived from percent rock-type point-counting are presented in Table 1 and graphically summarized in Figure 8.

Figure 8 illustrates the large-scale vertical variations in drill-cuttings composition. The highest level examined was from the uppermost pre-Mt. Simon interval at 2800 feet; it contains glauconitic carbonate (40%) which clearly represents contamination of the sample from the overlying Eau Claire-Bonneterre interval (McKay, this volume). Samples from 3000 and 3500 feet contain 80 percent loose grains, primarily quartz and feldspar and lesser amounts of other grain types (Table 1). Intervals, such as this one, which are dominated by loose grains probably indicate sparse or weak cementation, a condition that allowed the drill bit to break off individual detrital grains from sandstones. This interval is termed Unit H (Witzke, this volume) and is of uncertain age.

Loose grain content decreases and cemented-chip content increases substantially in samples from 3790 to 4000 feet, where greater than 50 percent of the samples are cemented chips. The transition in drill-cuttings content across the 3500 to 3790-foot sample intervals, along with other data presented by Witzke (this volume) and McKay (this volume), suggests that Unit H differs from underlying Keweenawan units in terms of compositional and textural maturity, and cementation history.

The 4000 to 10,500-foot interval is dominated by well-cemented chips of very fine- to medium-grained sandstone with subordinate amounts of medium- to coarse-grained sandstone, siltstone, mudstone, shale, and cataclastic sandstone. This interval corresponds to units E, F, and G of the mudlog, as interpreted by Witzke (this volume). Moderate increases in siltstone, mudstone, and shale content at 5000 to 5500, 6500 to 7100, 10,000 to 10,500-foot depths correspond to mudlog subdivisions of units F-3, F-1 and E-1. Chips of cataclastic sandstone and siltstone, displaying a microbrecciated texture, are present in all but one sampled interval in this sequence and they attain a maximum concentration in the 7,000 to 10,000 foot interval (Figs. 9 and 10; Table 1).

A major siltstone, mudstone, and shale package spanning the interval from 10,500 to 12,500 feet corresponds to Witzke's units D-3 and D-4. Associated sandstone is very fine- to fine-grained and cataclastic sandstone content decreases to near zero.

The interval from 12,500 to 15,000 feet (units D-1 and D-2) is a heterogeneous, siliciclastic sequence which contains a large quantity of weakly calcite-cemented sandstone as indicated by the large percentage of loose quartz and feldspar grains (Fig. 8). Sorting and texture of sandstone varies substantially and there is a marked increase in average grain size and a decrease in sorting from units D-3 and D-4 to units D-1 and D-2. Lithic and mineralogic point-count data in this interval (Tables 1 and 2; Figs. 8 and 10) documents slightly greater clay/oxide cements and significantly greater quantities of calcite cements and carbonate spar cuttings chips. This suggests that the loose grains of this interval are probably derived from variably calcite-cemented sandstones.

The interval from 15,000 to 16,500 feet corresponding to Unit C contains abundant calcareous siltstone and shale with lesser quantities of calcareous sandstone. Shale is commonly silty, and shale color ranges from medium grey-green to dark grey to black. Some core in this unit (core #3, 15,096 - 15,120 feet) contains thinly interbedded calcareous sandstone, siltstone, and shale cut by calcite veins displaying abundant multiple sets of intersecting deformational glide twins. Sandstone beds in the cored interval contains extensive calcite spar as intergranular and replacive cements, and detrital intrabasinal carbonate grains (Barnes, this volume) including peloids, ooids, and other types of coated grains. Trace amounts of fine crystalline limestone were noted in the mudlog description of

Table 1. Point-counts of Rock Types in Drill Cuttings in the MGE Drillhole.

Sample interval (feet)	Medium- to coarse-grained sandstone	Fine- to medium-grained sandstone	Very fine- to fine-grained sandstone	Mudstone	Siltstone	Shale	Quartz grains	Crystalline carbonate	Microbrecciated sandstone	Chert	Microcline	Other K-feldspar
2800-2830	34	0	15	0	0	1	32	0	0	0	0	0
3000-3010	24	0	0	0	7	0	210	0	2	4	6	37
3500-3510	50	0	0	0	7	4	163	0	0	1	2	10
3790-3800	93	2	0	1	0	2	80	0	6	1	1	6
4000-4010	97	1	0	0	0	0	81	0	2	2	1	5
4500-4510	3	141	0	9	0	1	2	1	1	0	0	0
5000-5010	0	5	149	26	14	2	2	0	2	0	0	0
5500-5510	0	12	144	19	5	8	1	0	5	0	0	0
5930-5940	0	74	101	8	5	7	0	0	5	0	0	0
6000-6010	0	84	98	5	2	3	1	0	6	0	0	0
6500-6510	21	65	36	13	6	31	0	1	0	0	1	0
7000-7010	4	25	54	13	7	27	0	0	1	0	0	0
7100-7010	8	51	46	17	9	19	0	1	12	0	0	0
7340-7350	5	57	134	3	10	8	0	0	7	0	0	0
7490-7504	4	44	77	7	13	17	0	1	13	0	0	0
8000-8010	2	46	141	2	4	6	0	0	8	0	0	0
8500-8510	1	60	138	2	4	8	0	0	8	0	0	0
9000-9010	0	35	167	0	5	10	0	0	3	0	0	0
9420-9430	2	17	112	4	5	7	2	0	7	0	0	0
9500-9510	0	44	76	1	12	13	0	0	11	0	0	0
10,000-10,010	0	12	156	2	6	14	0	0	4	0	0	0
10,080-10,090	2	58	113	1	28	17	0	0	1	0	0	0
10,500-10,510	0	9	96	2	59	18	0	0	3	0	0	0
11,000-11,010	0	2	49	0	86	43	0	0	0	0	0	0
11,320-11,330	0	1	5	1	97	36	0	0	0	0	0	0
11,500-11,510	0	0	0	0	159	79	0	0	0	0	0	0
12,000-12,010	0	0	18	0	154	43	0	0	1	0	0	0
12,500-12,510	0	15	64	1	63	40	59	1	3	0	0	2
13,000-13,010	1	27	38	1	17	0	66	0	1	0	0	4
13,420-13,430	3	27	33	2	11	11	108	2	4	0	9	30
13,500-13,510	7	24	23	2	23	11	66	13	5	0	1	14
14,000-14,010	4	26	14	0	4	3	91	1	2	0	4	24
14,500-14,510	1	5	13	27	8	120	53	3	0	0	0	6
14,740-17,750	2	15	26	0	8	13	117	2	2	0	1	19
15,000-15,010	0	22	78	5	36	43	8	2	2	0	0	2
15,240-15,250	3	16	17	0	43	57	17	14	1	0	0	0
15,680-15,690	7	34	41	0	10	45	42	6	2	0	4	7
15,840-15,850	0	3	20	0	34	50	4	35	0	0	0	0
16,000-16,010	0	2	5	0	20	52	2	49	0	0	0	0
16,240-16,250	0	0	5	0	23	59	2	71	0	0	0	0
16,460-16,470	1	18	54	0	8	48	35	8	3	0	0	0
16,500-16,510	1	15	33	2	27	49	29	8	2	0	0	0
16,750-16,760	5	63	58	0	5	13	21	2	3	0	0	0
16,960-16,970	3	10	29	0	1	9	123	2	3	0	0	13
17,000-17,010	5	18	16	0	4	10	128	0	1	0	0	24
17,100-17,010	3	9	16	0	5	2	114	3	1	0	6	16
17,500-17,510	4	42	21	0	6	14	100	0	1	0	5	9
17,740-17,744	1	9	23	0	15	63	68	7	0	0	5	15

Table 1. (continued)

Sample interval (feet)	Metamorphic rock fragment	Mafic rock fragment	Indeterminate quartz rock	Rhyolite	Plutonic rock fragment	Silicic volcanic rock fragment	Calcitized basalt fragment	Spherulitic quartz	Opaque minerals	Sandy dolomite	Glauconitic limestone	TOTAL
2800-2830	0	0	0	0	0	0	0	0	0	5	57	144
3000-3010	0	1	0	0	0	0	0	0	2	7	0	300
3500-3510	0	3	3	5	1	0	0	1	0	1	0	251
3790-3800	1	0	1	0	1	0	1	0	4	0	0	200
4000-4010	0	0	1	0	0	10	0	0	0	0	0	200
4500-4510	0	0	0	0	0	0	0	0	0	0	0	158
5000-5010	0	0	0	0	0	0	0	0	0	0	0	200
5500-5510	0	0	0	0	0	0	0	0	0	0	0	194
5930-5940	0	0	0	0	0	0	0	0	0	0	0	200
6000-6010	0	0	0	0	0	0	0	0	0	0	0	199
6500-6510	0	0	0	0	0	0	0	0	0	0	0	174
7000-7010	0	0	0	0	0	0	0	0	0	0	0	131
7100-7010	0	0	0	0	0	0	0	0	0	0	0	163
7340-7350	0	0	0	0	0	0	0	0	0	0	0	224
7490-7504	0	0	0	0	0	0	0	0	0	0	0	176
8000-8010	0	0	0	0	0	0	0	0	0	0	0	209
8500-8510	0	0	0	0	0	0	0	0	0	0	0	221
9000-9010	0	0	0	0	0	0	0	0	0	0	0	220
9420-9430	0	0	0	0	0	0	0	0	0	0	0	156
9500-9510	0	0	0	0	0	0	0	0	0	0	0	157
10,000-10,010	0	0	0	0	0	0	0	0	0	0	0	194
10,080-10,090	0	0	0	0	0	0	0	0	0	0	0	220
10,500-10,510	0	0	0	0	0	0	0	0	0	0	0	187
11,000-11,010	0	0	0	0	0	0	0	0	1	0	0	181
11,320-11,330	0	0	0	0	0	0	0	0	0	0	0	140
11,500-11,510	0	0	0	0	0	0	0	0	0	0	0	238
12,000-12,010	0	0	0	0	0	0	0	0	0	0	0	216
12,500-12,510	0	0	0	0	0	0	0	0	0	0	0	248
13,000-13,010	0	0	0	0	0	0	0	0	1	0	0	156
13,420-13,430	0	0	0	0	0	0	0	0	0	0	0	240
13,500-13,510	0	0	0	0	0	0	0	0	0	0	0	189
14,000-14,010	0	0	1	0	0	0	0	0	0	0	0	174
14,500-14,510	0	0	0	0	0	0	0	0	0	0	0	236
14,740-17,750	0	0	0	0	0	0	0	0	0	0	0	205
15,000-15,010	0	0	0	0	0	0	0	0	0	0	0	198
15,240-15,250	0	0	0	0	0	0	0	0	0	0	0	168
15,680-15,690	0	0	0	0	0	0	0	0	0	0	0	198
15,840-15,850	0	0	0	0	0	0	0	0	0	0	0	146
16,000-16,010	0	0	0	0	0	0	0	0	0	0	0	130
16,240-16,250	0	0	0	0	0	0	0	0	0	0	0	160
16,460-16,470	0	0	0	0	0	0	0	0	0	0	0	175
16,500-16,510	0	0	0	0	0	0	0	0	0	0	0	166
16,750-16,760	0	0	0	0	0	0	0	0	0	0	0	170
16,960-16,970	0	0	0	0	0	0	0	0	0	0	0	193
17,000-17,010	0	0	0	0	0	0	0	0	0	0	0	206
17,100-17,010	0	0	0	0	0	0	0	0	0	0	0	185
17,500-17,510	0	0	0	0	0	0	0	0	0	0	0	202
17,740-17,744	0	0	0	0	12	0	0	0	0	0	0	218

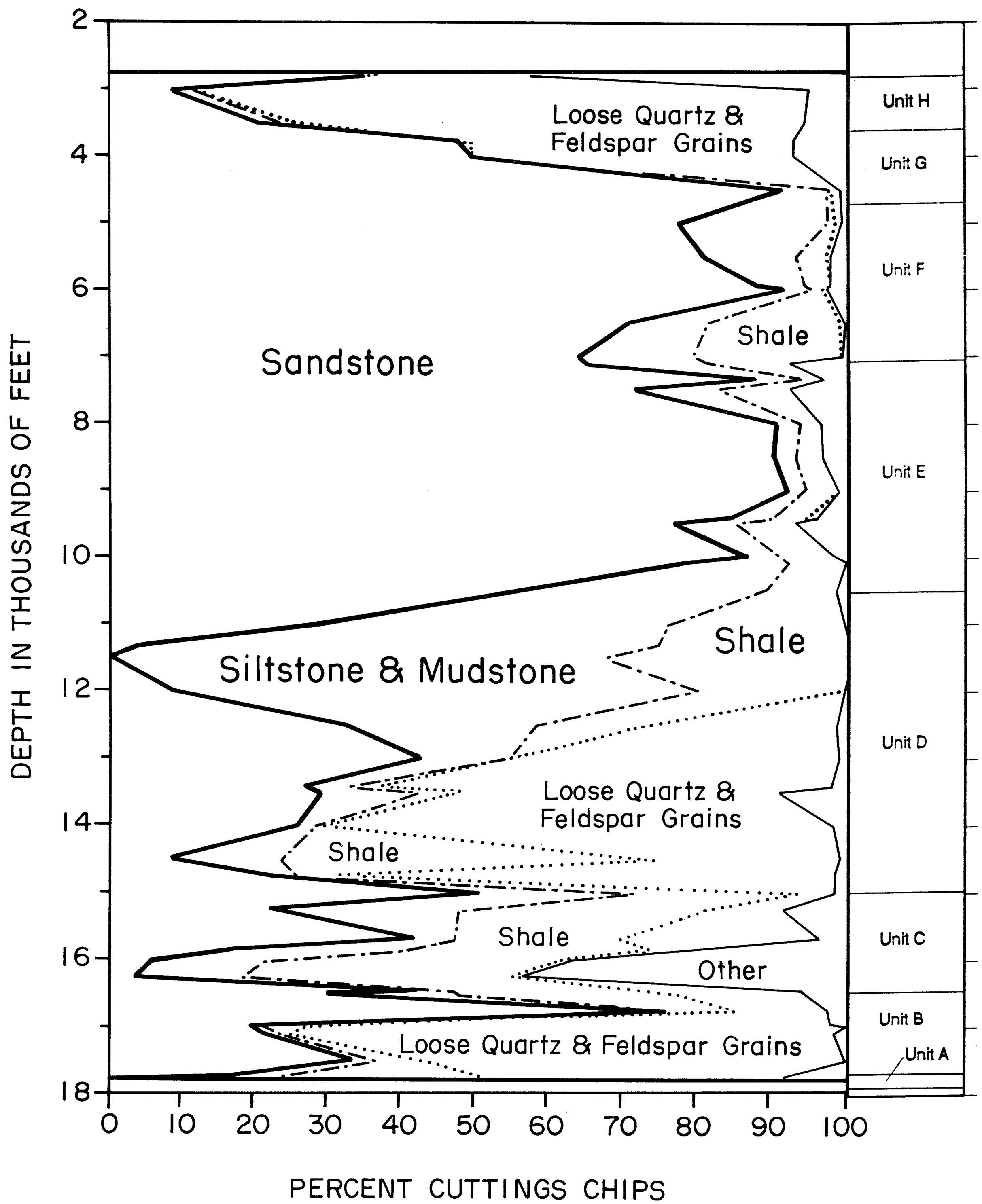

Figure 8. Stratigraphic variations in lithology of drill-cutting samples recovered from the MGE drillhole.

.his unit.

The large increase of "other" chips in samples from 15,840 to 16,240 feet (Fig. 8) is the result of a peak occurrence of calcite spar chips (Fig. 10). During point-counting, all chips dominated by carbonate spar were placed in a single category, but three distinct types of calcite spar chips are recognizable. Type I spar chips consist of a randomly oriented, equant to bladed mosaic of fine-to coarse-crystalline calcite. Crystals range in size from 0.04 to 0.50 mm and commonly display intersecting sets of deformation glide twins. Small amounts (≤ 5 %) of silt- to very fine sand-size quartz and feldspar grains occur floating in the crystal mosaic. Type II spar chips consist of an equant mosaic of micritic to finely crystalline calcite. Pyrite is present in small amounts and minor amounts of brown to black organic flecks and flakes are distributed throughout. Varying amounts of silt and very fine quartz and feldspar grains float in the spar and micrite or are concentrated in thin laminae. Siliciclastic content varies and is great enough to class some chips as calcareous siltstone to very fine-grained sandstone. Type III carbonate spar chips consist of organic-rich, laminated, micritic to fine crystalline calcite spar. Calcite-rich laminae range in thickness from 0.05 to 0.20 mm, and organic-rich laminae range in thickness from 0.02 to 0.20 mm. The organic material is dark brown to black in color and occurs as flecks and flakes concentrated in discrete laminae with varying quantities (1 to 20%) of silt-size quartz and feldspar and finely crystalline to micritic calcite. Organic-rich laminae are continuous to discontinuous across a chip, and exhibit a parallel wavy to crinkly form. Internally, the organic-rich laminae exhibit a microanastomosing fabric around intralaminar calcite crystals and silt grains.

It appears that Type II and III spar chips are similar in overall composition and represent gradations from nonlaminated, organic-poor calcite (Type II) to laminated organic-rich calcite (Type III). Type II and III spar chips in Unit C-1 can be reasonably interpreted to represent fragments of limestone in this interval, and appear to be similar to carbonate laminites of the Keweenawan Nonesuch Formation in the type area as described by Milavec (1986). Type I spar chips lack laminae, organic material, and a significant siliciclastic content, and are much coarser in crystal size and display abundant glide twins. These are interpreted to represent either fragments of cement from sandstone intervals or calcite from veins.

The interval from 16,500 to 17,700 feet, corresponding to Unit B, is dominated by very fine- to medium-grained sandstone and loose quartz and feldspar grains. Subordinate lithic types include medium- to coarse-grained sandstone, siltstone, and shale. Carbonate spar chip content is significantly lower than overlying Unit C, but carbonate as cement in cemented chips maintains a moderate abundance. Intergranular black residues in sandstones which were noted in the mudlog description were observed in a few sandstone chips.

The material is black and opaque, and exhibits a pinkish-blue color under unpolarized incident illumination. Its composition has not been investigated further to date.

The Keweenawan sedimentary sequence in this well terminates at a depth of 17,700 feet where drill-cuttings content includes medium-crystalline gabbro. Gabbro of Unit A comprises all the drill cuttings between 17,700 feet and the well's total depth of 17,851 feet. Core #5 (17,733 to 17,742 feet) was studied by Van Schmus and others. (this volume). Only a small sample has survived destructive analysis for age determination.

Discussion

This analysis of various rock types as estimated from drill-cuttings confirms the general lithic trends documented in the well-site mudlog description and adds some new information. The low (≤ 7 percent) but consistent percentage of cataclastic sandstone chips displaying a foliated microbrecciated texture (in 36 of the 47 samples examined) is significant. These grains are cut by an anastomosing network of intergranular fractures and intragranular cracks, with variable amounts of carbonate and phyllosilicate cements. These rock types, along with the brittle tectonic fabrics displayed in the caved intervals (see Ludvigson and Spry, this volume), are considered to provide evidence that the Keweenawan sedimentary succession is pervasively cut by a large number of small-scale reverse faults, apparently in response to a late Keweenawan phase of compressive deformation.

Chips of carbonate spar which occur sporadically between 2,800 and 13,000 feet and increase in abundance between 13,000 and 17,700 feet document the presence of sparsely to extensively calcite-cemented siliciclastic rocks and variable amounts of crystalline limestone and

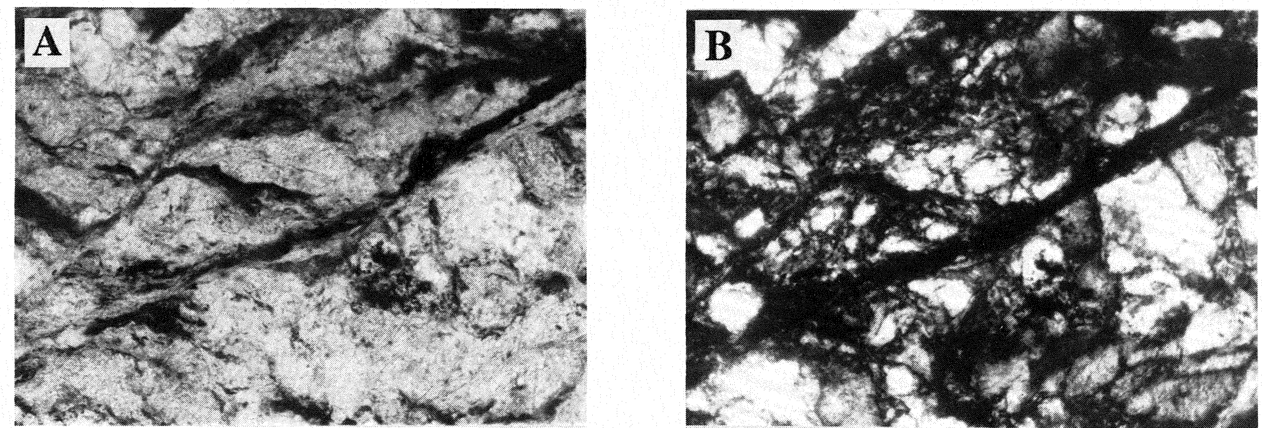

Figure 9. Photomicrographs of cataclastic sandstone in cuttings samples recovered from the MGE drillhole. Sample from 5500-5510 feet. Both micrographs have a 0.65 mm field of view. A) Foliated microbreccia with anastomosing network of darkly colored transgranular fractures filled by iron oxide and calcite cements, plane-polarized light. B) Same view, cross-polarized light; note the comminution of siliciclastic framework grains by intragranular fractures.

calcite vein-fillings. The peak occurrence of Type II and Type III spar chips in the 16,240-foot sample indicates the presence of organic-rich limestone intervals associated with the presumably organic-rich dark colored shales of Unit C-1. These limestones are similar to those described from the Nonesuch Formation of the Keweenaw Peninsula, Lake Superior.

One discrepancy of note between the mudlog and our data is the mudlog's notation of possible anhydrite in numerous samples between 3000 and 8500 feet. Six of our samples (3790, 4000, 4500, 5930, 7100, 7340 feet) correspond to intervals noted to contain anhydrite on the mudlog. We did not observe anhydrite in any of these samples nor have we noted anhydrite in any sample thus far examined.

Sandstone petrology

Sandstones were point-counted using the Gazzi-Dickinson method (see Zuffa, 1984, for methodology) in order to minimize apparent differences in composition that are artifacts of different grain-size distributions. Grain parameters were defined using guidelines discussed in Ingersoll and others (1984). Noteworthy labile constituents include plagioclase feldspars (P), potassium feldspars (K), volcanic rock fragments (Lv), and aphanitic quartz-mica tectonite, mica tectonite, and well-crystallized phyllosilicate hornfels, all grouped as metamorphic rock fragments (Lm).

Recognition of volcanic lithic detritus is an especially important issue. Petrographic observations of sandstone samples by Barnes (this volume) indicate that these grain types are largely absent from the cored Keweenawan sedimentary rocks in the MGE drillhole. All of the cored sandstones were sampled below the 8835-foot level, Unit E-2, however, and the peak occurrences of this grain type are stratigraphically higher in the drillhole (Fig. 11). Volcanic rock fragments in the MGE drillhole are composed of an aphanitic, devitrified matrix with abundant opaque inclusions, and plagioclase microlites (Fig. 12). With increasing depth, the microlites are altered to secondary minerals, mostly quartz, and all replaced microlites are in optical continuity within the grain.

Metamorphic rock fragments (Lm) were distinguished from aphanitic sedimentary rock fragments (Ls), first by the presence of foliated tectonite fabrics, and second, in the absence of foliation, by high matrix birefringence indicating recrystallization of claystones to hornfels.

Provenance of the sediments

QFL and QpLvLsm values were calculated for

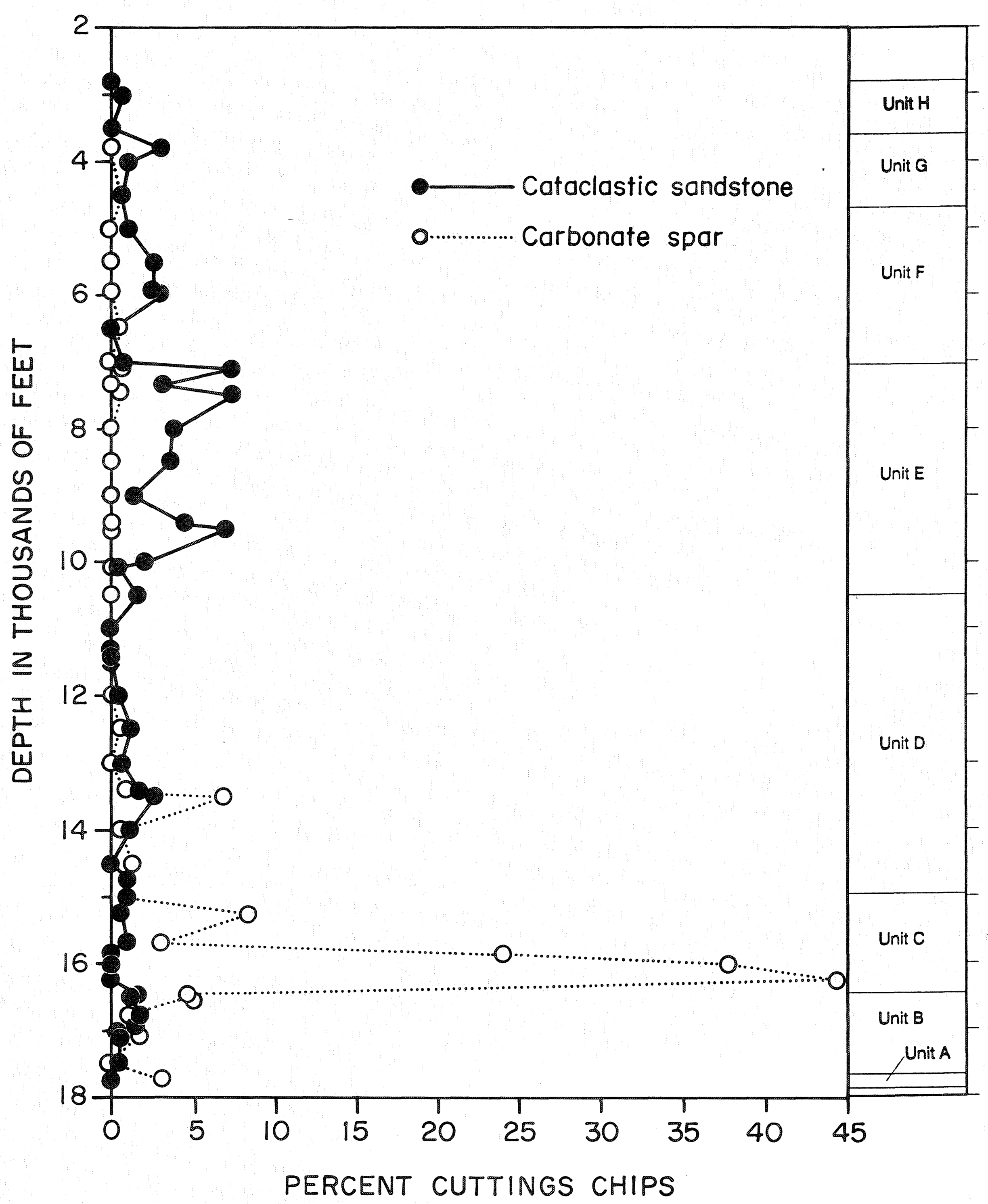

Figure 10. Stratigraphic variations in the abundance of chips of cataclastic sandstone and carbonate spar in drill-cutting samples recovered from the MGE drillhole.

Table 2. Point-counts of Detrital Framework Grains from Sandstone in drill cuttings in the MGE Drillhole.

Stratigraphic unit	Sample interval (feet)	Monocrystalline quartz	Polycrystalline quartz	Plagioclase feldspar	Potassium feldspar	Sedimentary rock fragment	Metamorphic rock fragment	Volcanic rock fragment	Detrital mica	Heavy minerals	Quartz cement	Carbonate cement	Clay & oxide cements
Unit H	2800-2830	263	2	0	59	1	0	2	13	7	20	19	14
Unit H	3500-3510	136	1	0	39	1	0	0	5	0	5	3	10
Unit G	3790-3800	286	3	3	41	17	2	7	4	2	3	16	16
Unit G	4000-4010	286	1	1	60	6	2	14	0	4	12	4	8
Unit G	4500-4510	271	3	2	58	5	7	19	0	8	13	1	10
Unit F	5000-5010	223	3	22	45	9	16	3	0	18	7	26	28
Unit F	5500-5510	221	0	15	71	16	14	12	1	21	12	0	17
Unit F	5930-5940	251	2	9	65	10	12	18	1	11	14	0	7
Unit F	6000-6010	268	2	12	66	1	7	15	0	14	8	0	7
Unit F	6500-6510	263	0	17	61	15	10	3	0	7	4	5	14
Unit F	7000-7010	228	1	27	61	5	15	13	2	11	5	16	16
Unit E	7100-7110	224	0	22	64	21	8	25	0	19	1	3	13
Unit E	7340-7350	320	9	49	116	13	11	14	0	14	7	0	47
Unit E	7490-7504	323	10	20	93	20	20	14	3	8	17	8	64
Unit E	8000-8010	333	9	60	75	17	13	34	0	15	10	6	26
Unit E	8500-8510	359	10	55	74	26	18	17	1	16	5	6	13
Unit E	9000-9010	349	18	55	60	18	20	15	3	21	6	14	21
Unit E	9420-9430	334	7	37	78	23	24	24	0	35	3	2	33
Unit E	9500-9510	127	9	1	12	10	12	1	0	5	1	4	18
Unit E	10,000-10,010	107	2	7	13	18	11	3	0	9	2	0	28
Unit E	10,080-10,090	110	2	6	25	7	12	2	1	6	4	3	22
Unit E	10,500-10,510	104	2	12	14	14	11	1	2	13	2	4	21
Unit D	11,000-11,010	117	3	14	13	5	8	5	0	12	0	1	22
Unit D	12,500-12,510	113	1	10	20	2	5	0	3	8	2	15	21
Unit D	13,000-13,010	118	0	6	34	11	0	0	1	5	1	0	24
Unit D	13,420-13,430	123	0	12	31	2	1	1	0	5	1	10	14
Unit D	13,500-13,510	360	13	35	97	3	2	3	4	17	1	42	25
Unit D	14,000-14,010	456	3	8	82	5	3	3	4	11	2	7	16
Unit D	14,500-14,510	130	0	11	25	1	0	0	0	2	3	5	15
Unit D	14,740-14,750	293	2	6	62	2	1	0	9	4	2	4	15
Unit D	15,000-15,010	235	0	37	23	9	0	0	30	8	2	31	25
Unit C	15,240-15,250	56	0	12	13	0	0	0	2	1	0	15	1
Unit C	15,680-15,690	244	4	3	51	3	2	14	3	8	0	50	17
Unit B	16,460-16,470	302	9	6	35	2	1	0	5	2	1	20	17
Unit B	16,500-16,510	281	9	4	45	0	1	1	7	7	3	23	19
Unit B	16,750-16,760	310	9	6	27	4	0	1	2	2	1	16	22
Unit B	16,960-16,970	175	2	3	14	0	0	1	0	0	0	5	0
Unit B	17,000-17,010	169	5	2	15	1	0	0	0	1	1	3	3
Unit B	17,100-17,110	183	1	0	14	0	0	1	0	0	0	0	1
Unit B	17,500-17,510	301	1	5	52	0	1	0	1	2	5	6	26
Unit B	17,740-17,744	137	3	14	26	0	2	0	5	0	4	3	6

each sample, grouped by major Keweenawan stratigraphic units delineated in the MGE drillhole (see Witzke, this volume). Mean values are plotted on triangular diagrams, with surrounding hexagons showing the standard deviation values from the mean for each grain parameter (Fig. 13). In addition, plots were prepared showing stratigraphic variations in QFL (Fig. 14), LsLmLv (Fig. 11), and P/K (Fig. 15) for each sample, according to position in the drillhole. The results show several significant trends.

There are two stratigraphic trends showing changes in the apparent detrital framework modes in Keweenawan sandstones from the MGE drillhole. The first trend occurs through units B, C, and D, and is characterized by an upward decrease in mineralogical maturity. Conversely, the succession through units E, F, and G show an upward increase in mineralogical maturity. This trend continues upward into the recently designated Unit H (see Tables 1 and 2). These relationships are best exemplified in Figure 14, showing the cumulative QFL percentages as a function of depth in the drillhole. The principal constituents affecting the changes in detrital modes are lithic grains and quartzose grains, which have complementary relationships. Feldspar contents in all the sandstones are relatively uniform.

Figure 11 shows the cumulative LsLmLv percentages as a function of depth in the drillhole. Trends in units B, C, and the lower part of D are difficult to interpret because the lithic contents are extremely small, and occurrences of a few grains effect large changes in percentage. From about 14,000 feet to the top of the Keweenawan interval, however, volcanic lithic detritus increases in abundance at the expense of metamorphic and sedimentary rock fragments. This upward change is, in part, paralleled by upward increases in plagioclase/K-feldpsar ratios (Fig. 15), that also are indicative of the increasing importance of volcanic source rocks.

For purposes of comparison, sandstones were grouped into the major stratigraphic units (B, D, E, F, and G) and plotted on QFL and QpLvLsm triangular diagrams (Fig. 13), to facilitate comparisons with other sandstone suites, and evaluate tectonic settings of the provenance with the widely used plate tectonic compositional fields outlined by Dickinson and Suczek (1979).

Proterozoic sandstones in the MGE drillhole are notably quartz-rich compared to many other well-studied Keweenawan successions from the Lake Superior area and southeast Minnesota (Thwaites, 1912; Myers, 1971; Morey, 1972, 1974, 1977; Morey and Ojakangas, 1982; Daniels, 1982). Quantitative compositional data on Keweenawan sandstones from the Texaco Poersch #1 well in Kansas are not currently available (Berendsen et al., 1988). Mean QFL compositions of sandstones in units G, D, and B fall within the "continental block provenance" field of Dickinson and Suczek (1979), whereas those in units E and F straddle or fall within the mutual boundary of the "recycled orogen provenance" field (Fig. 13). According to Dickinson and Suczek (1979, p. 2173-2175), the "continental block provenance" field encompasses sandstones derived from the erosion of continental interiors, including cratonic sandstones at the quartz-rich end-member, and uplifted basement sources at the more feldspar-rich end-member. Such provenance settings can include basement uplifts bounding yoked sedimentary basins, and incipient rift belts (ibid.). The "recycled orogen provenance" field refers to sediments eroded from older sedimentary rocks and lavas that were deformed along collisional plate margins (ibid.).

Mean QpLvLsm compositions of sandstones in units B and D plot along the "collision orogen sources" field of Dickinson and Suczek (1979). Except for Unit B, all of the sandstone populations are largely divided by differences in volcanic versus combined sedimentary and metamorphic lithic detritus, with the latter dominating (Fig. 13). Compositional changes through the upward stratigraphic succession in units D, E, F, and G are principally controlled by an increase in volcanic rock fragments at the expense of combined sedimentary and metamorphic rock fragments, until the mean composition of sandstones in Unit G straddles the "arc orogen sources" field (Fig. 13). According to Dickinson and Suczek (1979, p. 2176-2178), the "collision orogen sources" field refers to sediments eroded from thrusted sedimentary and metamorphic rocks along collisional continental margins. The "arc orogen sources" field includes sandstones eroded from volcanic arcs along convergent plate margins, with undissected active volcanic arcs being represented by sandstones at the Lv end-member, and dissected inactive volcanic arcs supplying sediments characterized by sandstones that plot toward the upper-right of the field (ibid.).

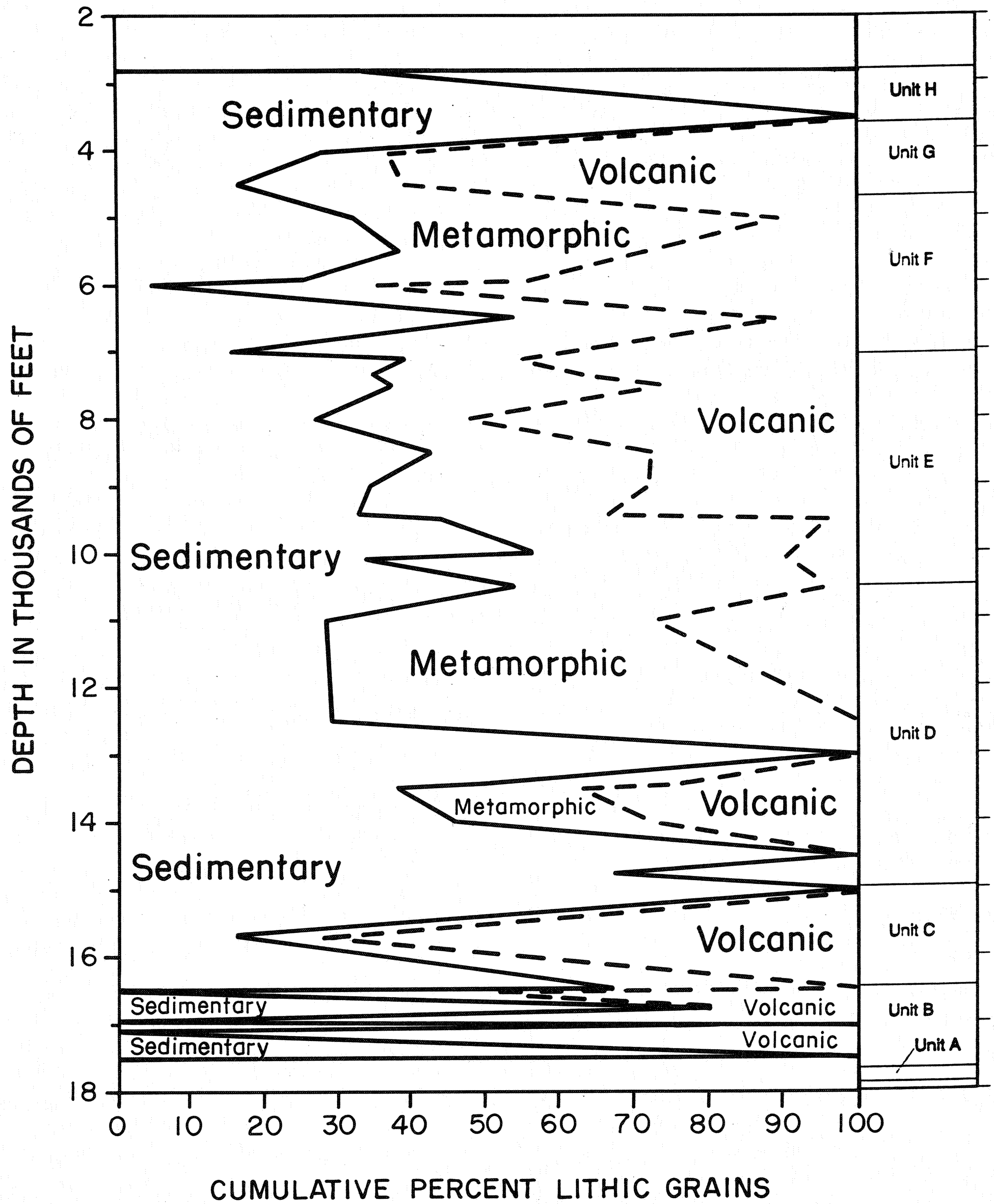

Figure 11. Stratigraphic variations in the abundance of sedimentary, metamorphic, and volcanic lithic grains in the detrital framework of sandstone chips in drill-cutting samples recovered from the MGE drillhole.

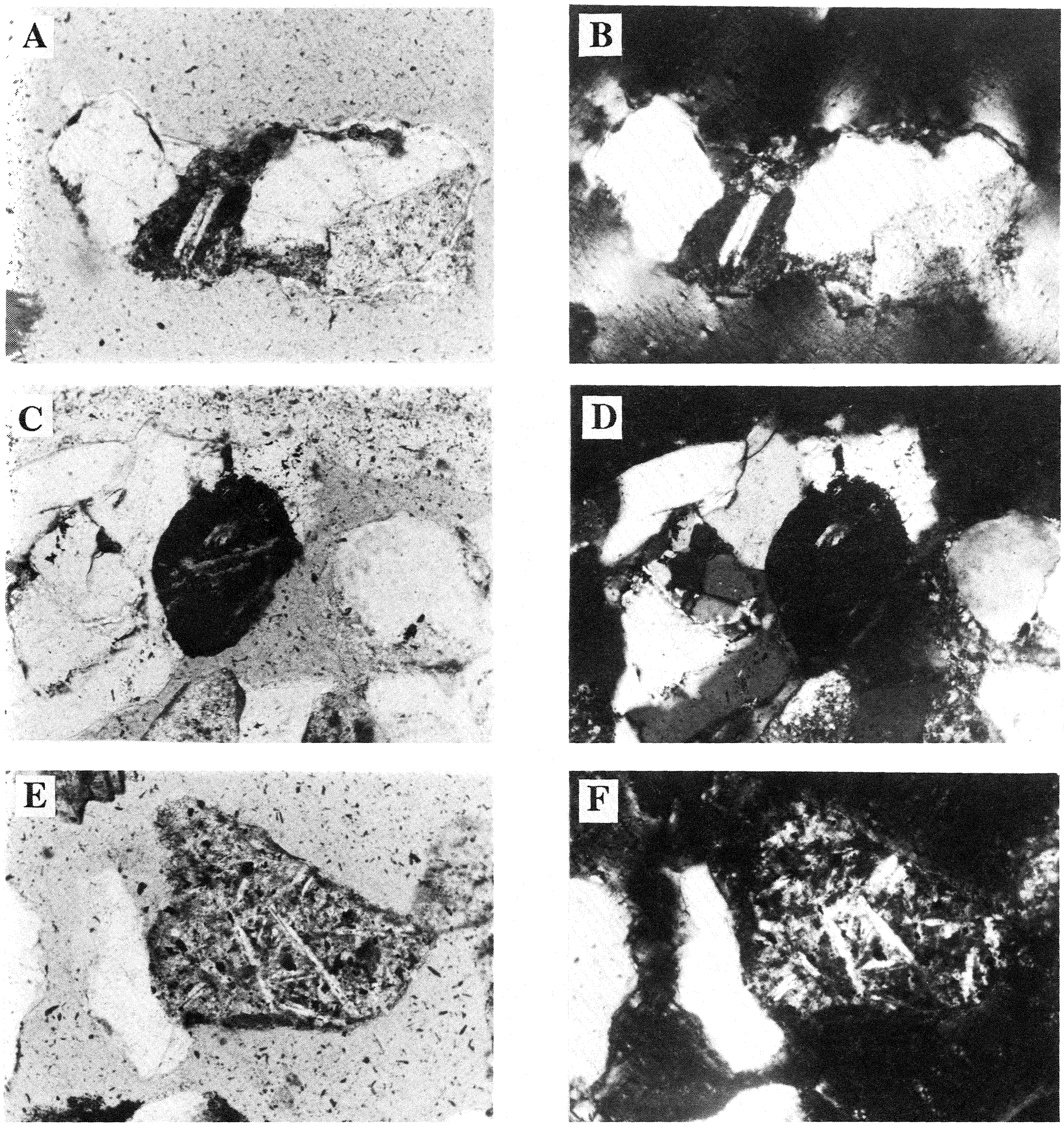

Figure 12. Photomicrographs of volcanic lithic grains from sandstone chips in cuttings samples recovered from the MGE drillhole. All micrographs have a 0.65 mm field of view. A) Volcanic rock fragment (VRF) with plagioclase lath, in sandstone chip, 6000-6010 feet, plane-polarized light. B) Same view, cross-polarized light. C) VRF with altered plagioclase laths and opaque mineral inclusions in the groundmass, plane polarized light. D) Same view, cross-polarized light. E) Loose VRF of densely-packed plagioclase microlites in an isotropic groundmass, plane-polarized light. F) Same view, cross-polarized light.

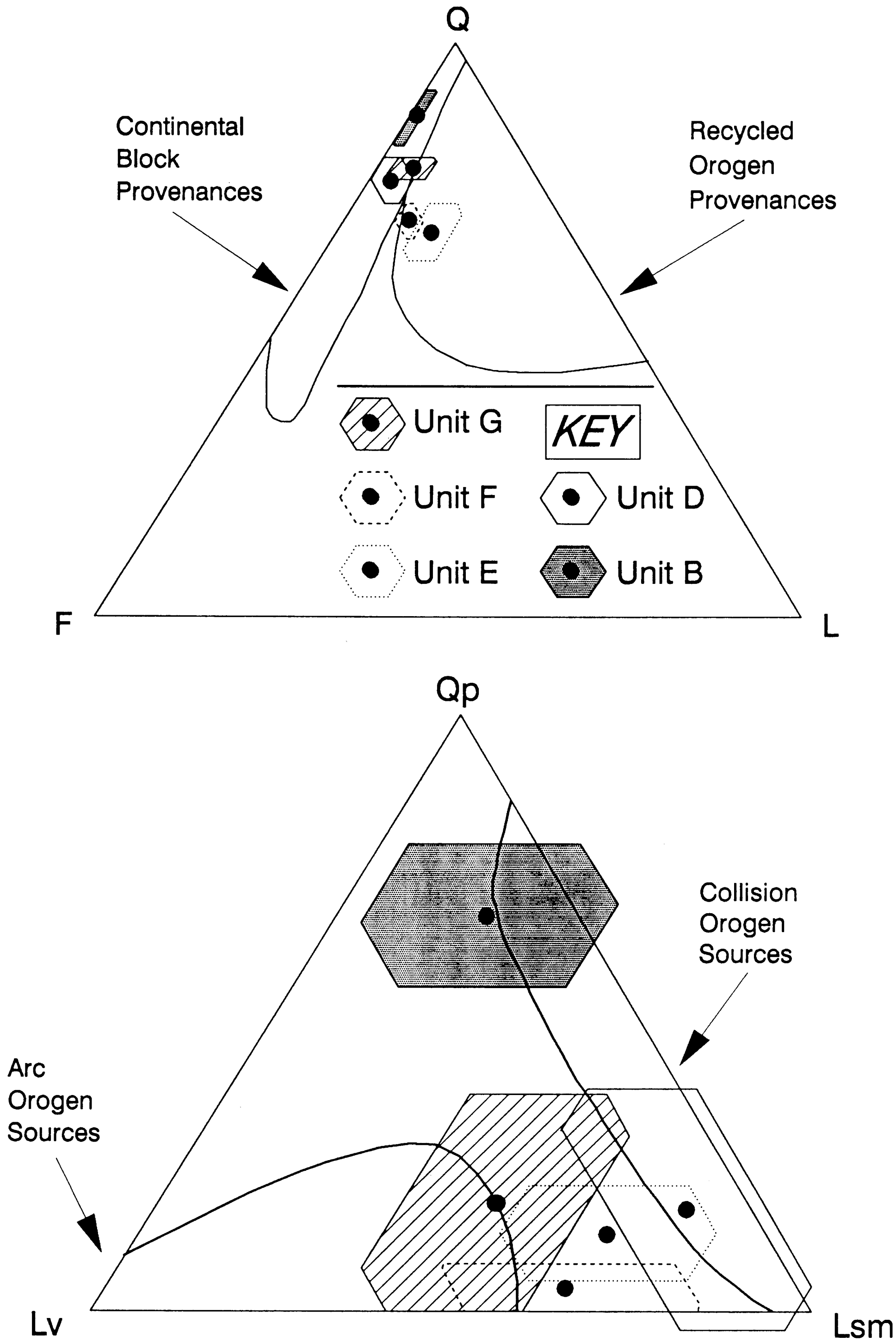

Figure 13. QFL (quartz-feldspar-lithic grains) and QpLvLsm (polycrystalline quartz-volcanic rock fragments-sedimentary and metamorphic rock fragments) triangular plots of the detrital modes of sandstones in major stratigraphic units of the MGE drillhole, compared to the compositional fields defined for different plate tectonic provenances by Dickinson and Suczek (1979). Filled circles represent the mean composition for sandstones in each unit, and the dimensions of the enclosing hexagonal prisms are determined by the standard deviations of the three grain parameters in each plot.

Cement and porosity distribution

Pore space is optically resolvable in blue-dyed resin-impregnated thin sections down to a depth of about 8000 feet. Below that depth, no porosity was observed (Fig. 16). Porosity largely occurs as secondary networks within partially dissolved feldspar grains. Intergranular ferric oxide cements are abundant in units G through E, where porosity occlusion may have largely resulted from compaction (Barnes, this volume). Intergranular, replacive, and vein-filling carbonate cements occur throughout the Keweenawan rocks of the MGE drillhole, but reach their peak occurrence in units B,C, and D (Fig. 17). Barnes (this volume) presents convincing arguments that these cements were emplaced in the rocks very early in their history.

Discussion

Compared with other well-studied Keweenawan sedimentary sequences, and the sandstone types generally expected in continental rift settings, the rocks from the MGE drillhole are exceptionally quartz rich. As emphasized by Dickinson and Suczek (1979, p. 2173), plots of modal composition identifying provenance fields should be used with caution, because no single scheme can anticipate all possible geologic scenarios. The diagrams simply provide a catalog of the range of compositions that would ordinarily be expected. The Midcontinent Rift System cuts obliquely across a variety of older Archean and Proterozoic terranes. Accordingly, the older rift-bounding rock types that were eroded into rift-fill sedimentary sequences should reasonably be expected to vary along the trend of the feature. In addition, distances from contemporaneous volcanic centers during rift basin subsidence could influence the local importance of volcaniclastic contributions to the sediment pile.

The observation that the mean compositions of sandstones in units E and F plot within the "recycled orogen" field of Dickinson and Suczek (1979) is considered to be significant. While the overlying and underlying Keweenawan units plot within the "continental block" field generally expected for rift-filling sediments eroded from continental basement rocks, predictions about expected sandstone compositions must also be based on details of the regional Archean-Proterozoic crustal development. If continental basement rocks were always homogeneous masses of granitic rocks, then one would be able to confidently predict that purely quartzo-feldspathic sandstones would always be produced from their erosion. Anderson's (1988; this volume) syntheses of the regional Precambrian history, however, shows that the local country rock along the Iowa portion of the Midcontinent Rift System is an ancient complex of island arcs and related sediments that were deformed and accreted to North America during the Penokean Orogeny about 1880 to 1760 Ma. The occurrence of metamorphic tectonite rock fragments in the sandstones of the MGE drillhole are best understood as the products of locally uplifted Penokean belt rocks marginal to the rift system, rather than the products of a single tectonic-depositional cycle.

Another influence on the apparent maturity of the Keweenawan sandstones in the MGE drillhole may have been the erosion of a cover of Early Proterozoic Baraboo Interval quartzites that buried the Penokean Belt across much of the upper midwest (Anderson and Ludvigson, 1986; Anderson, 1988).

One of the most significant provenance variations of the MGE clastic sedimentary rocks from other well-characterized Keweenawan successions is the relative dearth of volcanic lithic detritus, especially in the lower units. Keweenawan sandstones from the Lake Superior region and southeast Minnesota, especially those of the Oronto Group, were largely eroded from volcanic sources. Despite apparent similarities in the gross lithic sequences between the MGE drillhole and the exposed Oronto-Bayfield succession of Wisconsin and Michigan, it is evident that a somewhat different type of tectonic evolutionary history is recorded in the rocks of the Defiance Basin of western Iowa. Peak occurrences of volcanic rock fragments occur in the uppermost portions of the "Red Clastic" Sequence, although they never constitute a major component in the siliciclastic sediment shed into the rift. The upward increase in volcanic lithic grains noted in units D through G might have resulted from the erosion of Keweenawan volcanic rocks during uplift of the axial Iowa Horst. If so, this would imply that a major part of the sedimentary sequence overlaps with the late phase compressive deformation of the Midcontinent Rift System.

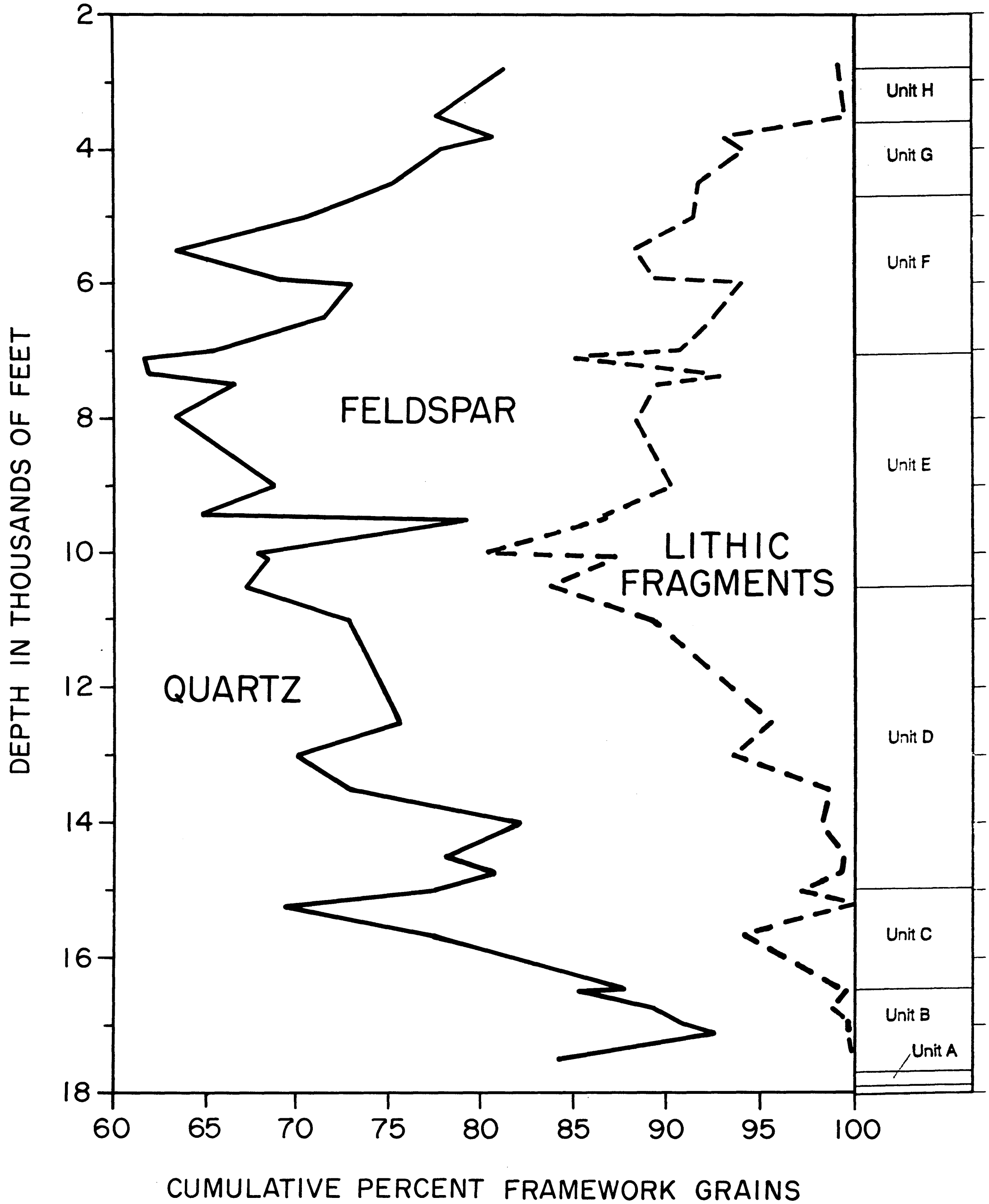

Figure 14. Stratigraphic variations in the QFL detrital modes of sandstone chips in drill-cutting samples recovered from the MGE drillhole.

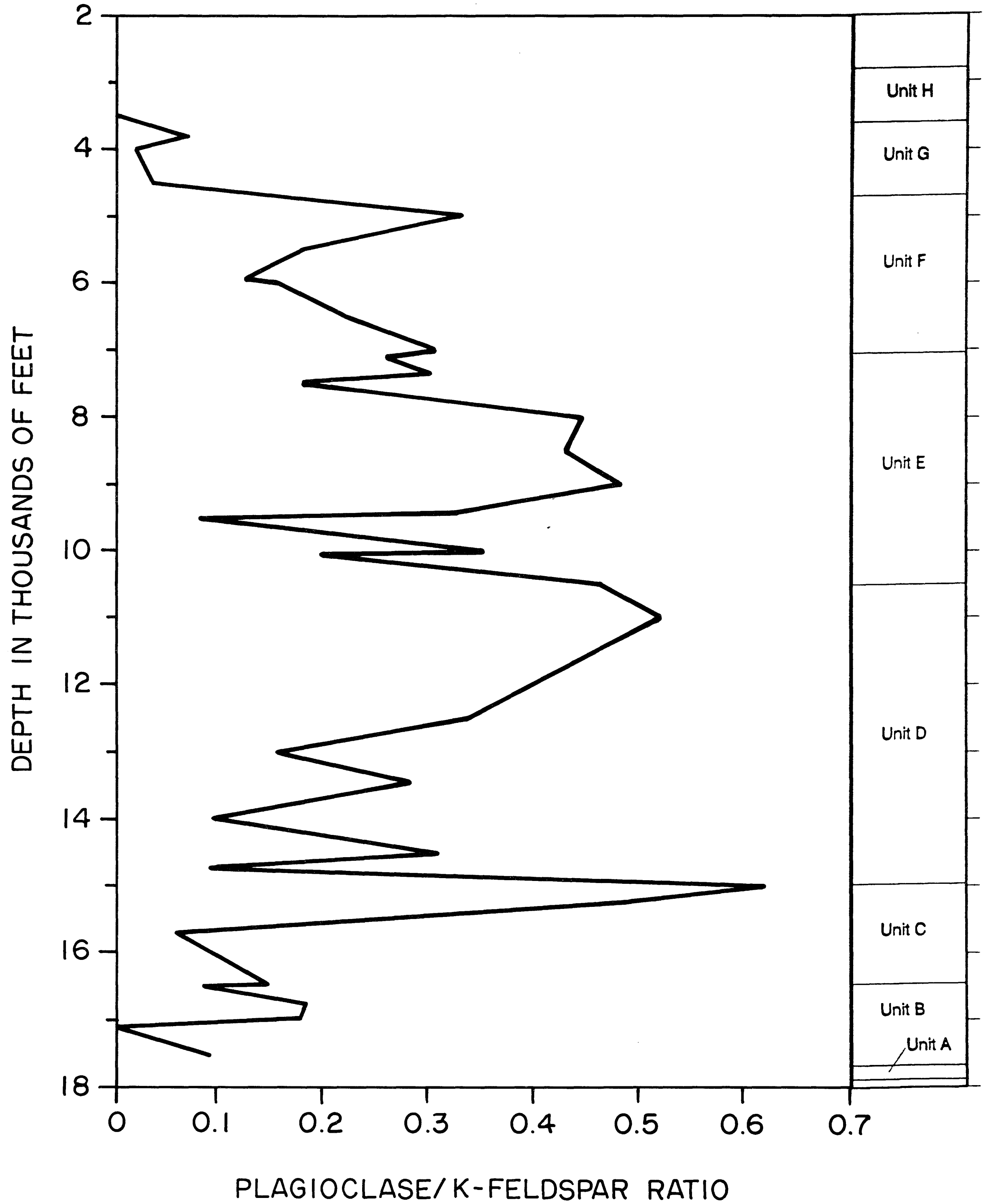

Figure 15. Stratigraphic variations in the plagioclase/potassium feldspar ratios in the detrital framework populations of sandstone chips in drill-cutting samples recovered from the MGE drillhole.

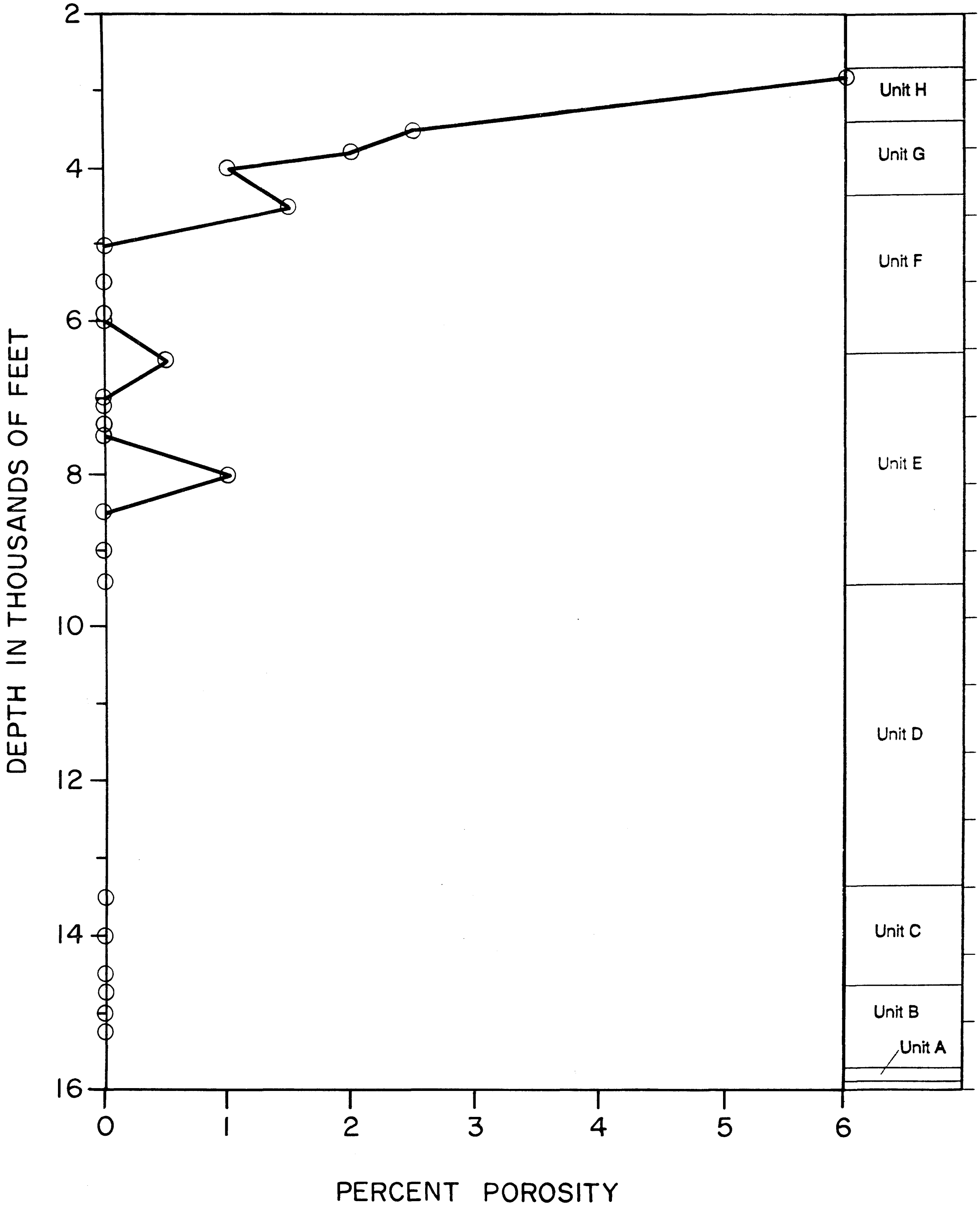

Figure 16. Stratigraphic variations in the percentage of petrographically-resolvable porosity in sandstone chips in drill-cutting samples recovered from the MGE drillhole.

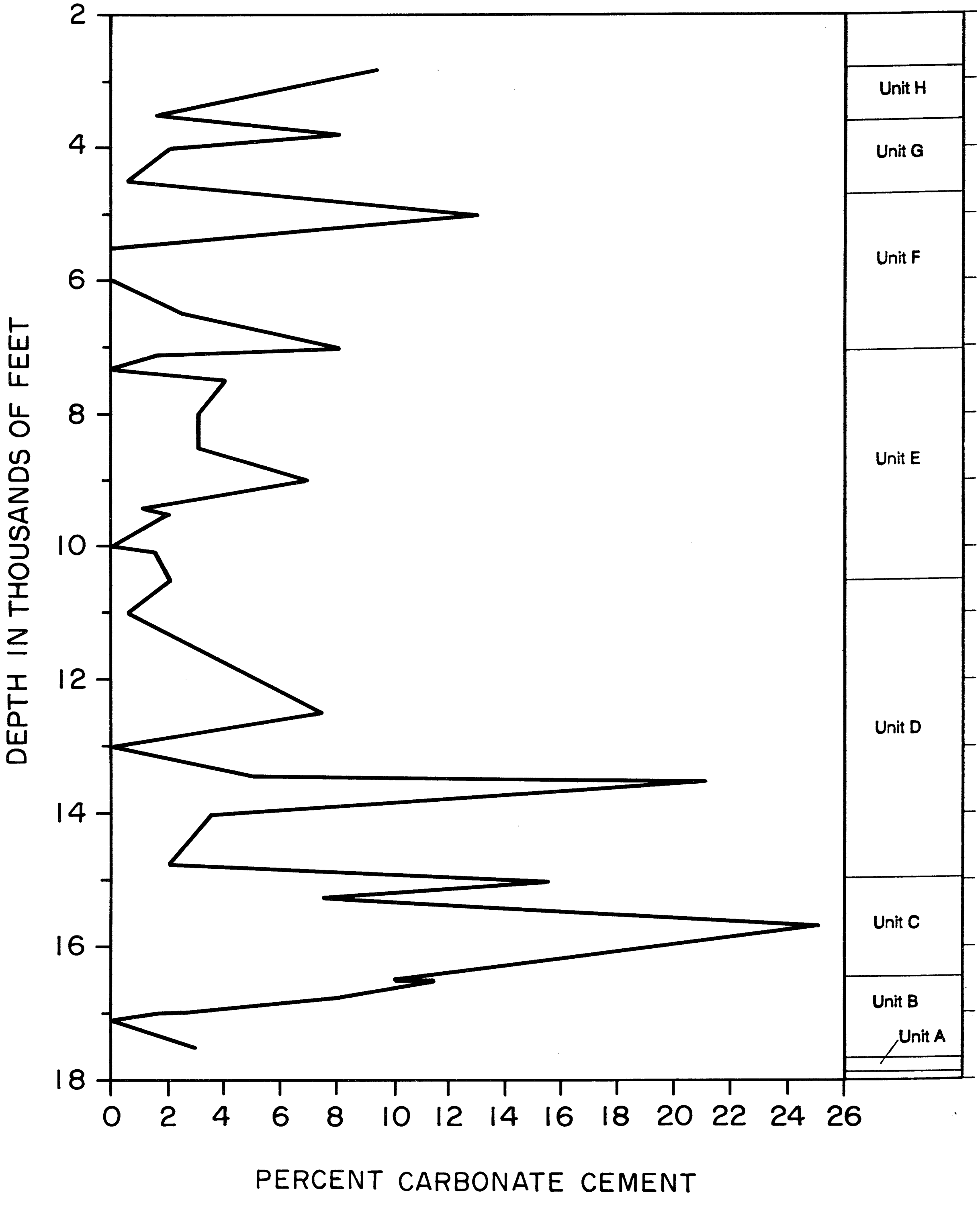

Figure 17. Stratigraphic variations in the percentage of carbonate cement in sandstone chips from drill-cutting samples recovered from the MGE drillhole.

CONCLUSIONS

While the sedimentary succession in the Amoco M.G. Eischeid #1 drillhole shares many stratigraphic and depositional similarities with the classically-known Oronto Group-Bayfield Group sequence, petrographic evaluation of detrital modes of sandstones reveal substantial differences in sediment composition. The differences in sediment composition are considered to result from differences in the local crustal history and the absence of local contemporaneous rift-related volcanism during the deposition of the sedimentary rocks.

Optically resolvable porosity is preserved in the sandstones to depths of 8,000 feet. Porosity occlusion in the upper units was mainly accomplished by compaction, while the lower units were pervasively cemented by early pore-filling carbonate spars.

ACKNOWLEDGEMENTS

Thin sections of drill-cutting chips used by us and of cored sandstone used by Barnes (this volume) were prepared quickly and carefully by Orrin Plocher, and we are thankful for his skill and promptness. We also wish to acknowledge the U.S. Geological Survey for partial support of laboratory costs for this study through their Midcontinent Strategic and Critical Minerals Program. Conversations with Brian Witzke and David Barnes influenced our thinking during work on the project. We thank Bill Bunker and Mary Pat Heitman for assistance in preparation of the manuscript; and Kay Irelan and Pat Lohmann for assistance in the preparation of figures. Photographic prints were prepared by Orrin Plocher. Early drafts of the manuscript were reviewed by Brian Witzke, David Barnes, and G.B. Morey, and formal reviews were provided by Mary Howes and Paul VanDorpe.

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APPENDIX A

M.G. Eischeid #1

Core #1 8,834-8,844 feet
Cored 10 feet, Recovered 36% (3.6 feet)
Depth below Kelly bushing

8834.0 - 8834.0 feet. Sandstone, brownish red, fine, dense, well cemented, hematitic, horizontal to low-angle planar stratified, micaceous, slight grain size variation between laminae, laminae average 2-4 mm in thickness, rare flat red shale clasts 0.5 mm thick by 2 mm long.

8834.9 - 8836.0 feet Sandstone, brownish red, fine to coarse, with some (10%) very coarse to granule size mudstone to shale clasts, massively stratified, variable hematite staining, mudstone-shale clasts flat to equidimensional, up to 3 mm diameter.

8836.0 - 8837.6 feet Sandstone, brownish red, fine to medium, hematite color mottled, low-angle planar stratified, micaceous laminae 2-4 mm thick, flat red shale clasts 0.5 mm thick by 2 mm long.

8837.6 - 8844.0 feet No core.

Core #2 11,381-11,395 feet
Cored 14 feet, Recovered 89% (11.6 feet)
Depth below Kelly bushing

11,381.0 - 11,382.6 feet. No core.

11,382.6 - 11,383.5 feet Sandstone, red, silty to very fine, sets of unidirectional small-scale cross-strata, sets 1-4 cm thick with horizontal to low-angle laminae topping each set. Foreset laminae slightly concave downward and defined by silty laminae. Basal 0.1 feet lag of red shale clasts 1 - 6 mm long by 1 - 2 mm thick.

11,383.5 - 11,385.0 feet Sandstone, red, silty to fine, small-scale unidirectional tabular and trough cross-strata, slightly micaceous.

11,385.0 - 11,388.5 feet Sandstone, red, fine to silty, hard, dense, horizontal to low-angle discontinuous and slightly crinkly layers and laminae; silt-rich and mud-rich laminae, laminae 1 mm or less, micaceous, some very thin red shale-mudstone flakes or chips (< 1 mm thick); conchoidal fracture.

11,388.5 - 11.389.2 feet Interlayered sandstone and mudstone. Sandstone 90%, red, coarse to silty, dense, hard. Mudstone, red, nonlaminated. Three graded bed sequences each 8 cm thick; basal part either parallel horizontally-laminated sandstone or low-angle laminae; grades up to massive central part with fine to coarse sandstone and randomly oriented red mudstone flakes; upper part horizontally-laminated sandstone which grades to symmetrical very small (2 - 3 mm high) ripples and capped by 1 - 1.5 cm thick red mudstone.

11,389.2 - 11,390.2 feet Sandstone, red, silty to very fine, calcareous dense. Low-angle cross-strata at base, grades up to unidirectional small-scale tabular cross-strata and then up to parallel horizontal to low-angle laminae. Upper 0.5 feet has a 4 cm wide disrupted, brecciated vertical zone with angular clasts up to 2 cm wide; some clasts rotated 90°.

11,390.2 - 11,391.5 feet Sandstone, red, very fine to silty, dense, micaceous, calcareous, intersecting sets of small-scale trough cross-strata.

11,391.5 - 11,393.0 feet Sandstone, red, very fine to silty, dense, well cemented calcareous, micaceous, large-scale low-angle cross-strata with fine silty foreset laminae, some reactivation surfaces. Basal 0.2 feet small-scale trough cross-strata. Sharp base. One vertical tubular disturbance at 11,392.3 feet.

11,393.0 - 11,393.3 feet Siltstone to mudstone, red, laminated.

11,393.3 - 11,393.9 feet Sandstone, red, silty to very fine, parallel horizontal laminated, but structurally inclined 30° .

11,393.9 - 11,394.2 feet Sandstone, red, silty to very fine, small-scale reverse thrust fault dipping 30-40° with respect to core axis, parallel-laminated sandstone in footwall below thrust fault has a same sense of dip, hanging-wall parallel-laminated sandstones which are drag folded into overturned anticlinal features with 2.5 cm wavelengths cut by overlying reverse faults. Pull-apart calcite veinlets are abundant in these deformed beds.

11,394.2 - 11,395.0 feet No core.

Core #3 15,096.0 - 15,120.0 feet
Cored 24 feet, Recovered 98% (23.4 feet)
Depth below Kelly bushing

15,096.0 - 15,096.7 feet Interlayered shale, siltstone to sandstone. Shale, 30%, dark grey to black, silty, calcareous, laminated. Siltstone to very-fine sandstone, 70%, light grey, calcareous, pyritic. Graded sandstone/siltstone to shale layers 3 mm - 13 mm thick predominate. Bases of layers are both erosive and draping; internal laminae parallel-horizontal, to wavy, pinch and swell laminae, incipient lensing. Small, 1-2 mm long, compressed, v-shaped, siltstone-filled, shrinkage cracks at 15,096.2. Common calcite veinlets, vertical, 1 mm wide, highly compressed and telescoped at 15,096.2 and 15,096.6 feet.

15,096.7 - 15,096.8 feet Shale, dark grey, silty, calcareous, pyritic. Ten percent thinly interlayered light grey siltstone. Brecciated tabular and angular clasts 0.5 - 4.0 cm wide.

15,096.8 - 15,097.0 feet Interlayered shale and siltstone. Shale, 50%, dark grey to black, noncalcareous, micaceous, silty, hard, dense, pyritic. Siltstone 50%, light grey, calcareous, hard, dense, pyritic to very pyritic. Layers 1.0 to 7.0 mm thick. Graded siltstone to shale layers most common. Siltstone filled, v-shaped shrinkage crack at 15,096.9 feet, very calcareous; compaction-deformed laminae above and below crack.

15,097.0 - 15,097.4 feet Shale, black, laminated, very minor silt laminae, dense, hard, noncalcareous, pyritic.

15,097.4 - 15,099.5 feet Interlayered shale and sandstone to siltstone. Shale, 30%, dark grey to black, silty to micaceous in part, laminated, rough facet surface parallel to laminae. Sandstone, 70%, light grey, very fine to silty, calcareous, moderately pyritic. Shale in layers < 1 mm - 5 mm. Sand in lenses and layers 0.5 - 1.5 cm thick, small-scale cross-strata, with silty shale, flasers, incipient pinch and swell laminae and lenses, bidirectional lenses, bundled lenses, horizontal-parallel grading to cross-lamination. Some graded layers < 2 cm thick. Vertical calcite filled veins < 1 mm wide and 1 to 4 cm long, black to grey. Minor sand-filled shrinkage cracks in shale layers.

15,099.5 - 15,099.7 feet Sandstone, light grey, very fine to fine, calcareous, one set low angle cross-strata, bulbous load structure at base with 3 cm relief into underlying shale, minor shale clasts in sandstone.

15,099.7 - 15,100.1 feet Interlayered shale and siltstone. Shale, 60%, medium grey, laminated, noncalcareous, variably silty, hard, dense, slightly micaceous. Siltstone, 40%, light to medium grey, calcareous, hard, dense, very fine sandy in part. Parallel horizontal laminae; some graded layers.

15,100.1 - 15,101.1 feet Interlayered siltstone and sandstone. Sandstone, light grey, calcareous very fine to coarse, finely interlayered and small-scale cross-strata in layers and lenses. Vertical black calcite filled fractures. Parallel horizontal to wavy lamination, small-scale scour surfaces, pinch and swell laminae, bidirectional bundles and lenses.

15,101.1 - 15,102.2 feet Sandstone, light grey, very fine to granule, some pebbles, angular to subrounded, calcareous, dense, hard, angular, medium grey shale clasts to 1.5 cm long by 3 mm thick, cross-stratified in upper 0.3 feet, massive for remainder. Vertical oriented sets of dark grey veins < 1 mm wide by 1 to 7 cm long. Crudely graded bed with coarsest material at base; some cross-strata at base. Sandstone infills shrinkage cracks in underlying shale unit.

15,102.2 - 15,104.2 feet Interlayered shale and siltstone. Shale, 50%, medium to dark grey, laminated, silty, slightly micaceous, dense, hard, noncalcareous. Siltstone, light grey, calcareous, dense, hard. Layers 1 mm to 1 cm thick, thinly interlayered, continuous parallel horizontal laminae with some laminae truncation, some crinkly laminae; some small-scale cross-strata. Sandstone-filled, v-shaped cracks at top with contact of overlying coarse-grained sandstone. Minor compressed calcite veinlets throughout. Some black shale flecks in siltstone.

15,104.2 - 15,106.2 feet Sandstone, light grey to grey-green, fine to silty, calcareous, micaceous, hard, dense, parallel horizontal laminae, multiple truncation surfaces, small-scale wave structures, pinch and swell laminae, bidirectional lensing, shale draping and flasers, incipient lenses, microlenses, some tabular shale clasts.

15,106.2 - 15,110.2 feet Interlayered sandstone, siltstone and shale. Sandstone, 20%, light grey, very fine to coarse, some very coarse to granule size, poorly sorted, calcareous, shale clasts, micaceous. Siltstone, 65%, light to medium grey, calcareous, laminated, sandy, poorly sorted. Shale, 15%, medium grey to dark grey, noncalcareous, laminated. Graded layers in upper part 2 to 6 mm thick, silt to shale. Other layers up to 1.5 cm thick, parallel horizontal to wavy laminae, small-scale unidirectional cross-strata, poorly sorted silt to very coarse sand lenses and layers, shale clasts, small-scale trough sets, vertical shrinkage crack with coarser fill, load and flame on base of sandstones with associated water escape structure.

15,110.2 - 15,110.4 feet Sandstone, light grey, silty to very coarse, calcareous, hard, dense, fills vertical v-shaped shrinkage crack in underlying siltstone and shale.

15,110.4 - 15,111.8 feet Interlayered shale and siltstone. Shale, 40%, medium greenish-grey, silty, noncalcareous. Siltstone, 60%, light to medium grey, very fine sandy, calcareous, hard, dense. Layers 0.2 to 3.0 cm thick. Micrograded laminae <1-2 mm thick, unidirectional and bidirectional cross-strata, parallel horizontal to slightly wavy laminae predominate. Small, calcite-filled, tension cracks; large, 6 cm long, sand-filled vertical shrinkage crack at top. Minor convolute laminae.

15,111.8 - 15,112.1 feet Sandstone, light grey, fine to very coarse, poorly sorted with shale clasts to 1.3 cm, calcareous, large scale cross-stratified, scoured base; sand-filled shrinkage cracks in underlying shale. Vertical black calcite fractures in sandstone. Carbonate peloid grains present.

15,112.1 - 15,112.7 feet Interlayered siltstone and shale. Shale, 60%, medium to dark grey, silty, micaceous, dense, hard, laminated. Siltstone, 40%, light to medium grey, calcareous, dense, hard. Layers 1 mm to 3 cm thick, parallel horizontal to wavy laminae, minor graded laminae, minor unidirectional small scale cross-strata and incipient lensing. Sand-filled shrinkage cracks at top, 6 cm long.

15,112.7 - 15,112.9 feet Sandstone, light grey, fine to granule, poorly sorted, calcareous, clay clasts to 2 cm long by 3 mm thick, massive, sharp upper and lower contacts.

15,112.9 - 15,113.5 feet Interlayered sandstone, siltstone and shale. Graded layers predominate, maximum thickness of 1 cm, parallel horizontal to wavy lamination, minor sandstone lenses, sandstone very fine to fine.

15,113.5 - 15,114.0 feet Sandstone, light to medium grey, fine to silty, calcareous, common microhummocky cross-strata, pinch and swell laminae, shale drapes, small scale trough sets, convolute laminae at top. Vertical calcite-filled fractures.

15,114.0 - 15,116.0 feetInterlayered siltstone and shale. Siltstone, 80%, light to medium grey, micaceous, calcareous, hard, dense. Shale, 20%, medium grey, hard, dense, silty, micaceous. General structure is parallel horizontal laminae, graded silt to shale layers 3 mm to 1 cm thick; siltstone layers up to 10 cm. Brecciated interval from 15,114.0 to 15,115.5 feet; breccia interval 10 cm wide at top and tapers downward over 30 cm. Pyrite concentrated along several siltstone laminae. Noncompressed calcite veinlets associated with large breccia interval. Soft sediment fold structure at 15,115.8 feet with 3 cm amplitude.

15,116.0 - 15,117.5 feet Interlayered siltstone and shale. Siltstone, 70%, light grey, calcareous, hard, dense. Shale, 30%, medium grey. Main structure is graded siltstone to shale layers 0.5 - 2 cm thick; some silt lenses with parallel horizontal laminae.

15,117.5 - 15,118.2 feet Siltstone, medium grey, shaley, slightly calcareous, massive, no apparent lamination.

15,118.2 - 15,119.4 feet Interlayered sandstone, siltstone and shale. Sandstone, 60%, light grey, very fine to fine, calcareous, hard, dense. Siltstone, 30%, light grey, calcareous, hard, dense. Shale, medium grey, micaceous. Graded sandstone/siltstone to shale layers up to 2 cm thick with parallel horizontal laminae. Minor small scale cross-strata as lenses. Disrupted, possibly soft sediment deformed laminae at 15,118.8 feet. At 15,118.6 feet are a mass of anastomosing bedding-parallel calcite veinlets in 2 bands of 3 and 8 mm thick with associated mineralized slickenslides. At 15,119.1 to 15,119.4 feet are sets of S-shaped black veins, 1 to 5 mm wide and 2 to 7 mm in vertical length. Veins cut sandstones. Minor reverse thrust with 1 cm displacement at 15,119.1 feet.

15,119.4-15,120.0 feet No core.

Core #4 16,043 - 16,058 feet
Cored 15 feet, Recovered 60% (9 feet)

This entire core interval has a high angle of structural dip ranging from a low of 60° to vertical to slightly overturned. Much of the core is broken into golfball to baseball size chunks. Coring substantially followed vertical bedding and total stratigraphic sequence is only half or less of the recovered footage.

Interlayered siltstone and shale. Siltstone, 60%, light to medium grey, calcareous, hard, dense. Shale, 40%, medium to dark grey to black, organic in part. Parallel-horizontal laminae, some graded siltstone to shale layers, a few siltstone to very fine sandstone lenses with unidirectional, small-scale cross-strata. Common slickensided fault surfaces with rough facets indicate reverse faulting.

SANDSTONE PETROLOGY FROM CONVENTIONAL CORE IN THE M.G. EISCHEID #1 WELL, CARROLL COUNTY, IOWA

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INTRODUCTION

Thin sections of sandstones from conventional core in the M.G.Eischeid #1 well in Carroll County, Iowa were studied using the petrographic microscope in order to determine framework grain composition, visible porosity characteristics, and the nature of authigenic mineral cements. Sixteen thin sections were available from four cored intervals in the Upper and Lower "Red Clastics" Sequence in the well from 8834.3 feet to 16,046.5 feet. No other samples were available for this study. Thin sections were impregnated with blue-dyed epoxy and stained with sodium cobaltinitrate and amaranth solution for determination of potassium and plagioclase feldspars. The modal composition for eight representative samples from cores in the Eischeid well was determined by point count of 250 points per section using the Gazzi-Dickinson method (see Zuffa, 1984, for methodology). Modal analysis was not done for a calcareous siltstone, the only sample from the lower-most cored interval in the well (Unit C-1, 16,046.5 feet) because of the fine grain size. Significant grain size variation, from coarse- to very fine-grained and silt size, between point-counted samples suggests that modal composition may be influenced not only by provence variation through the section but by variation in grain size (Zuffa, 1984).

FRAMEWORK GRAIN MINERALOGY

Sandstones from the Upper and Lower "Red Clastic" Sequence (Witzke, this volume) are all subquartzose sandstones (see Dickinson, 1970) and contain less than 75% quartz (Table 1; Fig. 1). Samples range from feldsarenites to lithic feldsarenites to feldspathic litharenites according to the classification scheme of Folk and others (1970). The samples from the shallowest cored interval in Unit E-2 are moderately sorted, medium- to fine-grained with mostly subrounded to subangular grains. These samples are feldspathic litharenites and contain mostly monocrystalline quartz, potassium and plagioclase feldspar, and microplutonic and microtectonite rock fragments. Minor components of epidote, opaque minerals and mica are also present. The plagioclase to K-feldspar (potassium feldspar) ratio ranges from 1.75 to 0.44. However, varying degrees of

Table 1. Percentages of components: framework grains, detrital matrix, and cement based on counts of 250 points in thin sections from the M.G. Eischeid #1 well, Carroll Co. Iowa.

Unit	Depth	Quartz	K-spar	Plagio-clase	Rock Fragments	Heavies	Matrix	Albite Cement	Calcite	Iron Oxide
E-2	8834.3	52	10	6	25	0	0	2	1	4
E-2	8835.6	51	16	7	23	1	0	1	0	0
E-2	8836.5	56	4	7	16	5	0	4	tr	7
D-4	11,387.5	36	5	17	5	6	4	0	1	26
D-4	11,392.6	38	12	14	6	11	1	0	6	12
C-2	15,101.9	40	3	14	10	tr	0	0	33	0
C-2	15,107.6	42	13	13	7	3	3	0	17	0
C-2	15,109.0	40	12	10	5	14	3	0	15	0

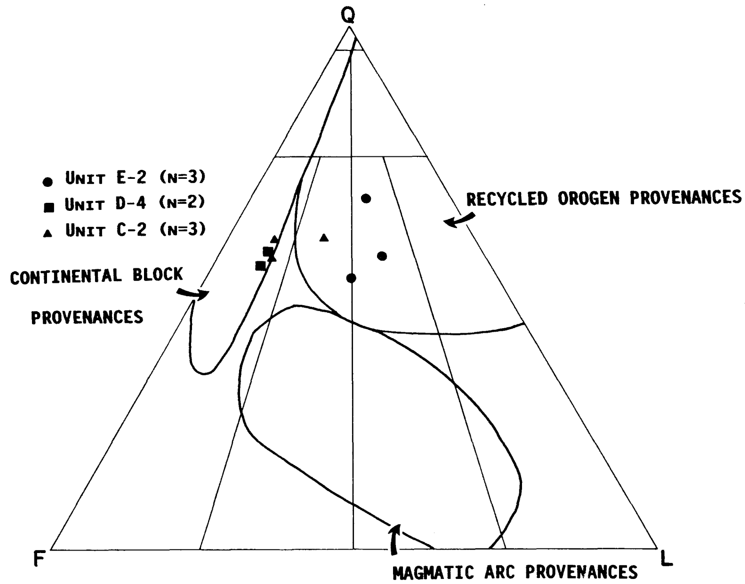

Figure 1. Triangular plot of normalized quartz (total; Q), feldspar (F) and lithic fragments (L) based on point count analysis of 250 points per thin section from the "Red Clastic" sequence in the M.G. Eischeid #1 well, Carroll Co. Iowa. See Table 1 for modal analysis data.

albitization of feldspars in portions of the "Red Clastics" makes the feldspar ratios somewhat questionable as an indicator of the original proportions of potassium feldspar and plagioclase (see Authigenic Mineralogy section, below).

Samples from Unit D-4 are moderately to poorly sorted, very fine-grained to silty with mostly subrounded to subangular grains. These samples are feldsarenites and contain monocrystalline quartz, plagioclase and potassium feldspar, opaque minerals, mica, epidote and finely crystalline rock fragments. Plagioclase to K-feldspar ratio ranges from 3.4 to 1.2.

Sandstone samples from Unit C-2 are moderately to poorly sorted, fine- to very coarse-grained and mostly subangular. The samples are feldsarenites to lithic feldsarenites and contain mostly monocrystalline quartz, quartzo-feldspathic plutonic rock fragments, plagioclase and K-feldspar, mica (both biotite and muscovite), epidote and minor recrystallized intrabasinal carbonate fragments. Plagioclase to K-feldspar ratio ranges from 4.7 to 0.8.

An interbedded, calcareous, fine- to coarse-grained siltstone sample from Unit C-1 was described but not point counted due to the fine grain size. The main components of this sample are quartz, feldspar, mica, opaque minerals, and probable recrystallized intrabasinal carbonate fragments. Feldspar types could not be resolved.

Excluding the influence of grain size on the modal composition of sandstones (in part minimized by the Gazzi-Dickenson point-counting technique) a trend from more feldspathic sandstones to more microcrystalline lithics-rich sandstones is observed in the "Red Clastic" sequence from base to top. Although many grains in the lowermost point-counted interval (Unit C-2) are polycrystalline rock fragments the dominant sand-size minerals are quartz and feldspar. In the upper-most interval studied (Unit E-2) microcrystalline rock fragments (grains composed of crystalline aggregates with crystal size less than about 50 microns) are more abundant. These rock fragments are mostly felsic microplutonic or micaceous micro-tectonite fragments. Obvious porphyritic or devitrified volcanic fragments are not common anywhere in the samples studied.

The variation in feldspar composition and plagioclase to K-feldspar ratios in the samples studied is not considered significant. Some error in the determination of original feldspar composition

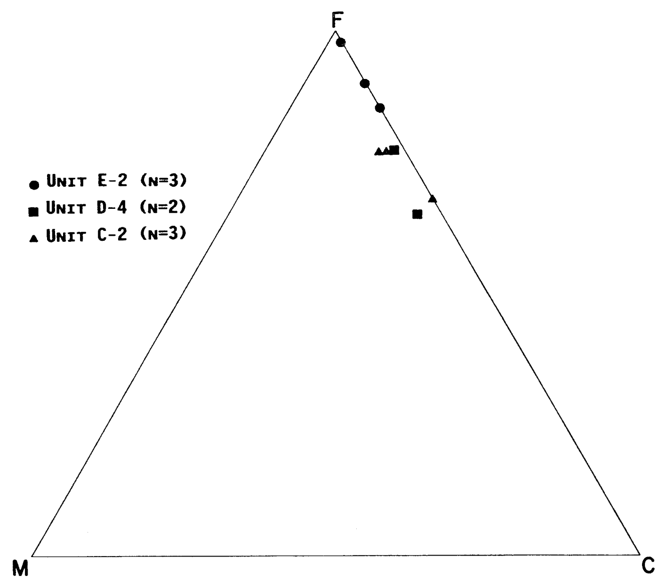

Figure 2. Ternary plot of modal framework grains (F), detrital matrix (M) and cement (C) from thin section point counts from the "Red Clastic" sequence in the M.G. Eischeid #1 well, Carroll Co. Iowa. See Table 1 for modal analysis data.

is likely due to variability of the quality of staining in the thin sections and the variable diagenetic modification of some K-feldspars to albite. Also, it has been shown that the feldspar composition in sandstones of similar provenance may be significantly influenced by grain size variation (see Odom et al., 1976; Zuffa, 1984). The wide variation in grain size of samples used in this study was dictated by the limited availability of sandstone samples in core.

SANDSTONE DIAGENESIS

The modification of the original fabric and mineralogy of sandstone samples from the "Red Clastic" sequence is variable. However, due to compaction and cementation only trace visible porosity is present in any of these samples. A plot of framework grains, detrital matrix and cement is presented in Figure 2. The highest value for minus-cement porosity (the percentage of porosity plus cement; the percentage of cement in the samples studied here; Table 1) is 33% in the sample from Unit C-2 at 15,101.9 feet. This value may be too high because of partial to complete replacement of some detrital grains by calcite, masking their detrital origin, and the presence of recrystallized carbonate detrital grains not easily distinguished from cement, mostly in Unit C-2.

Fabric

The modification of depositional fabrics by compaction in samples from core in the Eischeid well is variable. The samples range from moderately to strongly compacted, with long grain contacts and clear ductile grain deformation, to moderately open fabrics, with point and "floating" grain contacts. The degree of compaction is due to both original framework grain composition and the timing of cementation as determined by packing geometries.

Samples from Unit E-2 are generally moderately to strongly compacted. Deformed ductile grains are common and the maximum minus-cement porosity is 11%. The generally higher proportions of ductilely deformed, micaceous micro-tectonite fragments is consistent with this generally low minus-cement porosity value. Quartz overgrowth cement is present (see Authigenic Minerals section, below) but was not quantitatively distinguished from detrital quartz. Therefore, the minus-cement porosity presented here is a minimum value.

Samples from Unit D-4 are generally moderately open-packed based on the minus-cement porosity values of 18% and 27% (Fig. 2). The visual packing geometry in these samples indicates mostly long grain contacts suggesting moderate to strong compaction. This contradiction can be explained because the majority of cement in these samples is opaque, consisting of iron oxide coatings on very fine to silt-size grains. Point-count analysis is, therefore, biased toward cement due to the large surface area of grains coated by cement relative to the actual volume of that cement.

The fabric of samples from Unit C-2 is generally moderately open based on minus-cement porosity values ranging from 15% to 33%. Early carbonate cement has preserved significant intergranular space, and ductile framework grains, primarily mica, are only moderately deformed. Partial to complete replacement of some detrital grains and the presence of recrystallized detrital carbonate grains suggests that the minus-cement porosity values are maximum for these samples.

Authigenic Mineralogy

The primary mineralogy of sandstone samples has been moderately to substantially modified by precipitation of mineral cements and some replacement of framework grains. Early cementation apparently resulted in only minimal grain alteration in some samples while significant replacement of labile (unstable) grains in other samples suggests relatively advanced stages of chemical diagenesis.

Cements

Sandstones from Unit E-2 in the basal Upper "Red Clastic" Sequence contain up to 11% intergranular cements. The cements include, in variable proportions, quartz overgrowths, iron oxide grain coatings and inclusions, albite(?), and minor calcite. The precise amount of quartz cement was not determined because overgrowths could not be reliably distinguished from detrital quartz grains. Reddish iron oxide is common as inclusions especially in intergranular albite(?), making the petrographic identification of the albite cement equivocal. The paragenesis of these cements is quartz followed by calcite, minor oxide grain coatings, and finally albite(?) and additional iron oxide.

The cements in sandstones from Unit D-4 include both iron oxide and calcite. Calcite cement is volumetrically much less abundant than iron oxide grain coatings but does preserve areas with less compacted textures and minor grain coatings. The paragenesis of these cements is patchy early calcite followed by iron oxide grain coats.

Sandstones in Unit C-2 are dominated by calcite cement. The calcite occurs as minor isopachus grain rims, poikilotopic spar, and as an anhedral intergranular mosaic. Sandstones in this unit contain up to 33% intergranular calcite. This cement is clearly early and has preserved open framework grain packing textures.

Framework Grain Alteration

Sandstones in the "Red Clastic" sequence contain abundant chemically labile framework grains, especially plagioclase and K-feldspar. The labile grains contain varying proportions of alteration products as a function of the original composition of the grains, differing cementation histories and advanced stages of chemical diagenesis due to elevated subsurface temperature.

Sandstone samples from both Units E-2 and D-4 contain framework K-feldspar and plagioclase grains which exhibit significant alteration. The alteration is not uniform, however, and may be, in part, inherited from the precursor sediment. K-feldspar grains commonly contain small-scale intergrowths of albite(?) in a habit that is similar to perthite. More thorough alteration of K-feldspar is less common. Plagioclase grains in these two cores are commonly dusty in appearance, due to small inclusions, and contain patchy albite(?)-epidote-sericite alteration. Pressure solution textures in plagioclase grains are observed in association with more completely albitized grains. Other grain alteration, most common in Unit D-4, is the replacement or coating of mica grains by iron oxide.

Samples from Unit C-2 are characterized by less alteration of framework grains compared to overlying units although replacement/overlap by calcite is more common. The degree of alteration of individual feldspar grains is also more variable than in overlying units. Albite, epidote, and sericite alteration occurs in some grains but most feldspar grains are relatively unaltered. These relationships indicate the high original ratio of relatively unaltered grains to altered grains in Unit C-2 and may be representative of the amount of inherited grain alteration in overlying units in the well. The textural relationships in samples from Unit C-2 suggest that *in situ* feldspar grain alteration may have been inhibited by early carbonate cementation.

PROVENANCE

The modal compositions of sandstones from the "Red Clastic" Sequence in the Eischeid #1 well resemble sandstones from the Twin Cities Basin (Morey, 1972) and other portions of the Proterozoic section in the Midcontinent Rift province as summarized by Ojakangas (1986).

However, the sandstone modal composition of the samples from Eischeid #1 shows that lithic constituents were more abundant at shallow stratigraphic levels in contrast to the tendency for lithic constituents to decrease upward elsewhere in the "Red Clastic" Sequence (Ojakangas, 1986). No explanation of the reversed trend in composition can be made at this time. The compositions of the samples studied are plotted on a triangular diagram of quartz (total), feldspar, and lithic constituents (Fig. 1).

Superimposed on this diagram are the fields, based on sandstone modal composition, for provenance types in the plate tectonic settings of Dickinson (1984). The distribution of compositions from this study suggests that samples low in the section (Units C-2 and D-4) are near or within the field of continental block provenances while samples from Unit E-2 fall within the field for recycled orogen provenances.

The tectonic setting recently suggested by some workers (Dickas, 1986, Anderson, this volume) for the thick Proterozoic "red clastic" sequence in Iowa and elsewhere is a complex, arrested continental rift. The petrographic data from this study are, in part, consistent with an incipient rift belt provenance (Dickinson, 1984).

Geologic evidence suggests that the "recycled orogen" provenance indicated for the E-2 samples on Figure 1 is incorrect. This is apparently an example of the "error populations" in standard sandstone provenance studies described by Mack (1984).

The results of petrographic analyses of the E-2 samples from complex, arrested continental rift settings polotted on Q-F-L diagrams suggest that standard techniques to determine provenance do not distinguish between the complex, arrested rift setting and the recycled orogen setting. The former is not well represented on standard provenance diagrams.

ALTERATION IN BURIAL REGIME

Interpretation of the level of thermal alteration of samples based on the chemical diagenesis of sandstone samples are qualitative and tentative. Inherited alteration of labile detrital grains, particularly feldspars, is not easily distinguished from *in situ* diagenetic alteration. Also, early cements have probably diminished permeability and the transfer of mass by circulating aqueous fluids, thereby inhibiting equilibrium diagenetic alteration, especially in Unit C-2.

Detrital K-feldspar and plagioclase from the highest cored interval in Eischeid #1 (E-2) are apparently altered to the albite-epidote-sericite assemblage. This alteration mineral assemblage as well as the presence of albite(?) cement in feldspathic sandstones of Unit E-2 has been recognized in other sandstone suites as an indicator of "intermediate" levels of low-temperature thermal alteration by many workers (Boles and Coombs, 1975; Surdham and Boles, 1979; Surdam et al., 1989) and suggests minimum alteration temperatures of 80° to 130° C.

Complicating factors concerning the determination of thermal alteration in addition to early cementation and inhibited fluid circulation (as suggested above) must also be considered. Boles and Ramseyer (1989) suggest that the temperature window indicated by feldspar alteration, in particular albitization, is influenced by factors including the kinetics of feldspar dissolution, structural state and composition of feldspars, thermal histories, and stress-induced dissolution. Therefore, the determination of thermal regime based on the authigenic mineralogy in samples from the Eischeid #1 well remains subject to re-interpretation.

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PETROLEUM SOURCE-ROCK ASSESSMENT OF MIDDLE PROTEROZOIC (KEWEENAWAN) SEDIMENTARY ROCKS, EISCHEID #1 WELL, CARROLL COUNTY, IOWA

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ABSTRACT

Petroleum source-rock assessment has been made of the thickest section (14,100 ft; 4,298 m) of Precambrian sedimentary rocks sampled anywhere along the Midcontinent Rift System. Assessment is based on analysis of 40 core and cutting samples from the 17,851-foot (5,441 m) deep Amoco M. G. Eischeid #1 well, which was drilled in 1987 in a half-graben-like basin northwest of the medial horst, near the town of Halbur, Carroll County, Iowa. Underlying a 3,600-foot (1,100 m) thick Phanerozoic section of sedimentary rocks, the Precambrian rocks encountered consist of a 6,900-foot (2,103 m) thick Upper "Red Clastic" Sequence that resembles rocks of the Middle Proterozoic Bayfield Group in Wisconsin and a 7,200-ft (2,195 m) thick Lower "Red Clastic" Sequence broadly correlative to the Middle Proterozoic Oronto Group of Wisconsin. The Oronto and Bayfield groups are part of the Keweenawan Supergroup.

All of the rocks in the Upper "Red Clastic" Sequence and 80 percent of the rocks in the Lower "Red Clastic" Sequence are extremely lean in hydrocarbon-generating organic matter [total organic carbon (TOC) contents less than 0.1 percent and genetic potentials (S_1 + S_2) less than 0.1 mg HC/g rock], strongly implying no petroleum source rock potential now or in the geologic past. In sharp contrast to the above predominantly red, reddish brown, and green clastic rocks, a darker colored section, containing a cumulative thickness of 200 to 300 feet (60-90 m) of thin interbeds of medium- to dark-gray, and partly black, pyrite-bearing, laminated shale, occurs in the Lower "Red Clastic" Sequence at depths between 15,000 and 16,425 feet (4,570-5,006 m). This darker colored section is believed to be stratigraphically equivalent to the Nonesuch Shale of the Oronto Group of northern Michigan and Wisconsin.

These laminated shale beds are thermally overmature with respect to oil generation and are characterized by TOC contents as much as 1.4 percent (average 0.6), genetic potentials (S_1 + S_2) range from about 0.1 to 0.4 mg HC/g rock, hydrogen indices range from about 20 to 80 mg HC/g TOC, and extractable bitumen contents range from about 10 to 60 ppm. At present, these shale beds have no potential of generating commercial petroleum but may have generated significant amounts of hydrocarbons in the geologic past. Furthermore, we speculate that equivalent shale facies might have fair to good petroleum source-rock potential if present at shallower depths of burial, and so subject to lower levels of thermal maturity. The area along the basin flanks, away from the frontal fault zone of the medial horst offers a more favorable situation for petroleum potential.

INTRODUCTION

Extensive research and exploration have been directed toward evaluating the oil and gas potential of Precambrian Keweenawan rocks along the Midcontinent Rift System (Fig. 1). In recent years, one of the boreholes drilled to test the petroleum potential of Precambrian sedimentary rocks in the Midcontinent Rift System is the 17,851-foot (5,441 m) deep Amoco M. G. Eischeid #1 well completed in 1987 near the town of Halbur, Carroll County, west-central Iowa. The borehole was drilled in a flanking basin (Defiance basin) west of the medial Iowa Horst (Figs. 1,2). After drilling through approximately 3,600 feet (1,100 m) of Phanerozoic

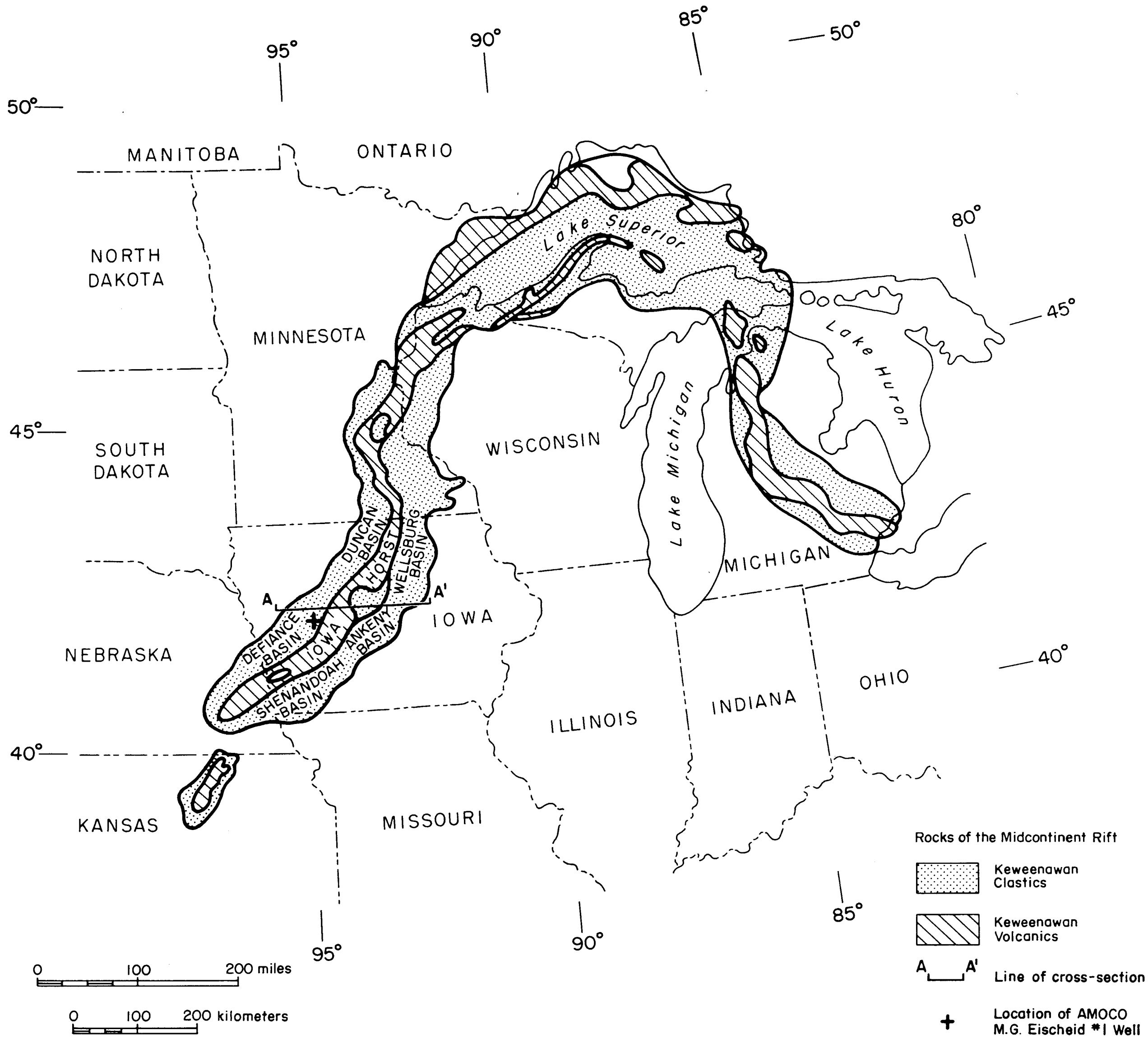

Figure 1. Map showing the general location and major rock types of the Midcontinent Rift System and the location of the Amoco M. G. Eischeid #1 well. Line A-A' indicates line of geologic cross section shown in Figure 2.

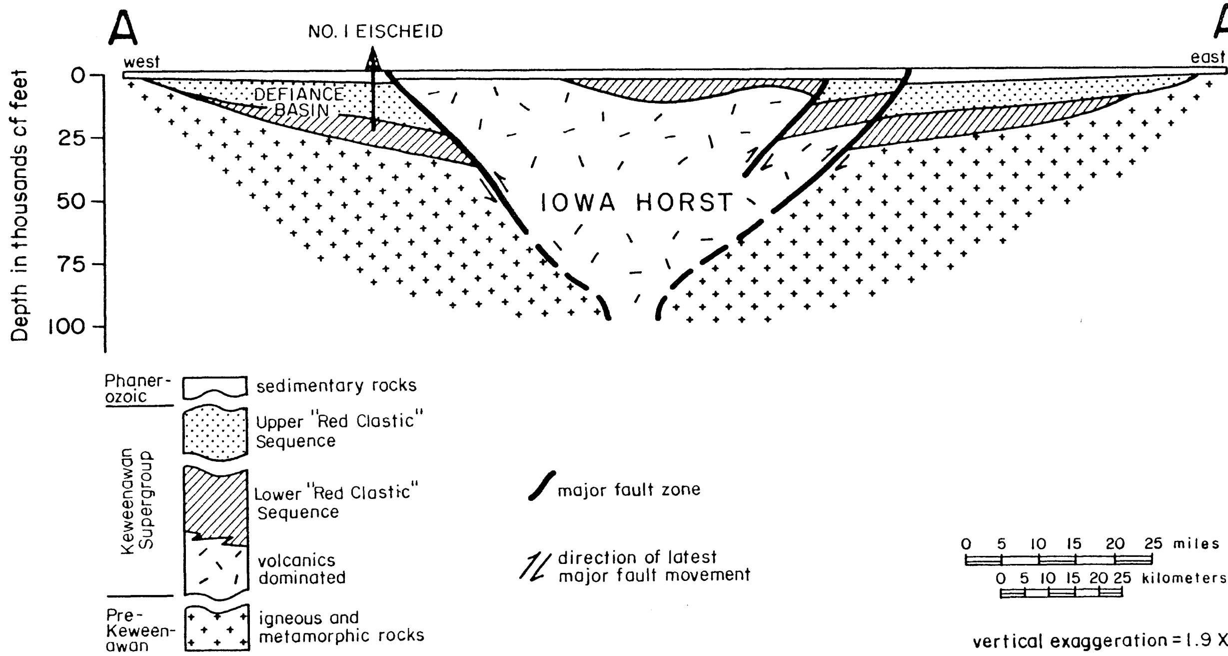

Figure 2. Schematic geologic cross section of the Midcontinent Rift System, central Iowa. Note approximate location of Amoco M. G. Eischeid #1 well with respect to Iowa horst. Location of cross-section is shown in Figure 1.

(mostly Paleozoic) rocks, the borehole penetrated 14,100 feet (4,300 m) of Precambrian unmetamorphosed clastic rocks. This is the thickest section of these rocks that has been sampled anywhere along the trend of the rift. The Precambrian rocks consist of a 6,900-foot (2,103 m) thick Upper "Red Clastic" Sequence broadly correlative with the Middle Proterozoic Bayfield Group of Wisconsin and a 7,200-foot (2,195 m) thick Lower "Red Clastic" Sequence broadly correlative with the Middle Proterozoic Oronto Group of Wisconsin (Fig. 3). The Oronto and Bayfield Groups have been assigned as part of the Keweenawan Supergroup (Goldich, 1968; Morey and Green, 1982). Below the Precambrian rocks, the Eischeid #1 well penetrated a little over 150 feet (46 m) of igneous rock before reaching total depth.

Factors that are commonly used in assessing the total petroleum potential of a sedimentary sequence are hydrocarbon source rocks, thermal maturity, reservoir rocks, timing of hydrocarbon generation, migration pathways, seals, traps, and structural style of tectonic evolution. This paper focuses on assessing the source-rock potential and maturation level of the Keweenawan rocks as sampled in the Eischeid #1 borehole. The only other detailed studies available to date that address the distribution and hydrocarbon-generating capacity of source beds of Keweenawan rocks of the Midcontinent Rift System are those by Imbus and others (1988) and Hieshima and others (1989) who evaluated the Nonesuch Shale of northern Wisconsin and Michigan and by Hatch and Morey (1985) who evaluated the Solor Church Formation of southeastern Minnesota. Earlier studies, such as by Barghoorn and others (1965), Eglinton and others (1966) and Johns and others (1966), focused on isolated rock and oil samples of the Nonesuch Shale in the White Pine copper mine district, northern Michigan.

GEOLOGIC SETTING

The Midcontinent Rift System is a failed rift that developed in the Midcontinent of North America about one billion years ago. The feature extends from the central Lake Superior region to east-central Kansas and is characterized over most of its length by a mafic volcanics-dominated axial

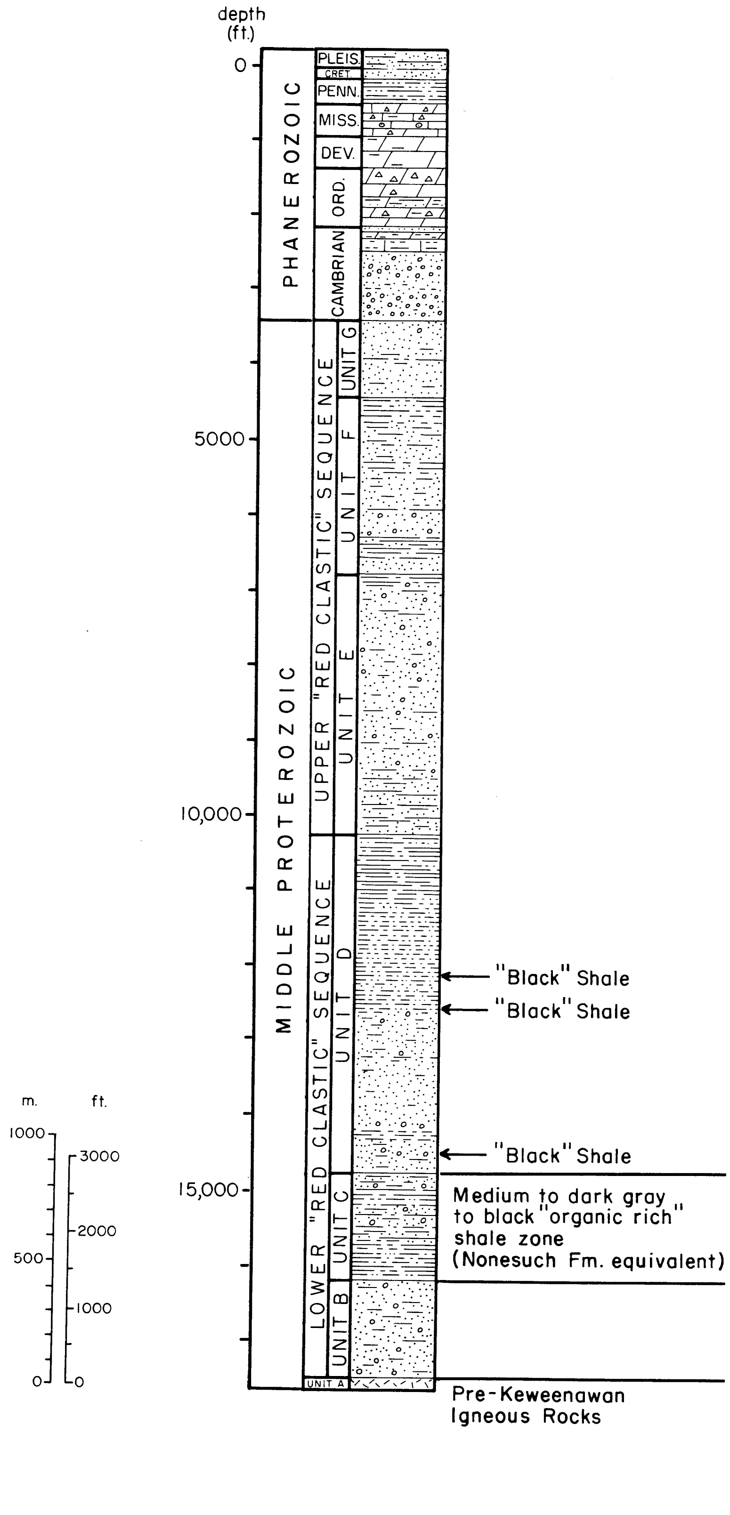

Figure 3. Generalized lithologic log of the Amoco M. G. Eischeid #1 well (modified after Witzke, this volume).

horst flanked by clastic-filled basins with a half-graben structure.

The rift system cuts across several Precambrian basement terranes. It is developed in the Archean greenstone-granite terrane (ca. 2600-2800 Ma) in the Lake Superior region, and granite-migmatite terrane (ca. 2600-3800 Ma) in southeastern Minnesota, as well as the Early Proterozoic Penokean volcanic belt (ca. 1850-1900 Ma) in Iowa, and the Central Plains orogenic belt (ca. 1600-1800 Ma) in Nebraska and Kansas. The Penokean volcanic belt and the Central Plains orogenic belt were subsequently intruded by two suites of anorogenic granitic rocks (and associated volcanic rocks) between 1500 and 1300 Ma, prior to rift formation.

In Iowa, the Midcontinent Rift System is dominated by the axial Iowa Horst (Fig. 2). The M.G. Eischeid #1 well penetrated the Proterozoic clastic rocks in the northern end of the Defiance basin, the western-most of the flanking basins north of the horst.

SAMPLES AND METHODS

Forty Precambrian and six Paleozoic (Cambrian to Pennsylvanian) drill cuttings (10 to 20 g) and core samples (50 to 150 g) were collected from the Eischeid #1 well for source-rock and/or thermal-maturity analyses. Depth intervals and generalized lithologic descriptions are given in Table 1. The cuttings had been prewashed in water to remove drilling mud residues. Binocular microscopic examination indicated little or no organic matter contaminants.

Sampling of Precambrian core material for source rock analyses was limited to two short core intervals, 15,096 to 15,120 feet (4601.3-4608.6 m) and 16,043 to 16,058 feet (4890-4894 m) (Fig. 3). Both core intervals are in the Lower "Red Clastic" Sequence believed to be equivalent to the Oronto Group which includes the Nonesuch Shale of Michigan and Wisconsin and the Solor Church Formation of Minnesota. The lower cored interval exhibited a high angle of dip, ranging from a low of 65.5° through vertical to slightly overturned; therefore, because of the uncertainties of establishing true depth and thickness of strata at depths of about 16,000 feet (4,875 m) and below, any evaluation of source-rock stratigraphic thickness in Unit C of the Oronto Group equivalent must be constrained.

The outer portions of the core samples, which contained variable amounts of greasy material (probably pipe dope or other heavy lubricants), were removed by a diamond saw, and the remainder of the cores were scraped exhaustively with a rotating steel brush. Small, representative chips, broken off from the core chunks by hammer, were ground with an agate mortar and pestle to a powder of about 100 to 150 mesh size and then submitted for Rock-Eval pyrolysis. Each remaining core chunk, prior to being ground to a powder in a Spex stainless steel ball mill apparatus, in preparation for Soxhlet chloroform extraction, was further cleaned by stirring in a chloroform bath for about one-half to one minute to remove any residual greasy material.

Petroleum source-rock characteristics, commonly defined by the quantity, quality, and degree of maturity of organic matter, were determined initially by the Rock-Eval II pyrolysis unit (Espitalié and others, 1977, 1985). The pyrolysis unit is also equipped with a module that determines total organic carbon (TOC) content, in weight percent of rock weight, which is a measure of the total organic matter content. Pyrolysis assay provides several basic measurements and calculated indices. The S_1 peak, expressed as mg hydrocarbons (HC) per gram of rock is related to the quantity of free hydrocarbons present in the rock, liberated by volatilization at 250° C. The S_2 peak (mgHC/g rock) is the amount of pyrolytic hydrocarbons produced mainly by cracking of kerogen during heating from 250° to 600° C, programmed at 25° C per minute. In effect, S_2 represents the residual amount of hydrocarbons that could be generated if the rock were subjected to additional thermal maturation. S_3 expressed as mgCO_2/g rock, records the quantity of carbon dioxide produced by pyrolysis of organic matter during the heating interval from 250° to 390° C. T_{max} (° C), used as a thermal maturity indicator, represents the temperature at the maximum rate of generation of hydrocarbons during pyrolysis of kerogen (T_{max} S_2).

The hydrogen index (HI), defined as the ratio of S_2 (pyrolyzable hydrocarbons) divided by TOC, and the oxygen index (OI), defined as the ratio of CO_2 yield divided by TOC, analogous to the atomic hydrogen/carbon and oxygen/carbon ratios, respectively, are used to evaluate type and maturity of kerogens. These indices are expressed in mgHC/g TOC and mgCO_2/g TOC, respectively.

The genetic potential, defined as the sum of the free hydrocarbons and pyrolyzable hydrocarbons, $S_1 + S_2$, is a measure of the total hydrocarbon-generating capacity of the rock. The ratio, $S_1/(S_2 + S_2)$, known as the production index (PI) or transformation ratio, is another indicator of thermal maturity as well as of oil staining.

Bitumen or extractable organic matter (EOM) was obtained by Soxhlet extraction with chloroform. Elemental sulfur was removed by refluxing with activated copper strips.

Kerogen substances, used for reflectance measurement of vitrinite-like particles, were isolated by a crush-and-float method described by Barker and Pawlewicz (1986).

ASSESSMENT OF SOURCE-ROCK POTENTIAL

Upper "Red Clastic" Sequence

The Upper "Red Clastic" Sequence of Precambrian age encountered in the Eischeid well, ranging in depths from about 3600 to 10,500 feet (1100-3200 m), has lithologies akin to those of the Middle Proterozoic Bayfield Group of the Keweenawan Supergroup (Anderson, "Review of Precambrian...," this volume). The sequence consists predominantly of red, reddish-brown, and, subordinately, green shale, silty shale, shaley siltstone, and arkosic sandstone. Total organic carbon content of the "red clastic" rocks is estimated to be less than 0.10 percent and the measured range is commonly between 0.01 and 0.05 percent (Table 1).

Because of the very low TOC contents, the Upper "Red Clastic" Sequence currently has no potential, nor had any potential in the geologic past to generate commercial quantities of oil and gas. Impoverishment of organic matter is attributed largely to the oxidizing conditions that prevailed in the depositional environments and possibly in part to thermal maturation. Attempts to determine levels of thermal maturity of the rock samples were in vain. Rock-Eval T_{max} measurements were totally unreliable due to the low S_2 values (≤ 0.15 mgHC/g; Table 1). The low TOC and oxidized nature of the organic matter, coupled with the small amounts of cuttings samples (≈ 15 g), precluded extraction of adequate amounts of bitumen from which molecular maturity indices could be obtained and isolation of sufficient kerogen particles for measurement of reflectance of vitrinite-like particles and atomic H/C ratios.

Lower "Red Clastic" Sequence (Units D and B)

The Lower "Red Clastic" Sequence of Precambrian age penetrated in the Eischeid well, broadly correlative with the Oronto Group of the Keweenawan Supergroup (Anderson, "Review of Precambrian...," this volume) and occurring at depths between 10,500 and 17,700 feet (3200-5393 m), is divided into three informal stratigraphic units: D, C, and B, listed in descending order (Fig. 3 and Witzke, this volume).

Units D and B, at depths of 10,500-15,000 feet (3200-4570 m) and 16,425-17,700 feet (5006-5395 m), respectively, which account for about 80 percent of the Oronto Group equivalent, consist of red clastic rocks not unlike the rocks of the overlying Bayfield Group equivalent. According to sample log descriptions, interspersed among the red clastic rocks are a few thin beds of dark gray or black shale. The location of these "black" shale beds is indicated in the right side of the columnar section of Figure 3. These darker shale beds were difficult to identify in the cuttings samples and to isolate for analysis due to dilution from cave-in material and from indigenous interbeds of lighter colored and more oxidized lithologies. Also included within the D and B units are two distinctive sandstone units, with a minimum cumulative thickness of about 1,720 feet (525 m), in which porosity evaluations were made by Schmoker and Palacas (this volume).

Geochemical analyses of representative samples (nos. S-20 to S-27 and S-49, Table 1) indicate that the fine-grained clastic rocks in the D and B units of the Oronto Group equivalent are lean in organic matter, having TOC contents less than 0.10 percent. As in the red clastic rocks of the Bayfield Group equivalent, these "red-colored beds" and other related non-source rock facies also have no source-rock potential for hydrocarbons. Again, no T_{max} or other maturity signatures were determined because of the very low organic-matter contents.

Table 1. Lithology and Rock-Eval Pyrolysis Data on Samples from Eischeid #1 Well, Carroll County, Iowa

[TOC = total organic carbon in weight percent; T_{max} = temperature at which yield of pyrolysis products (S_2) is at maximum; HI = hydrogen index, S_2/TOC, mgHC/g TOC; OI = oxygen index, CO_2/TOC, mgCO_2/TOC; PI = production index, S_1/S_1+S_2; S_1 = free hydrocarbons (HC), mgHC/g rock; S_2 = pyrolyzable HC, mgHC/g rock; S_3 = pyrolytic yield of CO_2, mgCO_2/g rock; — = data not reliable or not calculable; 1 foot = 0.3048 m; sh = shale; dol = dolomite; ls = limestone; ss = sandstone; slst = siltstone; lt = light; dk = dark; md = medium; gry = gray; grn = green; brn = brown; v.f. = very fine.]

Sample No.	Depth Interval Feet	Lithology (Age)	TOC %	T_{max} °C	HI	OI	PI	S_1	S_2	S_3
		Phanerozoic								
S-1*	520 - 540	coal, sh (Pennsylvanian)	61.73	415	211	46	.04	4.89	130.61	28.57
S-3	700 - 730	sh, dk, gry (Pennsylvanian)	6.90	424	148	40	0.06	.65	10.23	2.82
S-4	1,660 - 1,680	dol, lt gry (U. Ordovician)	.24	428	75	229	.18	.04	.18	.55
S-5	2,028 - 2,050	ls, lt gry (M. Ordovician)	1.03	439	588	131	.01	.06	6.06	1.35
S-7	2,900 - 2,920	sh, red & green (Cambrian)	.24	—	104	—	.48	.23	.25	—
S-8	3,150 - 3,180	sh, red & green (Cambrian)	.17	—	176	—	.44	.23	.30	—
		Middle Proterozoic - Upper "Red Clastic" Sequence ("Bayfield Group Equivalent") (Top ~3,600 ft)								
S-9	4,150 - 4,170	ss, slst, sh, red brn	.04	—	—	—	—	.04	.15	—
S-10	4,710 - 4,740	ss, slst, sh, red brn	.04	—	—	—	—	.03	.13	—
S-11	5,040 - 5,050	sh, slst, ss, red	.01	—	—	—	—	.01	.06	—
S-12	6,127 - 6,150	sh, slst, ss, dk red	.05	—	—	—	—	.03	.15	—
S-13	6,640 - 6,660	sh, slst, red	<.10**							
S-14	7,110 - 7,130	sh, slst, dk red	<.10**							
S-15	8,060 - 8,080	sh, slst, dk red	<.10**							
S-16	8,660 - 8,680	sh, slst, red, grn	.01	—	—	—	—	.01	.07	—
C-17	8,836.5 - 8,636.6	ss, brn, red	.03	—	—	—	—	—	—	—
S-18	9,260 - 9,280	sh, slst, dk red, grn	<.10**							
S-19	9,940 - 9,960	sh, slst, dk red, grn	<.10**							
		Middle Proterozoic - Lower "Red Clastic" Sequence ("Oronto Group Equivalent") (Top ~10,500 ft)								
			Unit D							
S-20	10,830 - 10,840	sh, slst, dk red, grn	<.10							
C-21*	11,387.5 - 11,387.6	slst, red, v.f.	.03	—	—	—	—	<.01	.02	—
S-22	12,420 - 12,440	sh, slst, dk red	.08	—	—	—	—	<.01	<.01	—
S-22A	12,840 - 12,870	sh, slst, red, brn, grn, gry	.08	—	—	—	—	.01	.02	—
S-23	13,360 - 13,380	sh, slst, red, brn, grn, gry	<.10**							
S-24	14,500 - 14,520	sh, slst, red, brn, grn, gry	<.10**							
S-25	14,590 - 14,600	sh, lt gry, red; ss, lt gry	<.10**							
S-26	14,600 - 14,610	sh, lt gry, red; ss, lt gry	<.10**							
S-27	14,750 - 14,770	sh, lt-md gry, red; ss, lt gry	<.10**							
			Unit C							
S-28	15,000 - 15,020	sh, lt-md gry, some ss	.22	—	—	—	—	.03	.06	—
C-28A	15,096.4 - 15,096.8	sh, dk gry, slst, pyrite	.79	506	45	22	.08	.03	.36	.18
C-29	15,097.4 - 15,097.6	sh, dk gry, slst, pyrite	.95	508	22	13	.05	.01	.21	.13
C-31	15,103.8 - 15,104.1	sh, md gry	.06	—	—	—	—	<.01	.08	—
C-32	15,106.3 - 15,106.5	sh, dk gry, slst, pyrite	1.40	508	26	5	.05	.02	.36	.08
C-34	15,109.0 - 15,109.1	sh, md gry	.05	—	—	—	—	<.01	.06	—
C-35	15,114 - 15,115	sh, dk gry	.42	497	40	40	.00	<.01	.17	.17
C-36	15,117.0 - 15,117.1	sh, dk gry	.27	498	77	44	.00	<.01	.21	.12
C-36A	15,117.1 - 15,117.2	sh, dk gry	.89	501	21	17	.18	.04	.19	.16
C-37A	15,199.9 - 15,120	sh, silty, lt gry	.05	—	—	—	—	.01	.10	—
S-38	15,270 - 15,290	sh, md gry, slst	.19	—	—	—	.10	.01	.09	—
S-39	15,540 - 15,570	sh, slst, red, some gry sh	.04	—	—	—	—	.05	.05	—
S-40	15,780 - 15,800	sh, slst, md gry; ss, lt gry	.09	—	—	—	.00	.00	.02	—
S-41	15,960 - 15,980	sh, slst, md gry; ss, lt gry	.12	—	25	—	.25	.01	.03	—
S-42	15,980 - 16,000	sh, slst, md gry; ss, lt gry	.10	—	20	—	—	.03	.02	—
S-43	16,030 - 16,040	sh, slst, lt to md gry	.17	—	11	—	—	.03	.02	—
C-44	16,043 - 16,045	sh, md dk gry to dk gry, slst	.10	—	40	—	.25	.01	.04	—
S-45	16,300 - 16,320	sh, md gry, slst	.21	—	23	—	.50	.04	.05	—
S-46	16,410 - 16,440	sh, md to dk gry, slst, ss	.07	—	—	—	—	.02	.04	—
			Unit B							
S-49	17,530 - 17,550	sh, red & gry	.04	—	—	—	—	.05	.05	—

*S = cuttings sample, C = core sample.

**TOC values based upon comparison with samples having the same color and lithology such as S-9,-10,-11,-12,-16,-22,-22A, and -49.

Lower "Red Clastic" Sequence (Unit C, Organic-Rich Unit)

Lithology and Thickness

In sharp contrast to the red- and reddish-brown-colored clastic rocks prominent throughout most of the Precambrian strata encountered in the Eischeid well, Unit C of the Oronto Group equivalent, at depths of 15,000 to 16,425 feet (4,570-5,006 m), is characterized predominantly by darker-colored, fine-grained rocks. The fine-grained rock types include pyrite-bearing, commonly laminated, partly calcareous shale and siltstone, with variable gradations between the two types, characterized chiefly by medium to dark gray and black colors and to a lesser extent light gray colors.

On the basis of petrographic analysis of thin sections from the 24-foot (7-m) core taken from 15,096-15,120 feet (4601.3-4608.6 m) (Ludvigson and others, this volume), shale makes up roughly 30 percent of the interval, siltstone 40 percent, and sandstone 30 percent. Interestingly, the wire-line logs, especially the neutron-density traces, do not clearly identify the sandstone beds primarily because they are much less than 4 feet (1.2 m) thick --a minimum requirement for adequate well-log resolution (Schmoker and Palacas, this volume). Of the shale beds examined in the 24-foot (7-m) core interval, the medium to dark gray laminated shale beds are estimated to make up about two-thirds of the cumulative shale thickness or about 20 percent of the entire core interval.

Should the proportions of rock types determined in the above core also apply to most of the strata in Unit C, it would follow that there would be at most about 300 feet (90 m), or conservatively about 200 feet (60 m), of the medium to dark gray to black laminated shale. The latter figure may be more reasonable in light of the presence of some interbeds of red clastics, but more so in light of the apparent misleading measurements of depth and thickness of strata in the lower part of Unit C due to significant hole deviations and the steeply dipping to overturned orientation of the beds. The remaining rocks, amounting to a maximum cumulative thickness of 1225 feet (373 m), would consist principally of light to dark gray siltstone, light gray shale, light gray sandstone, and subordinate amounts of red-colored clastic rocks.

Quantity and Quality of Organic Matter

Analyses of 9 cuttings samples (S-28 and S-38 to S-46), which represent the above "remaining rock types" (as much as 1,225 feet (373 m) in thickness), display very low TOC contents (average 0.13 percent) and very low genetic potentials (average 0.07 mg HC/g rock). These rock types, primarily siltstone and light-gray shale and sandstone, possess at present no hydrocarbon source-rock potential. The organic-matter contents are believed to be minimal due to high levels of thermal stress (discussed in the succeeding section). However, the very nature of these rock types--coarser grain sizes (siltstone, sandstone) and lighter colors, characteristics which normally reflect lower TOC contents--dictates against most of these rocks ever containing sufficient amounts of hydrogen-rich organic matter to generate economic quantities of petroleum. Of the above rock types, the only one that might have contributed significant amounts of hydrocarbons is the darker colored, possibly more organic-rich, laminated, shaley siltstone. However, samples of this rock type were not analyzed.

In contrast to the organically lean rock types described above, analyses of 8 core samples (C-28A to C-36A) show that the medium-to dark-gray laminated shale (200 to 300 feet (60-90 m) cumulative thickness in Unit C) contains total organic carbon as great as 1.4 percent and averaging 0.6 percent (Table 1). The TOC contents should also be considered as minimum values since the Rock-Eval pyrolysis unit, operating under limited temperature conditions (maximum 600° C), may not detect all refractory carbon material present in these overmature samples. According to previous studies by other laboratories, the minimum total organic carbon content for shale source rocks of petroleum is 0.5 percent, although some laboratories stipulate a 1.0 percent minimum (Tissot and Welte, 1984, p. 497). Therefore, based on the above minimum requirements of 0.5 percent TOC, the darker gray shale beds could be judged to have at least a marginal petroleum source-rock potential.

However, consideration of the genetic potential (S_1 + S_2), a measure of the quality or the hydrocarbon-generating capacity of the organic matter, yields a different evaluation. According to the classification scheme suggested by Tissot and Welte (1984, p. 513), genetic potentials less than 2 mg HC/g rock (2000 ppm) have no source potential for oil but some potential for gas. The genetic potential of the same 8 core samples (C28A-C36A) ranges from 0.07 to 0.39 and averages 0.22 mg HC/g rock. Thus, when the very low genetic potential is considered, these darker gray shale beds now have no oil or gas source potential. The hydrogen indices (HI), ranging from 21 to 77 and averaging 38 g HC/g TOC, also indicate little remaining hydrocarbon generating potential.

The minimum genetic potentials, hydrogen indices, and TOC contents are probably the consequence of high levels of thermal maturation. All in all, the data clearly indicate that the darker-colored, laminated shale beds at their present site, buried to depths of 15,000-16,425 feet (4,570-5,006 m) and subjected to high levels of thermal stress have no further hydrocarbon source-rock potential, but may have generated significant amounts of hydrocarbons in the geologic past. Furthermore, we speculate that equivalent shale facies might have good to excellent petroleum source rock potential if present at shallower depths of burial, under lower levels of thermal maturity, along the basin flanks, away from the frontal fault zone of the medial horst.

Some credence is lent to this speculation if we can assume that the medium to dark gray, laminated, partly calcareous shale beds of the "Oronto Group equivalent" in Iowa are equivalent in composition to the organic-rich, laminated, partly calcareous shale facies of the Nonesuch Shale in northern Michigan and Wisconsin. The shaley facies of the Nonesuch Shale are marginally mature to mature with respect to oil generation, and on the basis of limited data contain the following source-rock characteristics: TOC contents reading nearly 3 percent, genetic potentials of up to 11 mg HC/g rock and hydrogen indices as much as 500 mg HC/g TOC (Imbus and others, 1988; Hieshima and others, 1989; Hieshima, G.B., 1990, personal communication). Such characteristics indicate good potential for hydrocarbon generation.

INTERPRETATIONS

Thermal Maturity of Organic Matter

To evaluate the thermal maturity of organic matter in these Precambrian rocks, we employed several direct measurement techniques and one computational or predictive technique. This procedure was followed on the premise that using several techniques provides a greater level of confidence in defining precisely the level of maturation. The directly measured maturity indicators include: (1) the T_{max} index obtained by Rock-Eval pyrolysis, (2) reflectance measurement of vitrinite-like particles, (3) thermal alteration index (TAI) or visual color estimation of kerogen particles, (4) a bulk chemical parameter: ratio of extractable hydrocarbons to total organic carbon (HC/TOC), and (5) molecular (biomarker) indices: ratios of triaromatic to monoaromatic steroid hydrocarbons and low to high molecular-weight triaromatic steroids.

For the computational method we used Lopatin's (1971) time-temperature index of thermal maturity (TTI) as described by Waples (1980).

Direct measurement technique

In utilizing T_{max} as a maturity index, we observed that a minimum pyrolytic hydrocarbon yield of about 0.2 mg HC/g rock was required to obtain a well defined S_2 peak and hence a meaningful T_{max} value. Only six core samples, occurring at depths between 15,096 and 15,120 feet (4601.3-4608.6 m), met the above requirement. Analyses of these six samples (Table 1) showed T_{max} values ranging from 497° to 508° C and averaging 503° C. If 460-465° C can be considered the base of the window for oil generation, as suggested by Espitalié and others (1985), then a T_{max} of 503° C certainly indicates that the organic matter is overmature with respect to oil generation. The maturity level has advanced to at least the lower level of the wet gas zone and possibly has entered into the metagenetic or dry gas zone.

Interestingly, the maturity of the shale beds deeper than 15,000 feet (4570 m) is quite comparable to the level of maturity (T_{max} 494° C) of the broadly correlative mudstone beds of the Middle Proterozoic Solor Church Formation, southeastern Minnesota, which presently are at depths of only 2100-2800 feet (640-853 m) (Hatch and Morey, 1985). Although it is tempting to evoke a similar thermal history for both the Minnesota and Iowa fine-grained rock types, it is not warranted, not only because of lack of confirming geologic and geophysical data, but also because both rock sequences developed under different tectonic settings within the framework of the Midcontinent Rift System.

Table 2. Hydrocarbon (HC) content, thermal alteration index (TAI), and vitrinite-like reflectance data on samples from core interval 15,096-15,120 ft, Eischeid #1 well.

Sample number	Depth (ft)	HC ppm	HC/TOC mg/g	TAI	Vitrinite-like Reflectance (% R_o) Range	Average	N
C-29	15,097.4	27	3	3.5	2.03-2.76	2.4	11
C-32	15,106.3	46	3	~4.0	1.22-2.15	1.7	5
C-35	15,114.0	17	4	~4.0	—	—	—
C-36	15,117.0	7	3	~4.0	*	*	*
C-36A	15,117.1	nd	nd		1.90-2.30	2.1	2
					(weighted average) 2.2		

NOTE: HC = Sum of saturated and aromatic hydrocarbon estimated to be 80 (±10) % of the extractable organic matter (EOM) content; TOC = total organic carbon; TAI = thermal alteration index; N = number of measurements; --- = not detected; nd = not determined; 1 ft = 0.3048 m.

*Another population (with an R_o range 0.57-0.65%, mean 0.6%, n = 5), was also measured, but interpreted to be spurious due probably to drilling contaminants or low reflecting solid bitumen/pyrobitumen.

As another means of directly measuring maturity of indigenous organic matter, reflectance measurements were made on kerogen particles that resembled vitrinite. The question immediately arose as to the origin of these vitrinite-like particles, because woody vitrinite supposedly was not existent in pre-Silurian time (Gensel and Andrews, 1987; Gray, 1985). However, Buchardt and Lewan (in press) have provided rather strong evidence indicating that vitrinite-like particles do exist in the Cambrian Alum Shale of southern Scandinavia. They demonstrated that vitrinite-like particles, in their natural state and in their artificial state (i.e., when subjected to hydrous pyrolysis experiments), exhibit similar chemical and physical behavior to "suppressed type" vitrinites such as those in the Devonian and Mississippian black shale beds of the Midcontinent region. They suggest that the more hydrogen-rich suppressed type of vitrinite-like material is derived from organisms such as certain kinds of algae and fungi as opposed to the less hydrogen-rich, humic, woody types of vitrinite derived from vascular land plants rich in lignin. In short, Burchardt and Lewan (in press) concluded that traditional vitrinite reflectance measurements can also be effectively used to measure thermal maturation in pre-Silurian rocks.

If we can assume that most of the Precambrian vitrinite-like particles that were measured in the Eischeid well are comparable to those of the Alum Shale, the following results can be applied. Mean reflectance measurements of vitrinite-like particles in several core samples from the core interval 15,096 to 15,120 feet (4610.3 to 4608.6 m) range from R_o = 1.7 to 2.4% (Table 2). The weighted average R_o for the entire core interval, based on samples C-29, C-32, and C-36A, is 2.2%. This high reflectance value, consistent with the pyrolysis T_{max} data, also suggests that the organic matter, at depths of about 15,000 feet (4570 m) and below, is overmature with respect to oil generation and occurs at the transition between the wet gas and dry gas generation zones.

Some apparently anomalous vitrinite-like reflectance values were also obtained. In sample C-36 these anomalous measurements range from 0.57 to 0.67% and average 0.6% (n = 5). These values were not reported in Table 2 as they were judged to be unrealistic, due probably to measurement of either drilling contaminants or some low-reflecting solid bitumen or pyrobitumen.

Alternatively, if the high-reflecting organic particles identified (above) as vitrinite-like particles are indeed some form of dispersed solid bitumen or pyrobitumen, then some constraint may need to be applied. Jacob's (1985) comparative study of reflectance of solid bitumen versus reflectance of vitrinite macerals in the same sample for 139 different rock samples mainly from West Germany revealed the existence of a linear relationship, defined by the equation $R_v = 0.618\ R_s + 0.40$ (where R_v is the vitrinite reflectance and R_s the bitumen reflectance). In essence, Jacob showed that below a vitrinite reflectance of about 1.0 percent, solid bitumens show a lower reflectance than vitrinite and above the value a higher reflectance. Applying the above relationship to the Eischeid #1 Precambrian samples, an average reflectance of "solid bitumen/probitumen" of Rs = 2.2, according to the equation above, would indicate a vitrinite reflectance equivalent (VRE) value of 1.8 percent. In summary, taking into account both possibilities for the origin of the vitrinite-like particles, the results indicate that the mean VRE value for the organic matter at depths of 15,000 feet (4570 m) and below ranges between 1.8 and 2.2 percent.

In the absence of recognizable palynomorphs, thermal alteration index estimates, based on Staplin's (1969) classification, were made on the amorphous organic particles. Without exception, under transmitted light, the color of all the organic particles ranged from brownish-black to black, indicating a TAI of 3.5 to 4 (Table 2). Such TAI values strongly suggest a high level of thermal alteration, equivalent to the transition between wet gas and dry gas zones of hydrocarbon generation, again corroborating the previous two maturity determinations.

Thermal maturity was also determined using bulk and molecular indices of chloroform-extractable organic matter (EOM). One bulk chemical parameter commonly utilized is the ratio of hydrocarbons (HC) to TOC in mg/g, although the ratio of EOM/TOC applies equally well. HC/TOC ratios characteristic of the principal zone of oil generation or the "oil window" may be as much as 150 mg/g in Type I kerogen rocks--e.g., lacustrine Green River Formation rocks of Eocene age, Uinta basin, Utah (Tissot and Welte, 1984, p. 180); 120 mg/g in Type II-(I) kerogen rocks--e.g., Middle Proterozoic marine and lacustrine rocks, McArthur basin, northern Australia (Crick and others, 1988); and 75 mg/g in Type III kerogen rocks--e.g., Upper Cretaceous deltaic rocks, Douala basin, Cameroon (Albrecht and others, 1976). Regardless of the kerogen type, in all three basins the HC/TOC ratio falls dramatically below 10 mg/g when the organic matter has advanced to the overmature or gas-generation-zone phase of thermal maturation.

Using the above ratios as viable thermal maturity rankings, clearly the organic matter in the Precambrian rocks of the Eischeid well, at depths of about 15,000 feet (4570 m) and below, which exhibits HC/TOC ratios of about 3 mg/g (Table 2), has advanced well into the gas generation zone. In considering biomarker indices, the apparent thermal destruction of monoaromatic steroid and high-molecular-weight (C_{26}-C_{28}) triaromatic steroid hydrocarbons and prominent enrichment of low-molecular-weight aromatic steroids in the C_{20}-C_{21} region strongly suggest a high level of thermal stress beyond the main zone of oil generation (Mackenzie, 1984; Palacas and others, 1989).

Computational (predictive) technique

Previously, some of the geochemical indices of thermal maturity determined by direct measurement techniques were explored. Next, a computational index using the Lopatin TTI modeling method as described and evaluated by Waples (1980) will be examined.

TTI is calculated for a present-day depth of 15,200 feet (4,633 m) in the Eischeid #1 well, corresponding to the "organic-rich" zone, tentatively correlative with the Nonesuch Shale, upon which most of the geochemical data are based.

The assumptions of the three basic parameters--geothermal gradient, surface temperature and burial history--used to compute TTI are displayed graphically in Figure 4 and described briefly below. It must be emphasized that the burial and thermal reconstructions are somewhat poorly constrained and thus are subject to discussion and revision. However, the parameters seem reasonable and can be defended. They are consistent with known aspects of the rift system, the subsequent geologic history of the area, and the present-day thermal regimes.

The commonly used calibration between TTI and R_o (Waples, 1980) is based on rocks of

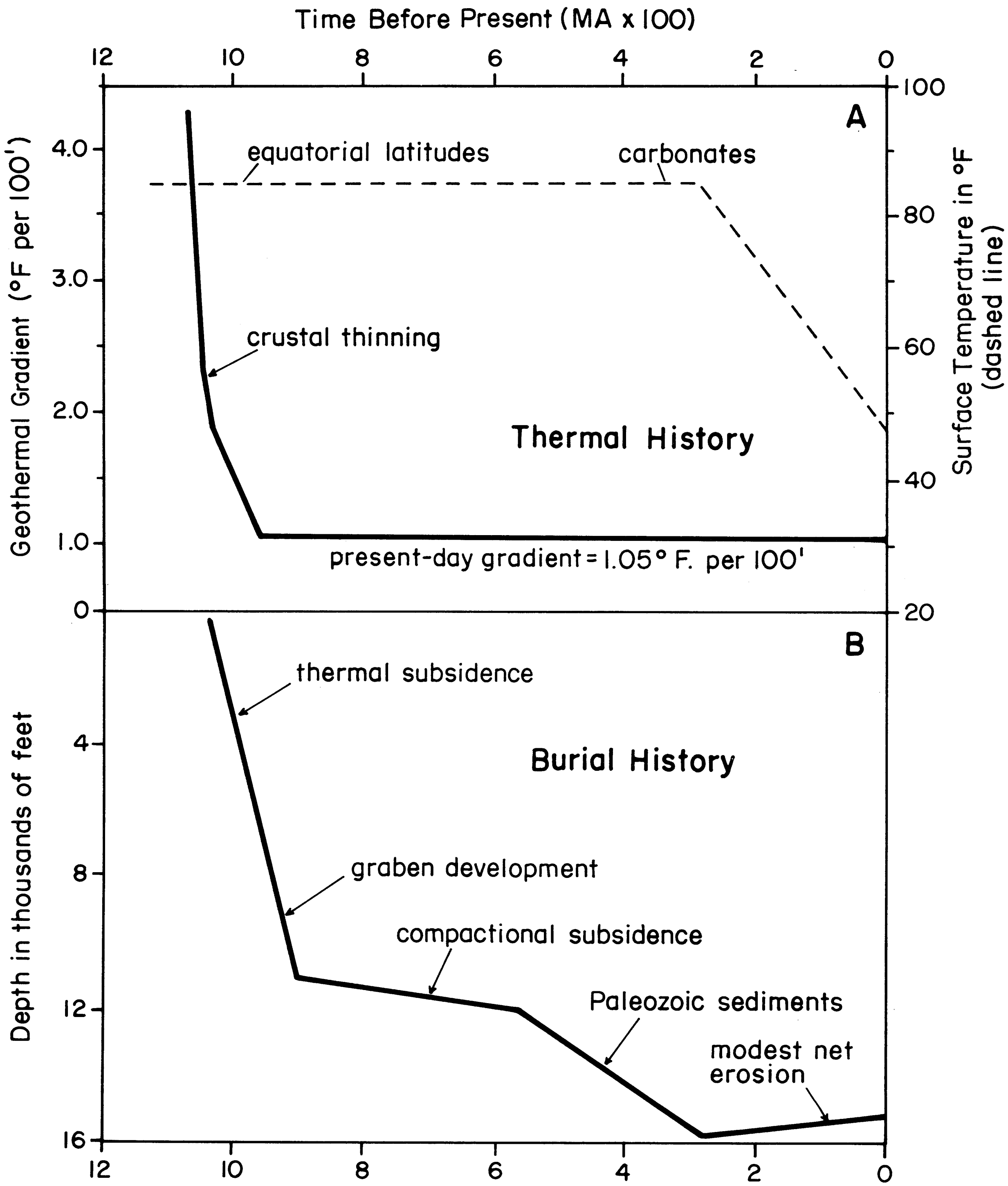

Figure 4. A) Thermal history reconstructions of the study area, west-central Iowa. B) Burial history reconstruction of the Nonesuch Shale equivalent in the Eischeid #1 well at a depth of 15,200 ft (4,633 m).

Paleozoic age and younger and thus may not properly represent the relative roles played by time and temperature in the ancient (1000 Ma) rocks studied here. For example, too much weight may be assigned to the time factor. Further uncertainty is also introduced for the overmature rocks under consideration due to the imprecise correlation between R_o and TTI for rocks of higher maturity levels (Katz and others, 1982; Waples, 1982). For these reasons, conclusions based on TTI calculations should be regarded as semi-quantitative, and yet we believe that Lopatin's approach offers insights that are of value and that are not available from direct maturity measurements made in the laboratory.

Geothermal gradient. The present-day geothermal gradient is assumed to be 1.05° F/100 ft (1.91° C/100 m) based on a present-day mean surface temperature of 47° F (8° C) and a corrected temperature of 206° F (96.7° C) at 15,200 feet (4633 m). As shown by the solid line in Figure 4A, the present-day, rather low, gradient is extended back in geologic time to 960 Ma, for lack of any evidence to the contrary. Between 960 and 1070 Ma, an increased thermal gradient is assumed due to higher heat flow associated with the rifting event. The heat pulse is modeled after calculations of Feinstein (1981), who examined the southern Oklahoma aulacogen.

Surface temperature. As stated above, the present-day mean surface temperature is 47° F (8° C) but in the geologic past it is assumed to have been higher (see dashed line in Fig. 4A). We have modeled it to be 85° F (29° C) in the Paleozoic, on the evidence of carbonate strata, which generally require warm waters for formation, and also at 85° F (29° C) in the Precambrian, on the evidence of paleomagnetic reconstructions showing the area to have been in equatorial latitudes at approximately 1000 Ma (Halls and Pesonen, 1982; Van Schmus and others, 1982). The straight line connecting these two time periods ignores possible surface-temperature fluctuations and is thus idealized to some extent.

Burial history. We assumed the Nonesuch Shale equivalent to be about 1040 million years old, as summarized by Hatch and Morey (1985) and Van Schmus and others (1982). Initial subsidence of the Oronto Group equivalent was rapid due to cooling and thermal subsidence during and after the rifting episode (Fig. 4B). Burial continued rapidly with deposition of the overlying Bayfield Group equivalent in response to horst and graben development and sediment loading by material shed off the horst. A quiescent period followed, which included minor increases in depth of burial due to compaction of the underlying sediment accumulation. Laterally extensive Paleozoic sedimentary rocks give evidence of regional subsidence not related to the rift system. Finally, we assumed 600 net feet (180 m) of erosion from Paleozoic time to the present.

Table 3. Results of TTI modeling of "Nonesuch Shale equivalent" at 15,200 ft.

Present depth = 15,200 ft (4,633 m)	
TTI = 1,092; Equivalent R_o = 2.1% (Waples, 1980; Wood, 1988)	
Onset of oil generation:	~900-950 Ma
Peak of oil generation:	~750-850 Ma
End of oil generation:	~600-700 Ma

The results of the time-temperature modeling technique are summarized in Table 3. The calculated TTI based on the above geologic parameters is equivalent to a vitrinite reflectance of approximately 2.1%, in excellent agreement with the geochemical indicators of thermal maturity. The TTI calculation suggests that the oil window spanned a substantial time period commencing about 900-950 Ma, reaching peak generation approximately 800 Ma, and terminating near the end of Precambrian time. If these calculations are reasonably correct, then it implies that development of traps for oil generated by the interval modeled would need to have occurred prior to roughly 800 Ma. The above calculations and results apply specifically to the rocks in the Eischeid well and vicinity.

SUMMARY AND CONCLUSIONS

Petroleum source-rock evaluations of 14,100 feet (4298 m) of Precambrian (Keweenawan) sedimentary rocks penetrated by the Amoco M. G.

Eischeid #1 well, Carroll County, Iowa, are summarized below:

- Except for a 1425-foot (435 m) thick dark colored clastic section within the Lower "Red Clastic" Sequence, the Precambrian rocks, including all those in the Upper "Red Clastic" Sequence and in most of the Lower "Red Clastic" Sequence, contain less than 0.1 percent TOC, strongly implying no hydrocarbon source rock potential now or in the geologic past.

- The 1425-foot (434 m) dark-colored section, possibly equivalent to the Nonesuch Shale of Wisconsin and Michigan, however, is characterized by a cumulative thickness of about 200 to 300 feet (60-90 m) of thin interbeds of medium to dark gray to black, pyrite-bearing, slightly calcareous, laminated shale.

- Five geochemical maturity indicators and one computational (TTI) maturity parameter, in concert, strongly suggest that the laminated shale beds are overmature with respect to oil generation and are at the transition between the wet gas and dry gas phases of thermal evolution.

- In these shale (or mudstone) beds, TOC contents average 0.6 percent but reach as much as 1.4 percent; genetic potentials range from about 0.1 to 0.4 mg HC/g rock (average 0.22 mg/g), hydrogen indices range from about 20 to 80 mg HC/g TOC (average $\approx$40 mg/g), and chloroform extractable bitumen ranges from about 10 to 60 ppm (average 30 ppm).

- The above geochemical parameters indicate that the laminated shale beds at their present site have no potential of generating commercial petroleum but may have generated significant amounts of hydrocarbons in the geologic past.

- We speculate that equivalent shale facies might have fair to good petroleum source-rock potential if present at shallower depths of burial, under lower levels of thermal maturity, along the basin flanks, away from the frontal fault zone of the medial horst.

- TTI calculations suggest that the oil window reached peak generation approximately 800 Ma. If this scenario is tenable, it means that development of traps for oil generated by the interval modeled would need to have occurred prior to roughly 800 Ma.

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POROSITY OF PRECAMBRIAN SANDSTONES IN LOWER PORTION OF THE EISCHEID #1 WELL, CARROLL COUNTY, IOWA

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ABSTRACT

Sandstone comprises a minimum of 1,721 net feet (525 m), or 29%, of the interval in the lower part of the Eischeid #1 well between 11,450 and 17,340 ft (3490-5285 m). Sandstone is distinguished from the siltstone and shale that make up the remainder of the interval by the character of photoelectric-absorption, density-porosity, and neutron-porosity log traces and, secondly, according to lithologic descriptions prepared from well cuttings. These arkosic sandstones are thought to be some 1,000 Ma and broadly correlative with the Middle Proterozoic Oronto Group of the Keweenawan Supergroup.

Sandstone porosity below 11,450 ft (3,490 m), as determined from compensated density and neutron logs, ranges between one and six percent and averages only 2.3%. Greater porosity of 3.5% or more does not correlate with depth, a particular sedimentary cycle, or the reported presence of "intergranular black residue." However, thorium/potassium ratios derived from the spectral gamma-ray log are higher in intervals of greater sandstone porosity than in intervals of lesser porosity, suggesting that greater porosity may possibly be related to feldspar diagenesis.

INTRODUCTION

The Amoco M.G. Eischeid #1 well, located 75 miles (120 km) west-northwest of Des Moines in Carroll County, Iowa, was drilled in 1987 to test the petroleum potential of sedimentary rocks of the Precambrian Midcontinent Rift System. The well penetrated approximately 3600 ft (1100 m) of Pleistocene, Cretaceous, and Pennsylvanian to Cambrian strata, 14,100 ft (4300 m) of unmetamorphosed Middle Proterozoic clastic sedimentary rocks, and over 100 ft (30 m) of gabbro and related mafic rocks before reaching total depth at 17,851 ft (5441 m).

This paper focuses on the porosity of sandstones in the lower part of the Eischeid #1 well between depths (corresponding to logging run #3) of 11,450 and 17,340 ft (3490-5285 m). The sandstones, siltstones, and shales in this depth interval are preserved in a half-graben (Defiance Basin) on the northwest side of the medial Iowa Horst (Dickas, 1986; Chandler and others, 1989) and are broadly correlative to the Middle Proterozoic Oronto Group of the Keweenawan Supergroup (Anderson, "Review of the Precambrian...," this volume).

The deeply buried sandstones studied here are thought to be roughly 1000 Ma, based on evidence summarized by Van Schmus and others (1982) and by Hatch and Morey (1985). Diagenetic processes associated with burial have acted upon these sandstones for roughly twice the length of time represented by the Cenozoic, Mesozoic, and Paleozoic eras combined.

The present study is based primarily on wire-line logs. Sandstone is distinguished from siltstone and shale according to the character of the photoelectric-absorption, density-porosity, and neutron-porosity log traces, with secondary confirmation of rock type based on lithologic descriptions prepared from well cuttings. Sandstone porosity is determined from the compensated density and neutron logs. No laboratory porosity measurements are available to confirm the electric-log interpretations; visible porosity on thin sections tends to be lower than that derived from the electric logs (Ludvigson and others, this volume). The distribution of sandstone porosity in the interval of investigation is presented, and porosity variations are discussed in terms of possible causal factors.

CRITERIA FOR SELECTING SANDSTONE INTERVALS

The sedimentary rocks in the lower part of the Eischeid #1 well range in a continuum from shale through siltstone to sandstone. "Sandstones" of this report represent an end member of this series and are selected according to the following log-based criteria:

1) Sandstone thickness must be at least 4 ft (1.2 m), which is the lower limit for adequate well-log resolution. Thin sandstones are thus not included in the data set of this paper.

2) Wellbore rugosity, which can distort log responses, must be minimal, as indicated by the caliper and density-compensation traces. Most zones rejected because of borehole rugosity appear to have lithologies of siltstone or shale.

3) The photoelectric-absorption cross-section (Pe, in barns per electron) must be less than 3.0. Pe is a non-linear measure of atomic number and thus varies with the atomic composition of minerals. The Pe of quartz is 1.81 whereas that of feldspar, clays, and micas is higher, ranging between roughly 2 and 6; Pe for "dirty sandstone" is approximately 2.7 and that for "average shale" is approximately 3.4 (Schlumberger, 1986, 1987). Pe for the sandstone intervals selected here ranges between 2.0 and 2.9 and averages 2.4. In the clastic sequence of the Eischeid #1 well, such values are indicative of quartz-rich but arkosic, and possibly lithic sandstones.

4) Apparent sandstone porosity of the neutron log and of the density log must be in close agreement. Such agreement indicates that log-sampled properties of an interval match those of sandstone, and, in addition, offers evidence that clays and micas are a minor component of the rock. Clays and micas tend to be more dense than quartz and feldspar, and incorporate water and hydroxyl components that are detected as porosity by the neutron log but not by the density log.

Litho-density/compensated-neutron log responses typical of the clastic sequence in the lower part of the Eischeid #1 well are reproduced in Figure 1. The criteria listed above appear to quantitatively isolate the intervals identified here as sandstone. The lithologic log prepared from well cuttings lacks the sharp definition of *in situ* log measurements, but generally supports log-based lithology identifications as illustrated in Figure 1.

Sandstones of the Oronto Group and its equivalents tend to be mineralogically immature and may contain appreciable volumes of feldspar and volcanic rock fragments (Morey, 1972, 1977; Dickas, 1986; Ludvigson and others, this volume). The term "arkosic" is often used by investigators in describing these rocks (Dickas, 1986).

In the present case, gamma-ray intensity is not a reliable criterion for identifying sandstones because gamma-ray values vary with both the clay content of siltstones and the feldspar and heavy-mineral content of sandstones. Gamma-ray intensity for the sandstone intervals selected here ranges between 35 and 150 API units and averages 82 API units. Subjective examination of the spectral gamma-ray log indicates that much of the variation of gamma-ray intensity in sandstone intervals is due to variations in thorium and potassium content, as opposed to uranium content.

Application of the log-based selection criteria described above is thought to result in the retention of most arkosic sandstones (Berendsen and others, 1988, their Table 3). Log responses of sandstones containing abundant volcanic rock fragments are more uncertain. However, basalt typically has a high density, high Pe, and high apparent neutron porosity (Berendsen and others, 1988). Sandstones with significant percentages of mafic volcanic grains would not be recognized by application of the log criteria adopted here.

DISTRIBUTION OF SANDSTONES

Sandstones selected according to the criteria described above have a cumulative thickness of 1721 feet (525 m), or 29% of the interval of investigation between 11,450 and 17,340 ft (3490-5285 m). Selected sandstone intervals are plotted as a function of depth in Figure 2. These sandstones are not uniformly distributed, but reflect large-scale episodic deposition that is presumably related to the tectonic evolution of the Midcontinent Rift System.

The strata in the lower portion of the Eischeid #1 well are significantly deformed in places, and commonly are steeply dipping. In consequence, depths and thicknesses measured with reference to the wellbore could possibly give a misleading impression of the sedimentary sequence.

An upper zone (Fig. 2) between 12,880 and 14,214 ft (3926-4332 m) contains a cumulative thickness of 782 feet (238 m) of sandstone. A lower zone between 16,439 and 17,340 ft (5011-5285 m)

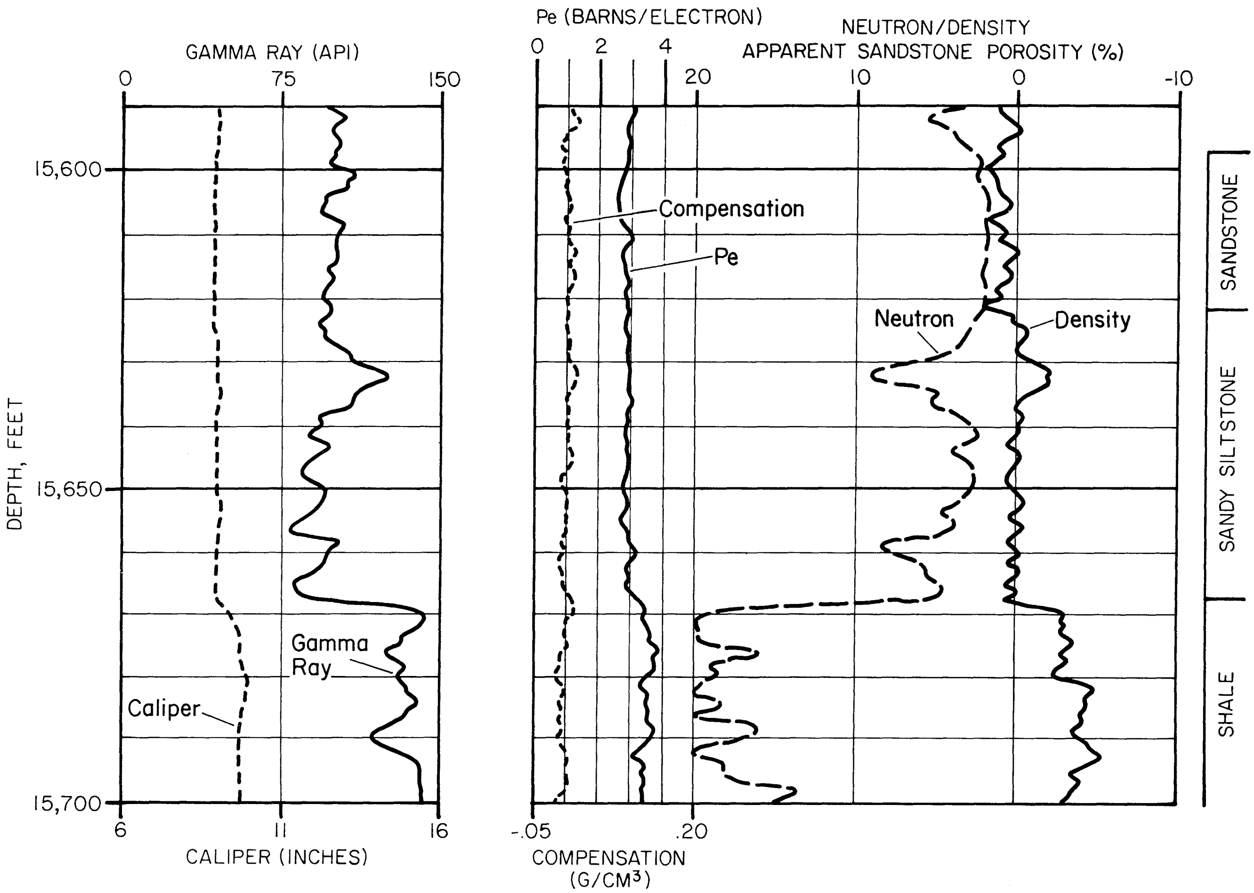

Figure 1. Log responses typical of the clastic sequence in the lower part of Eischeid #1 well. Pe is photoelectric-absorption cross-section. Sandstone intervals are selected on basis of thickness equaling 4 ft (1.2 m) or more, minimal borehole rugosity as shown by caliper and density-compensation traces, Pe less than 3.0, and close agreement of neutron-porosity and density-porosity traces.

contains a cumulative thickness of 738 feet (225 m) of sandstone. Thinly bedded sandstones are not included in these totals. The upper and lower sandstone zones together make up only 38% of the total interval of investigation but include 88% of the identified sandstone.

Hatch and Morey (1985) characterized major sedimentary cycles in the Oronto Group as fining-upward sequences marked by an upward increase in the thickness of finer-grained rocks. The upper sandstone zone together with the scattered sandstone intervals above it evidence such a fining-upward major cycle (Fig. 2). However, the upper termination of the lower sandstone zone is abrupt and does not reflect a fining-upward character similar to that of the upper sandstone zone.

The upper sandstone zone includes a few green or grey shales but is generally oxidized, characterized by reddish and brown colors. The lower sandstone zone includes grey and black shales and is described by colors such as light to medium grey, greenish, and olive-green, as well as by the reds and browns indicative of an oxidizing environment. The mud-logging unit detected traces of methane and ethane in portions of the lower sandstone zone, and some sandstones of the lower zone contain a bitumen- or pyrobitumen-like material described as "intergranular black residue." The upper and lower sandstone zones are

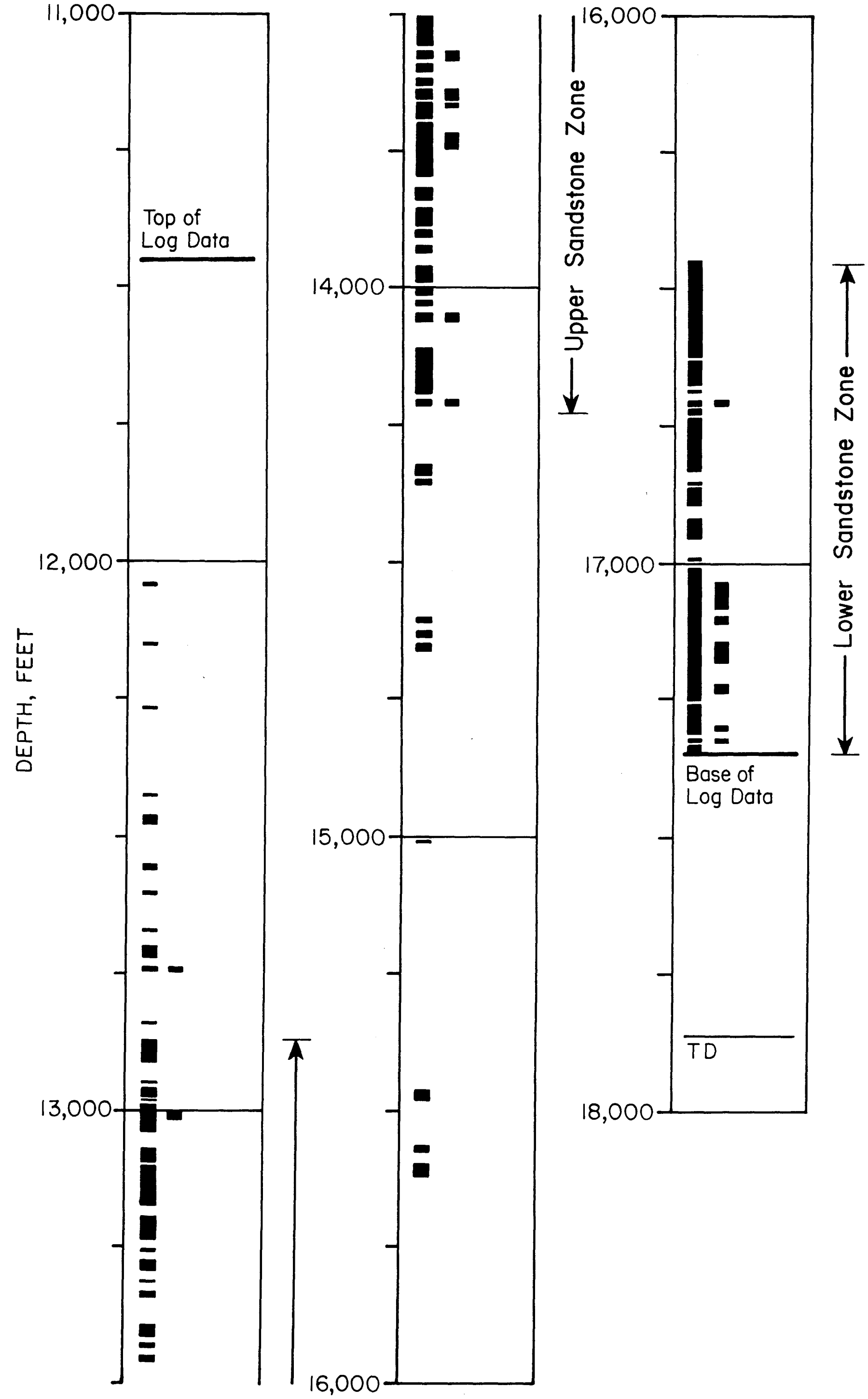

Figure 2. Occurrence of sandstone intervals with thickness of 4 ft (1.2 m) or more in lower part of Eischeid #1 well. Shaded intervals of first column mark sandstones; shaded intervals of second column mark sandstones with porosity greater than or equal to 3.5%.

separated by a thick, dark-colored shaley sequence containing organic carbon (Palacas and others, this volume) that is perhaps equivalent to the Nonesuch Shale of northern Wisconsin and Michigan.

SANDSTONE POROSITY

Sandstone porosity is measured here as the average, to the nearest one-half percent, of the neutron-porosity and density-porosity traces. The histogram of sandstone porosity for all selected sandstones between 11,450 and 17,340 ft (3490-5285 m) and the 10th, 25th, 50th, 75th, and 90th percentiles of this distribution are shown in Figure 3. Sandstone porosity ranges from 1 to 6% and averages 2.3%. The porosity distribution is skewed (Fig. 3), with only 14% of net sandstone thickness having a porosity of 3.5% or higher.

The distribution of sandstone porosity in the upper zone is essentially identical to that in the lower zone (Fig. 4). As discussed in the preceding section, the lower sandstone zone may be less oxidized than the upper sandstone zone. The lower zone also contains traces of light hydrocarbons and possibly bitumen or pyrobitumen. However, these differences seemingly did not significantly influence porosity evolution, as evidenced by the nearly identical porosity distributions of the two sandstone zones (Fig. 4).

HIGHER POROSITIES (3.5-6%)

Sandstone porosity in the lower part of the Eischeid #1 well, while generally very low, varies by a factor of six. Wire-line data are used here in a search for properties that differentiate the intervals of "better" porosity from the majority of sandstones. (No core was taken in the two sandstone zones.) Better porosity is defined as that between 3.5 and 6%.

Intervals of higher porosity are plotted as a function of depth in Figure 2. All but 6 ft (2 m), which occurs at a depth of 12,746 ft (3885 m), are within the upper or lower sandstone zones. A cumulative thickness of 109 ft (33 m) of higher porosity, averaging 4.3%, occurs in the upper sandstone zone. A cumulative thickness of 127 ft (39 m) of higher porosity, averaging 4.4%, is present in the lower sandstone zone. Higher porosity is evenly distributed between the upper and lower zones, and therefore is not linked to depth, a particular sedimentary cycle, the presence in the lower zone of hydrocarbons in trace amounts, or to other possible systematic differences between the upper and lower zones.

Feldspars can play major roles in processes of burial diagenesis and thus affect porosity evolution in the subsurface. The sandstone intervals selected here are assumed to include only minor amounts of clays and micas, because apparent sandstone porosities of the neutron log and of the density log are required to be in close agreement. Potassium content as measured by the spectral gamma-ray log may thus reflect K-feldspar content, and thorium content may reflect total feldspar content, in that other common aluminosilicate minerals that carry thorium (Macfarlane and others, 1989) are assumed to be minor components of the sandstones. Thorium can also be associated with heavy detrital minerals (Schlumberger, 1986).

In the lower sandstone zone, sharp fluctuations in thorium content, as shown by a spectral gamma-ray log may reflect, in part, the erratic presence of heavy detrital minerals in the basal sands of the rift system. In the upper sandstone zone, variations in thorium content seem more systematic. Intervals of higher porosity in the upper sandstone zone have an average thorium content of 7.1 ppm and an average potassium content of 2.6%. In contrast, the intervals of lowest porosity (1-1.5%) in the upper sandstone zone have an average thorium content of 5.4 ppm and an average potassium content of 2.5%. Taken as a whole, these spectral-log values are consistent with those of arkosic sandstones (Berendsen and others, 1988).

Potassium content and, by inference, K-feldspar content do not differ significantly between intervals of higher and of lowest porosity in the upper sandstone zone. However, thorium content is higher in the intervals of higher porosity. The interpretation of this finding is not straightforward. If, however, thorium content does in fact correlate to total feldspar content in these sandstones, as just discussed, an increased feldspar content for zones of higher porosity can be inferred. Furthermore, if K-feldspar content remains approximately constant, the increase is due largely to plagioclase feldspar. At any rate, the spectral-log data suggest that higher porosity in the sandstones studied here may possibly be linked to diagenesis involving feldspar. It should be emphasized that this inferred link is tenuous and based on speculative log interpretations.

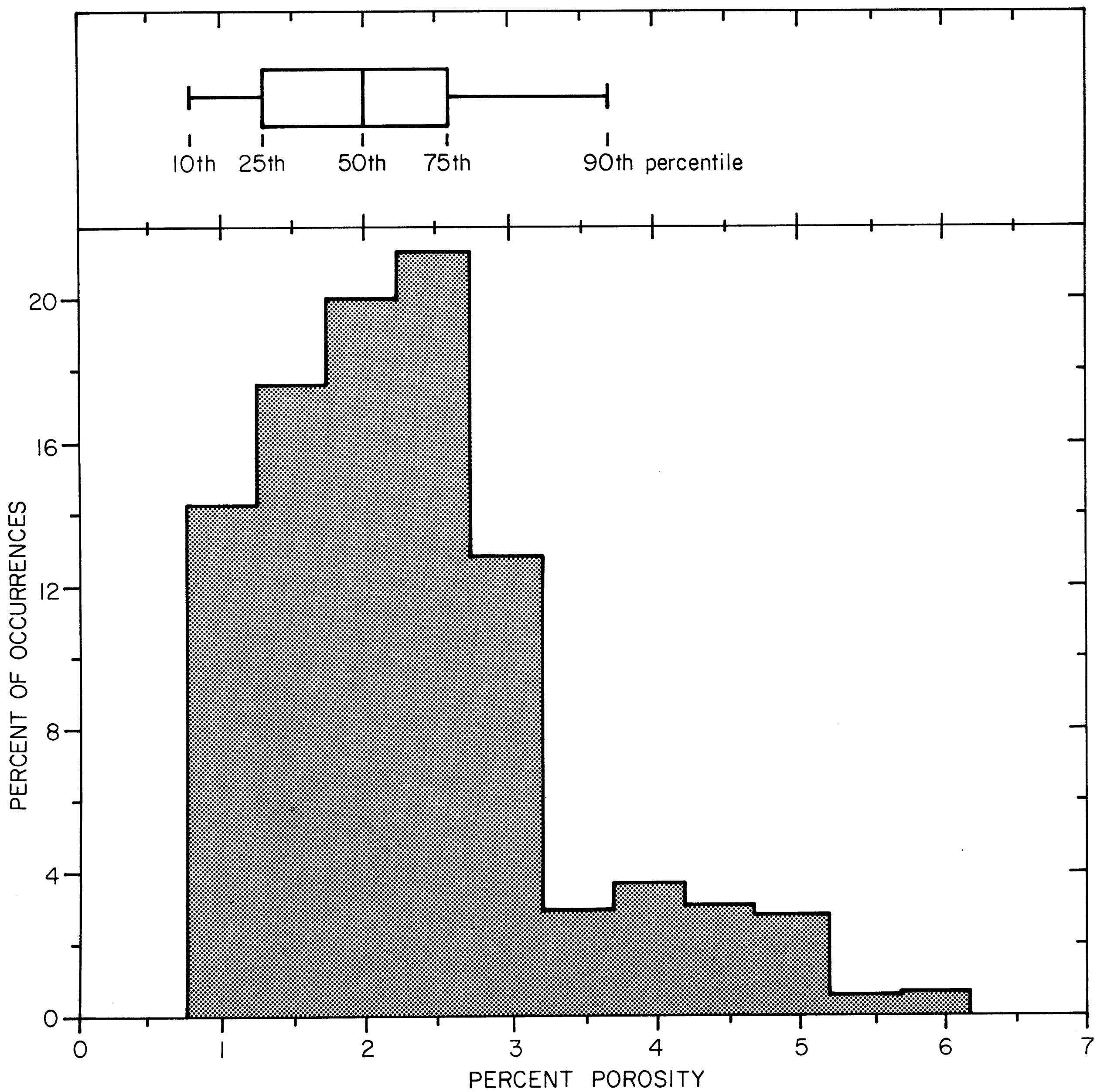

Figure 3. Porosity histogram for sandstones between 11,450 and 17,340 ft (3,490-5,285 m) in lower part of Eischeid #1 well. The 10th, 25th, 50th, 75th, and 90th percentiles of porosity distribution are shown by the box diagram at the top of the figure. Log-derived porosities are weighted according to interval thickness, so that the distributions reflect net-feet of a given porosity class rather than number of occurrences.

DISCUSSION AND CONCLUSIONS

Sandstones are common in the lower part of the Eischeid #1 well and comprise at least 29% of the interval between 11,450 and 17,340 ft (3490-5285 m). The sandstones studied here, which have a thickness of 4 ft (1.2 m) or more, occur in two distinct zones which are separated by a thick shaley section that may be equivalent to the Nonesuch Shale of northern Wisconsin and Michigan.

Sandstone porosity ranges between 1 and 6% and averages 2.3%. Only 14% of net sandstone thickness has porosity of 3.5% or higher. Thus, most if not all of the sandstones in the interval of investigation are not good reservoir rocks.

The one-billion year old sandstones studied here are exceedingly ancient by the norms of petroleum geology. Nevertheless, the electric-log data indicate that the reduction of porosity by burial diagenesis has not gone to completion. Tenuous evidence, based on the thorium and potassium contents indicated by the spectral gamma-ray log, suggests that the higher porosities measured here may be linked to diagenesis involving feldspar.

Sandstone porosity decreases during burial as the result of mechanical rearrangement and deformation of framework grains and the chemical modification and relocation of mineral components. These processes are extremely complex and have been described but not quantified in the literature. In the final analysis, however, all subsurface processes affecting porosity are dependent, at least in part, upon time and temperature. Porosity has been observed to decrease in the subsurface as a power function of increasing time-temperature exposure (Schmoker and Gautier, 1988, 1989).

The level of thermal maturity in the lower part of the Eischeid #1 well is classified as overmature with respect to oil generation (Palacas and others, this volume). The average porosity of Phanerozoic sandstones at this high level of thermal maturity is quite low (Schmoker and Gautier, 1989). The porosity of Middle Proterozoic sandstones measured in the lower part of the Eischeid #1 well is more or less in accord with that of much younger sandstones at equivalent levels of time-temperature exposure.

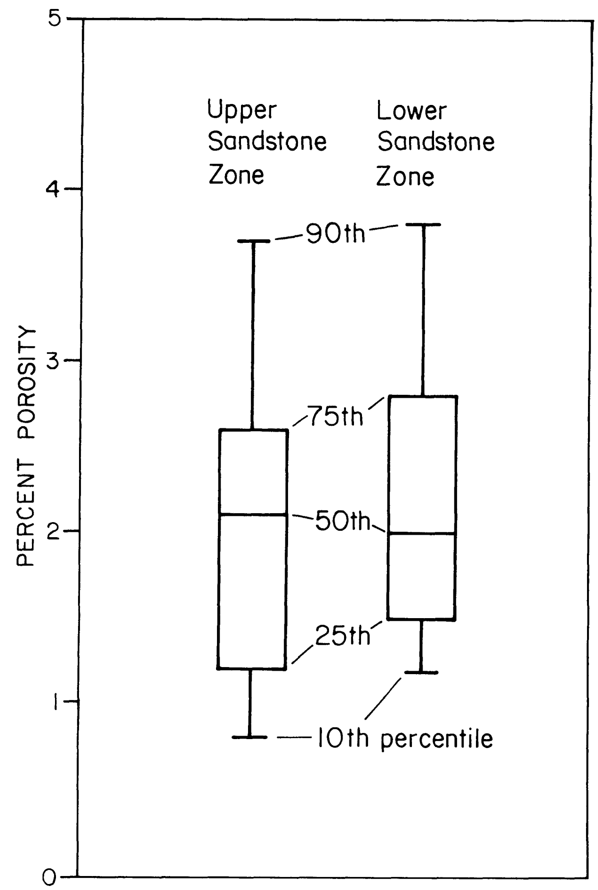

Figure 4. Box diagrams showing 10th, 25th, 50th, 75th, and 90th percentiles of porosity distributions for sandstones of upper and of lower sandstone zones (Fig. 2). Log-derived porosities are weighted according to interval thickness, so that distributions reflect net-feet of a given porosity class rather than number of occurrences.

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CLAY MINERALOGY AND BULK ROCK COMPOSITION OF SELECTED CORE AND CUTTING SAMPLES FROM THE AMOCO EISCHEID #1 WELL, CARROLL COUNTY, IOWA--A RECONNAISSANCE STUDY FROM X-RAY POWDER DIFFRACTION ANALYSIS

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ABSTRACT

A reconnaissance mineralogical profile was established by X-ray powder diffraction (XRD) analysis on selected samples from core and cuttings of the AMOCO Eischeid #1 well, Carroll County, Iowa. Qualitative and semiquantitative analyses of both bulk rock and clay mineralogies were used to determine general mineral character, to compare variations and relations among lithology and age, and to assess the thermal history of the well from clay diagenesis and geothermometry. Bulk rock mineralogies show that most samples contain calcite. Calcite is most abundant in Precambrian samples below 15,000 ft. Potassium feldspar was found in moderate quantities in all samples. A change in source material is indicated from feldspar composition and abundance for Precambrian samples, because feldspar content increases considerably in these samples. This increase is due to the addition of about 14 average-weight percent (wt %) plagioclase; total feldspar in Precambrian samples is as high as 35 wt % of the bulk rock. The amount of interstratified illite/smectite (I/S) and percent expandable layers in I/S generally decreases and ordering increases with depth. The type and amount of chlorite changes with depth. Chlorite is magnesium-rich and randomly interstratified with smectite in samples between 2,400 and 4,170 ft, with high (80-90 wt %) quartz plus feldspar content. Deep (> 15,000 ft) samples, however, contain abundant, non-expanding, iron-rich chlorite. These changes are consistent with burial diagenetic models. I/S geothermometry suggests that maximum burial temperatures were about 100-110° C at about 2,400 ft and about 175-180° C at 15,000 ft. A calculated geothermal gradient from these two depth-temperature points is about 6° C/1,000 ft. A projected maximum burial temperature at the bottom of the well (17,851 ft) is about 192-197° C suggesting significant cooling to the present-day measured, uncorrected bottom hole temperature (BHT) of about 94° C.

INTRODUCTION

X-ray powder diffraction (XRD) analysis is a basic tool for the mineralogic characterization of geologic samples. Although several new analytical techniques have been developed over the past decade for characterizing minerals, such as high resolution electron microscopy and nuclear magnetic resonance imaging, XRD is still the most powerful analytical technique for studying clay minerals. This report describes the mineralogy of a selected group of samples from core and cuttings of the Amoco M. G. Eischeid #1 well, based solely on XRD analysis, with particular focus on the clay minerals. Although only little petrographic analysis was performed in conjunction with XRD, several useful relationships and interpretations are demonstrated from this study. The clay mineral assemblages of sedimentary rocks can be useful in providing interpretations of the burial and thermal history. In particular, the composition and degree of ordering of illite/smectite (I/S) is a useful geothermometer for determining thermal history of rocks and basins (Hoffman and Hower, 1979; Eslinger and Pevear, 1988; Pollastro, 1989a). Some estimation of maximum burial temperature relative to degree of maturation of hydrocarbons also is attempted from this study.

The results of this study are preliminary; results of a more detailed investigation that will include additional samples in conjunction with petrographic analysis will be given in a later report.

ANALYTICAL METHODS

Thirteen samples of core and ten samples of cuttings were obtained from about 560 to 16,440 ft. All samples were collected by James Palacas

(U.S.G.S., Denver). X-ray powder diffraction (XRD) analysis was performed on bulk core samples after slabbing, and on representative splits of cuttings.

Samples for XRD analysis were washed and scrubbed to remove surficial contaminants, dried, and then ground to <35 mesh. Each sample was then split into two portions, using a Jones splitter, for (1) whole-rock XRD, and (2) carbonate dissolution and clay mineral analysis. Carbonate was dissolved in 1N HCl and the residue filtered and washed immediately after effervescence stopped, so as to minimize solution of noncarbonate minerals (Pollastro, 1977). The insoluble residue was dried overnight at 65° C. The weight percent of the residue and/or carbonate was then determined. A small portion of the residue was spot-checked for undissolved carbonate with 6N HCl.

Qualitative and semiquantitative estimates of the minerals in whole rock were made through XRD analysis of randomly-oriented powders that were ground to a maximum grain size of 44-μm (<325 mesh) and packed from the back side into aluminum specimen holders. Analyses were performed on a Philips-Norelco diffractometer equipped with a curved-crystal graphite monochrometer. A fine random texture was imparted onto the surface to be irradiated, in an attempt to further disrupt any preferred orientation created while mounting the sample (see Schultz, 1978). All samples were analyzed using copper K-alpha radiation. Semiquantitative weight percent values for total clay (phyllosilicates) and other minerals or mineral groups were calculated by comparison with several prepared mixtures of minerals with similar XRD characteristics by the procedures outlined by Schultz (1964) and Hoffman (1976), with those modifications described by Pollastro (1985). The semiquantitative relative weight percent values calculated for total carbonate minerals by XRD then were compared against those determined by chemical dissolution.

Oriented clay aggregates of the <2-μm and <0.25-μm (equivalent spherical diameter) fractions were prepared using a modified filter-membrane-peel technique (Pollastro, 1982) similar to that described by Drever (1973). Semiquantitative XRD analysis of the clay minerals in the <2-μm fractions was made using the method of Schultz (1964) with some modification (see Pollastro, 1985). Composition and ordering of interstratified I/S clay was determined on oriented, ethylene glycol-saturated specimens of both the <2-μm and <0.25-μm fractions. Interpretations of I/S are based on the methods of Reynolds and Hower (1970) and Reynolds (1980), with the understanding that XRD patterns of illite and I/S may also be interpreted as physical mixtures of fundamental illite and smectite particles (Nadeau and others, 1984a,b), rather than mixed-layer clays. Ordering types were defined using the "Reichweite" (R) notation where "R" signifies one of three ordering types of interstratification (Reynolds, 1980). These three ordering types are: (1) random I/S (R=0); (2) allevardite or short-range ordered I/S (R=1); and (3) Kalkberg or long-range ordered I/S (R≥3).

Finally, it should be noted that data and interpretations relative to sample depth from core samples are more reliable than those from cuttings, as material from sedimentary rocks uphole in the well can contaminate cuttings.

RESULTS AND INTERPRETATIONS

Bulk Rock Mineralogy

Semiquantitative mineralogy of the bulk rock is shown in Table 1. The data only reports the total relative weight percent (wt%) of each mineral phase; it does not distinguish between detrital or authigenic origin, or whether multiple forms of a particular mineral phase exists. Quartz and clay minerals comprise the bulk of most samples. Calcite was present in most samples; it is most abundant in samples below 15,000 ft. Dolomite/ankerite was present as a minor constituent in some samples; one sample (S-6) was mostly dolomite. Potassium feldspar was found in moderate quantities in all samples analyzed, averaging about 7-8 wt%. In Precambrian samples, however, plagioclase was more abundant than potassium feldspar averaging 14 wt% of the bulk rock. The abundance of feldspar in these rocks from XRD analysis suggests an arkosic composition. A brief examination of seven thin sections sampled from 8,000 to 15,000 ft confirms the detrital origin and arkosic composition.

Pyrite or hematite was also present in most samples. The reddish color in core and cutting samples is attributed mainly to the presence of hematite. A minor amount of siderite was present in the shallowest sample at 560 ft.

Table 1. Mineralogical data from X-ray powder diffraction for samples from the Amoco Eischeid No. 1 well, Carroll County, Iowa. [Data reported in relative weight percent. Samples prefixed with a C indicate core sample; S indicates cuttings. Depth in feet. Qtz = quartz; Cal = calcite; Dol/Ank = dolomite and(or) ankerite; sid = siderite; Plag = plagioclase; KF = potassium feldspar; Py = pyrite; Hem = hematite; I/S = illite/smectite; Chl = chlorite; tr = trace; -- = none detected; nd = not determined; sh = shale; ss = sandstone; slt = siltstone; dol = dolomite.]

Sample No./Code	Depth	Age	Lithologic Type	Bulk-Rock Mineralogy Clay	Qtz	Cal	Dol/Ank	Plag	KF	Py	Hem	<2 μm Clay Mineralogy Illite	I/S	Chl
1. S-2	560-580	Pennsylvanian	ss	15	51	8	3-sid	7	8	8	--	nd	nd	nd
2. S-6	2400-2420	Ordovician	dol	3	10	--	85	--	2	--	--	55	41	3
3. S-7	2900-2920	Cambrian	ss	8	70	5	4	--	13	--	--	27	40	33*
4. S-8	3150-3180	Cambrian	ss	10	60	5	5	--	18	--	3	37	26	37*
5. S-9	4150-4170	Precambrian	ss	20	70	tr	--	--	7	--	3	35	36	29*
6. S-11	5040-5050	Precambrian	sh	43	35	2	--	10	7	--	3	44	49	7
7. S-14	7110-7130	Precambrian	sh	39	43	2	--	7	7	--	2	52	41	7
8. C-17	8836.6	Precambrian	ss	19	55	tr	2	9	12	--	3	54	36	10
9. S-20	10,830-10,840	Precambrian	sh	28	34	1	--	24	11	--	2	60	31	9
10. C-21	13,387.5	Precambrian	slt	22	42	4	1	16	6	--	2	59	28	13
11. S-24	14,500-14,520	Precambrian	sh	35	38	4	--	11	8	--	4	72	24	4
12. C-29	15,097.5	Precambrian	sh	34	37	10	--	11	4	4	--	48	8	44
13. C-30	15,101.7	Precambrian	ss	5	31	30	--	23	11	--	--	60	14	26
14. C-31	15,104.1	Precambrian	sh	52	30	--	--	13	5	tr	--	31	6	63
15. C-33a	15,106.5	Precambrian	ss	21	44	6	1	18	10	--	--	52	9	39
16. C-33b	15,106.8	Precambrian	slt	25	35	12	--	14	8	6	--	46	15	39
17. C-34	15,109-15,110	Precambrian	sh	51	30	--	1	14	4	--	--	45	8	47
18. C-35	15,114-15,115	Precambrian	sh	50	26	12	--	7	3	2	--	38	17	45
19. C-36	15,117.0	Precambrian	sh	41	31	6	--	12	5	4	--	42	13	45
20. C-37a	15,118.6	Precambrian	slt	17	22	52	--	6	5	4	--	28	4	68
21. C-37b	15,118.7	Precambrian	sh	42	32	2	2	17	5	--	--	38	2	60
22. C-44	16,043-16,045	Precambrian	slt	26	20	35	--	14	4	--	--	28	4	68
23. S-47/48	16,420-16,440	Precambrian	ss	30	36	10	--	16	7	3	--	38	5	57

* Samples containing a magnesium-rich chlorite that is interpreted as randomly interstratified chlorite/smectite.

Clay Mineralogy

Semiquantitative clay mineralogy of the <2-μm fraction is shown in Table 1. Clay minerals of the <2-μm fraction are illite, interstratified illite/smectite (I/S), and chlorite. No definitive evidence for kaolinite was present on the XRD profiles. It is possible, however, that kaolinite may coexist with chlorite in some samples or that kaolinite is present in coarser fractions of the samples. No kaolinite was observed in any of the seven thin sections examined, however, its presence may be best determined from more detailed petrography, thin section, and SEM studies.

Illite is defined from XRD profiles of the oriented specimens as a discrete, nonexpanding, 10-angstrom phase with no change after solvation with ethylene glycol or heating to 300 °C. All I/S from the Eischeid #1 well is ordered I/S with R≥1. The relative weight percent of I/S, as determined from the XRD profiles, decreased with depth (Table 1), with the deepest samples containing only a few wt% I/S in the clay-sized fractions (Fig. 1); the ratios of illite/I/S and chlorite/I/S also increase with depth. In addition, the degree of ordering of I/S increases with depth. These changes in I/S abundance and ordering are illustrated in the XRD profiles of Figure 2. Pollastro (1985) reported similar relationships in Cretaceous and Tertiary rocks of two Rocky Mountain basins and suggested that illite forms at the expense of I/S. Chlorite is the dominant clay phase in many of the samples below 15,000 ft. Although chlorite was present in all samples analyzed, there are distinct differences in the XRD characteristics of chlorite with depth. These differences in XRD character are attributed to differences in chemical and mineral composition of the chlorites. Two, and perhaps three, forms of chlorite were recognized in the samples studied. These variations in chlorite form are based on: 1) the relative intensities of the first through fourth order basal reflections; and 2) changes in peak position and peak intensity upon solvation with ethylene glycol and heating to 300° C, respectively. However, the 001 basal reflection for chlorite at 14-angstroms of all forms was intensified after heating to 550° C. In general, samples show a progessive change from an expanding magnesium-rich chlorite to a nonexpanding iron-rich chlorite with depth.

Chlorite in cutting samples S-7, S-8, and S-9 (depths from 2,900 to 4,170 ft) is interpreted as an expanding magnesium-rich chlorite containing some random interstratification with smectite (Fig. 3) and is different than chlorite present in samples much deeper in the well. Magnesium-rich chlorite is characterized on XRD profiles of oriented specimens by stronger odd-number (001, 003, etc.) basal reflections and weaker even-number (002, 004, etc.) basal reflections (Brindley, 1961). In addition, the 14- and 7-angstrom basal reflections (001 and 002, respectively) of the magnesium chlorite expand after glycol saturation (Fig. 3), indicating some random interstratification with smectite. The composition compares well with calculated XRD profiles of randomly interstratified chlorite/smectite with a composition of about 85 percent chlorite and 15 percent smectite (see Reynolds, 1980, Fig. 4.20 and Table 4.5e). Also, there is a decrease in the intensity of the 14-angstrom (001) reflection and increase in intensity of the 4.7-angstrom (003) reflection after heating to 300° C. Such characteristics are typical of interstratified clay minerals. No changes were observed in either peak position after glycol solvation or peak intensity after heating to 300° C for chlorites other than those designated as magnesium chlorites. Lithologically, these cutting samples are interpreted to represent relatively clean sandstones or siltstones, because bulk-rock XRD shows that they have relatively low clay (<20 wt%) and high quartz plus feldspar (77-83 wt%) contents (Table 1).

Those samples from S-11 to S-24, and corresponding to depths from 5,040 to 14,520 ft, however, contain much lesser amounts of chlorite than those above or below (Table 1; Fig. 2A). Assuming that quantity has little or no affect on the intensities of individual basal reflections, these chlorites appear to have an intermediate chlorite composition. Basal reflections of this particular chlorite of intermediate composition, however, neither expand upon glycol solvation nor change in intensity after heating to 300° C (Fig. 2A).

In contrast, chlorite in samples beginning with C-29 at 15,098 ft and deeper contain chlorite of the iron-rich variety. Iron-rich chlorites in samples from C-29 and deeper have stronger even-number and weaker odd-number basal reflections (Brindley, 1961). These iron-rich chlorites show no evidence of expansion upon solvation with ethylene glycol (Fig. 2b). Although the clay and carbonate contents of samples containing iron-rich chlorite are generally higher than those of samples containing the magnesium chlorite, iron chlorite appears to vary only in quantity, not quality, and its occurrence in samples at 15,098 ft and greater appears to be independent of lithologic type. Although the data are limited, there is an apparent increase in the relative abundance of chlorite in the <2-μm fraction with depth of sample (Fig. 1). In samples C-31, C-37a, 37b, C-44, and S-47/48, the clay mineral assemblage is essentially iron-rich chlorite and illite (Table 1).

The interpretation that kaolinite is probably absent and only chlorite is present in the <2-μm fraction is based on the XRD criteria that: 1) no 002 basal reflection for kaolinite at 3.58-angstroms was clearly resolved in conjunction with the 004 basal reflection for chlorite at 3.54-angstroms in any of the samples (Biscaye, 1964; Elverhoi and Ronningsland, 1978; Pollastro, 1984); 2) no 7-angstrom doublet or split was resolved, particularly in samples containing iron-rich chlorite, which might indicate the presence of both kaolinite and chlorite; 3) all basal reflections of chlorite were present and easily distinguished; and 4) the 14-angstrom reflection of chlorite was greatly intensified after heating to 550° C, confirming the abundance of a chlorite phase. However, no acid

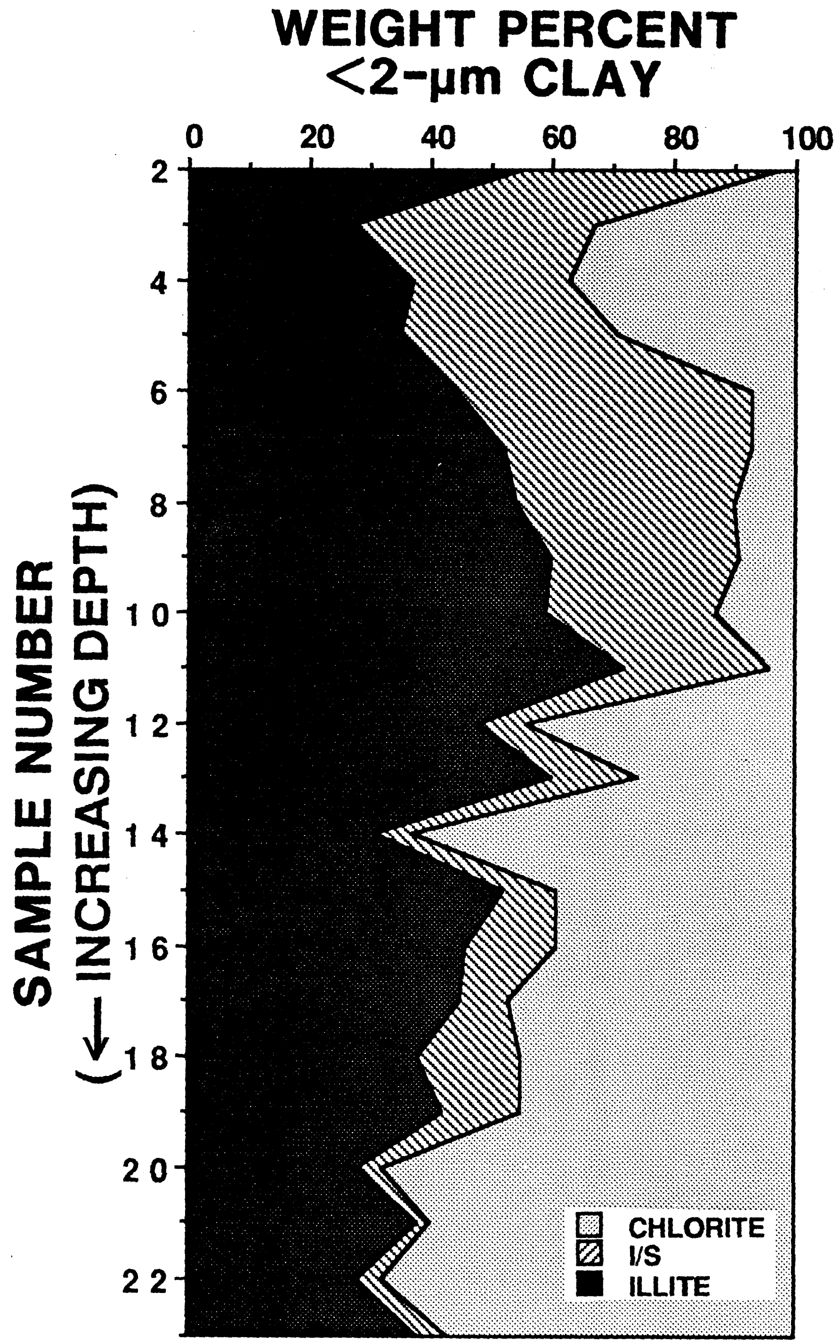

Figure 1. Relationship of weight percent of various clay minerals in <2-μm fraction versus sample number from Table 1. Depth is not scaled.

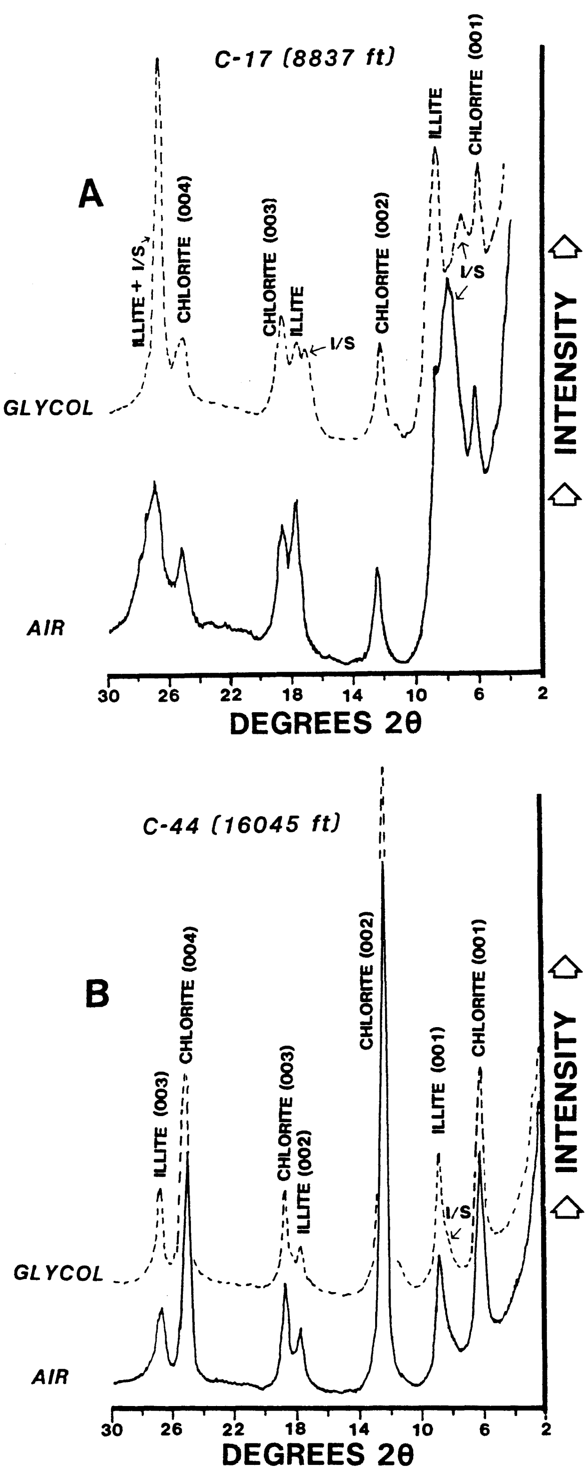

Figure 2. X-ray powder diffraction profiles of air-dried (solid line) and glycol-saturated (dashed line), oriented, <0.25-μm fractions of A) Precambrian core sample from depth of 8,837 ft, and B) Precambrian core sample from depth of 16,045 ft showing differences in interstratified illite/smectite (I/S) and chlorite. Cu K-alpha radiation.

dissolutions were performed to destroy chlorite in hopes of detecting kaolinite.

Composition and Ordering of Interstratified Illite/Smectite

The composition and degree of ordering of I/S clay was evaluated from both the <2-μm and <0.25-μm fractions. However, a better estimation of these parameters is made from XRD profiles of the <0.25-μm fraction as I/S is commonly enriched in the finest fractions relative to most other discrete mineral phases. All I/S clay in samples at depths >2,400 ft is ordered I/S (R≥1) as determined after glycol saturation and using the interpretive methods of Reynolds and Hower (1970) and Reynolds (1980); no randomly interstratified I/S was identified in any of the samples analyzed. This excludes cutting sample S-2 at 560 to 580 ft, as there was insufficient sample for clay analysis. The 001 glycol reflection of I/S migrates between 10° and 12.5° 2-theta indicating both short- and long-range ordering; both ordered phases (R = 1 and R≥3) coexist in samples between 5,000 and 14,500 ft. Only I/S with R≥3 ordering, however, was present in samples below 15,000 ft (Sample C-29). The most expandable I/S is present in samples S-11 and C-17 where the illite/smectite ratio is estimated at about 70/30-75/25 (R = 1). The least expandable I/S was present in sample C-44, the deepest core sample at 16,043 to 16,045 ft (Fig. 2B), which contained nearly pure illite plus chlorite. I/S in sample C-44 is present in only a small amount and is interpreted as R≥3 I/S, having little or no expandable component (<5 percent expandable layers in I/S).

Clay Diagenesis and Interpreted Thermal History

Reliable interpretations of diagenetic and thermal history using clay minerals are best made using control samples to establish a baseline knowledge of the detrital mineralogy, and in conjunction with thin section and scanning electron microscopy analyses to determine authigenesis and paragenesis. However, the interpretations of this report are limited to that suggested only from X-ray mineralogy. These interpretations are based on the assumptions that precursor clay mineral phases, mainly smectite or random I/S, were originally present in the rock and have been transformed to diagenetically more stable clays due to increased burial temperatures (Hower, et al., 1976). The assumption that diagenetic changes have likely occurred in I/S seems reasonable for samples of the Eischeid #1 well if one considers both the present burial depths and age of the samples (i.e., long periods of time exposed at elevated temperatures due to burial depth). This assumption is reasonable because studies of the Middle Protorozoic Belt Supergroup have shown that smectite diagenesis has occurred during burial metamorphism (Maxwell and Hower, 1967; Eslinger and Sellars, 1981).

In terms of diagenesis and thermal maturity, an important factor that may affect the smectite-to-illite reaction is time. Although little is still known about the effect of time on this reaction, there is evidence that time may play a secondary role in samples aging from about 10-350 Ma (Weaver, 1979; Pollastro and Schmoker, 1989). In the samples from this study, we have directly applied the model of Hoffman and Hower (1979) and, therefore, assumed that temperature is the main controlling factor driving the reaction.

The composition and degree of ordering of I/S based on the above assumption reflect minimum burial temperatures of 100-110° C at about 2,400 ft (sample S-6). A progressive increase in temperature due to geothermal gradient is assumed below this depth. This burial temperature interpretation is based largely on the diagenetic model of Hoffman and Hower (1979) and the senior author's experience with clay-mineral geothermometry (Pollastro and Barker, 1986; Pollastro and Scholle, 1986; Pollastro, 1989b; and Pollastro and Schmoker, 1989). In a progressive burial diagenetic setting, as in the Eischeid #1 well, the transformation of random I/S (R = 0) to short-range ordered I/S (R = 1) is documented to occur at about 100-110° C. As discussed in the previous section, only ordered I/S (R≥1) was present in samples analyzed for clays from depths > 2,400 ft. The most expandable I/S (i.e., that showing "minimum" diagenetic reaction) was interpreted as having R = 1 ordering and a composition of 70-75 percent illite layers and 25-30 percent expandable (smectite) layers (Fig. 2a).

Samples at 15,000 ft, however, contain I/S with only R≥3 ordering. Assuming smectite diagenesis has occurred and applying the clay geothermometry model of Hoffman and Hower (1979), a maximum burial temperature of about 175-180° C is indicated at 15,000 ft. The two temperature/depth points in

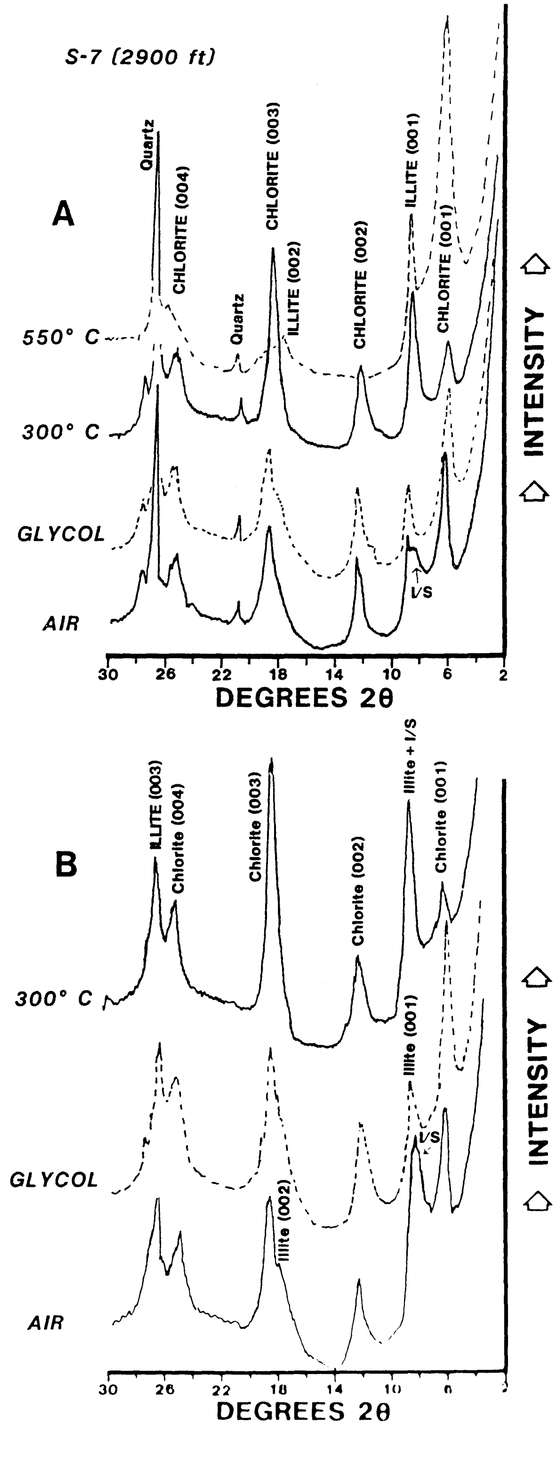

Figure 3. X-ray powder diffraction profiles of oriented clay specimens of A) < 2 μm fraction, and B) < 0.25 μm fraction after various treatments. Cutting sample from 2,900 ft contains magnesium-rich, randomly interstratified chlorite/smectite (chlorite), illite, and interstratified illite/smectite (I/S)

the well determined from changes in I/S give a geothermal gradient of about 6° C (11° F) per 1,000 ft from 2,400 ft to 15,000 ft and a projected temperature at the bottom of the well (17,851 ft), at maximum burial, of 192-197° C. These calculated temperatures are in excellent agreement with those estimated from fluid inclusion studies by Barker (this volume). Barker (this volume) concludes that minimum burial temperatures at 17,851 ft were about 200° C. The measured bottom-hole temperature (BHT) in the well is about 94° C. Barker used the AAPG method to correct the BHT to 105° C and concludes that the well has cooled markedly from minimum burial temperatures (temperature of formation) estimated from fluid inclusions. A similar conclusion is suggested from this study by the temperatures estimated from clay geothermometry.

SUMMARY

Our study of the Eischeid #1 well is prelimary and represents only a reconnaissance XRD analysis of the clay and bulk-rock mineralogies of relatively few samples over extremely large geologic time and depth intervals. In addition, the interpretations from this study are based on specific assumptions and models for progressive burial settings. Nevertheless, the clay mineral assemblages show specific phases, changes, and relationships relative to burial depth and age.

Bulk rock mineralogies show that most samples contain calcite. Calcite is most abundant in Precambrian samples below 15,000 ft. Potassium feldspar was found in moderate quantities in all samples. A change in source material is indicated from feldspar composition and abundance for Precambrian samples as feldspar content increases considerably. This increase is due to the addition of about 14 average wt % plagioclase; total feldspar in Precambrian samples is as high as 35 wt % of the bulk rock.

There is a decrease in the amount of I/S, and in percent expandable layers in I/S, with increased depth. Ordering of I/S increases as expandability decreases with increased depth; such relations suggest that smectite diagenesis has occurred in these rocks. The type and amount of chlorite also changes with depth in the well. In general, the amount of chlorite in the <2-μm fraction increases with depth in the well, particularly in the Precambrian rocks. Magnesium-rich, randomly interstratified chlorite/smectite is found in moderate quantities in cutting samples between 2,100 and 4,200 feet; chlorite/smectite of this type may be characteristic of shallower sandstones. Chlorite of intermediate composition is found in minor amounts within the <2-μm fraction in core and cutting samples at depths between 5,000 and 15,000 ft. Below 15,000 ft, chlorite is abundant and is of the iron-rich variety. Illite is abundant in all samples studied.

I/S geothermometry using the model of Hoffman and Hower (1979) suggests that burial temperatures at maximum burial were at least 100-110° C at about 2,400 ft and 175-180° C at 15,000 ft. A calculated geothermal gradient between these two depth-temperature points in the Eischeid well is about 6° C/1,000 ft. A projected temperature during maximum burial at the bottom of the well (17,851 ft) is about 192-197° C, suggesting that significant cooling has occurred relative to present measured temperatures, perhaps by major uplift and erosional events. These interpretations of thermal history are based on the assumption that time has had little or no affect on the smectite-to-illite reaction over hundreds of millions of years. The conclusions, therefore, must be viewed in this context.

ACKNOWLEDGEMENTS

We would like to thank Jim Palacas and Ray Anderson for their support and for allowing us the opportunity to contribute to the Amoco Eischeid well study. We also thank Dennis Eberl and Bruce Bohor for their helpful reviews of the manuscript. Any use of trade names is for descriptive purposes only, and does not imply endorsement by the United States Geological Survey.

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TECTONIC AND PALEOHYDROLOGIC SIGNIFICANCE OF CARBONATE VEINLETS IN THE KEWEENAWAN SEDIMENTARY ROCKS OF THE AMOCO M.G. EISCHEID #1 DRILLHOLE

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INTRODUCTION

Brittle deformational microstructures and mesostructures are noteworthy features of the cored Keweenawan sedimentary rocks in the Amoco M.G. Eischeid #1 (MGE) drillhole. These features include faults of various scales, slickensided surfaces with rough facets that can be used as kinematic indicators, and carbonate veinlets with pull-apart geometry. All kinematically-interpretable structural features observed in core from the MGE drillhole indicate that brittle deformation occurred in a reverse faulting mode, and that the Keweenawan sedimentary rocks in the Defiance Basin of western Iowa were deformed by lateral compression.

The Douglas Fault, exposed at Annicon Falls State Park, Wisconsin, has been interpreted as a Keweenawan reverse fault bounding the Saint Croix Horst (Ludvigson and Anderson, 1986). Pull-apart calcite veinlets were examined for comparison with the carbonate veinlets in the MGE drillhole.

The interpretations presented here are limited because they are based on only a few samples and a small data set. While it is certainly probable that the collection of more fluid inclusion and isotopic data would require modification of the hydrologic interpretations, the internal consistency of the extant data suggests that the general conclusions are probably valid. The logistical necessity for drawing scientific conclusions by integrating geologic observations from far-flung localities is one of the realities of geologic research. Conclusions that will be drawn from comparisons between calcite veins from the Douglas Fault in northwest Wisconsin and the MGE drillhole in west-central Iowa may invite skepticism. Nevertheless, both of the sampled vein systems are kinematically similar, and were formed by similar processes during the same regional tectonic event. These relationships establish a gross contemporaneity that might be further refined with more substantial research efforts. More importantly, alternative sample sets with better geographic constraints are not currently available.

STRUCTURAL OVERVIEW

The gross geometry of the Keweenawan Midcontinent Rift System (MRS) is reviewed elsewhere by Anderson ("Interpretation of Geophysical Data...," this volume). Iowa portions of the MRS are characterized by the axial Iowa Horst containing Early Keweenawan mafic volcanic rocks and related intrusives, flanked to the northwest and southeast by two asymmetric half-graben basins filled by clastic sedimentary rocks. The MGE drillhole penetrated the sedimentary rocks of a northwest flanking basin (Defiance Basin), and is located about five miles from the frontal fault separating the basin from the Iowa Horst. Combined gravity-magnetic modelling and interpretations of seismic reflection data indicate that the frontal faults dip inward beneath the Iowa Horst at angles of 15 to 50 degrees, and are interpreted as low-angle reverse faults. These interpretations are in accord with field observations on horst-bounding Keweenawan faults exposed in the Lake Superior area (Craddock, 1972).

The overall geometry of the MRS indicates that the evolutionary history of the structure, in part, involved a late phase of lateral compressive deformation that necessarily required a major shift in the crustal stress field. Reverse faulting microstructures and mesostructures in the MGE drillhole indicate that the deformational episode responsible for the uplift of the Iowa Horst probably also deformed the sedimentary rocks of the Defiance Basin. The presence of trace amounts of cataclastic sandstone and strained calcite cement and vein-fill throughout the drilled sequence of Keweenawan sedimentary rocks in the MGE drillhole (Ludvigson et al., this volume) provide additional evidence for pervasive deformation in the sedimentary sequence.

PETROLOGY OF DEFORMED SEDIMENTARY ROCKS

Structures in the core

Megascopic structural features in the MGE cores are instructive. At 11,394 feet, in Unit D-4 (Witzke, this volume), a small-scale reverse fault dipping 30° with respect to the core axis illustrates several salient features. Laminated siltstone in the footwall dips parallel to the fault plane, suggesting that the fault developed as a bedding-parallel feature that ruptured along an incompetent bed (Fig. 1A). Laminated siltstone units in the hanging wall are tightly bent into antiformal folds that are themselves cut by several smaller subsidiary microfaults (Fig. 1A). The antiformal folds are separated from overlying fault-parallel laminated beds by another fault plane, so that the folded units are enclosed in a 2.5 cm-thick interval that separates fault-parallel beds. This interval is cut by sigmoidal crossing microfaults that branch off from the two bounding fault planes, and cut the 2.5 cm folded interval into lozenge-shaped segments that are cut by a dense network of calcite veinlets, especially in the upper left of the photo (Fig. 1A). This low angle fault-bounded feature can be interpreted as a small-scale duplex structure, with the antiformal folds resulting from the stratigraphically-upward ramping of bedding-parallel fault surfaces.

At 16,043.3 feet, in Unit C-1 (Witzke, this volume), a cored interval of steeply-dipping shale is especially noteworthy. Figure 1B illustrates a saw-cut surface of the core cut parallel to the dip direction. The lower surface of the core is a slickensided brittle fault surface with a set of rough facets (Angelier et al., 1985, p. 352) resulting from secondary mineral growths during faulting. The downward-facing steep sides of the rough facets indicate that this core segment represents the hanging wall of a reverse fault. Smaller microfaults/veinlets branching off from the master fault surface cut across light-colored siltstone laminae on the saw-cut surface, and clearly illustrate reverse senses of displacement (Fig. 1B). The vein geometries along these microfaults are illustrative of pull-apart vein formation (Hancock, 1985, p. 441). Once again, it is important to note that the fault surface is bedding-parallel, indicating that rupture developed along structurally incompetent layers.

At 16,045.5 feet, in Unit C-1 (Witzke, this volume), a cored segment of steeply-dipping shale and siltstone cuts through the hinge of an open fold with a horizontal axial plane. Shale drapes over foreset siltstone laminae indicate that the facing direction of these steeply-dipping beds is to the right in Figure 1C, and that the upper limb is overturned. Mesostructures associated with the fold hinge include small-scale reverse faults tangentially cutting across beds on the right side of the photo (Fig. 1C). Dark-colored, pre-tectonic veinlets (also described in Ludvigson et al., this volume) cutting obliquely across bedding were rotated during the folding, and those in the upper limb are systematically offset along bedding surfaces, indicating that the fold developed by flexural-slip mechanisms. Finally, white calcite veins on the outer circumference of the fold hinge are interpreted as filled extension fractures.

Discussion

The mesoscopic structures in the MGE cored sequences demonstrate that the Keweenawan sedimentary rocks in the Defiance Basin in western Iowa were deformed by lateral compression. Consideration of the overall geometry and tectonic evolution of the MRS suggests that the deformation in the Defiance Basin was probably part of the same episode of Late Keweenawan compressive deformation responsible for the uplift of the Iowa Horst. Bedding-parallel reverse faults are characteristic wherever deformation is observed in the MGE cores. The steeply-dipping, faulted, and folded shale and siltstone in Unit C-1 show evidence of much larger-scale tectonic structures than that seen in overlying units. This could suggest that overlying strata may be allochtonous on some unspecified scale, and that a structural detachment occurred in Unit C, with northwestward tectonic

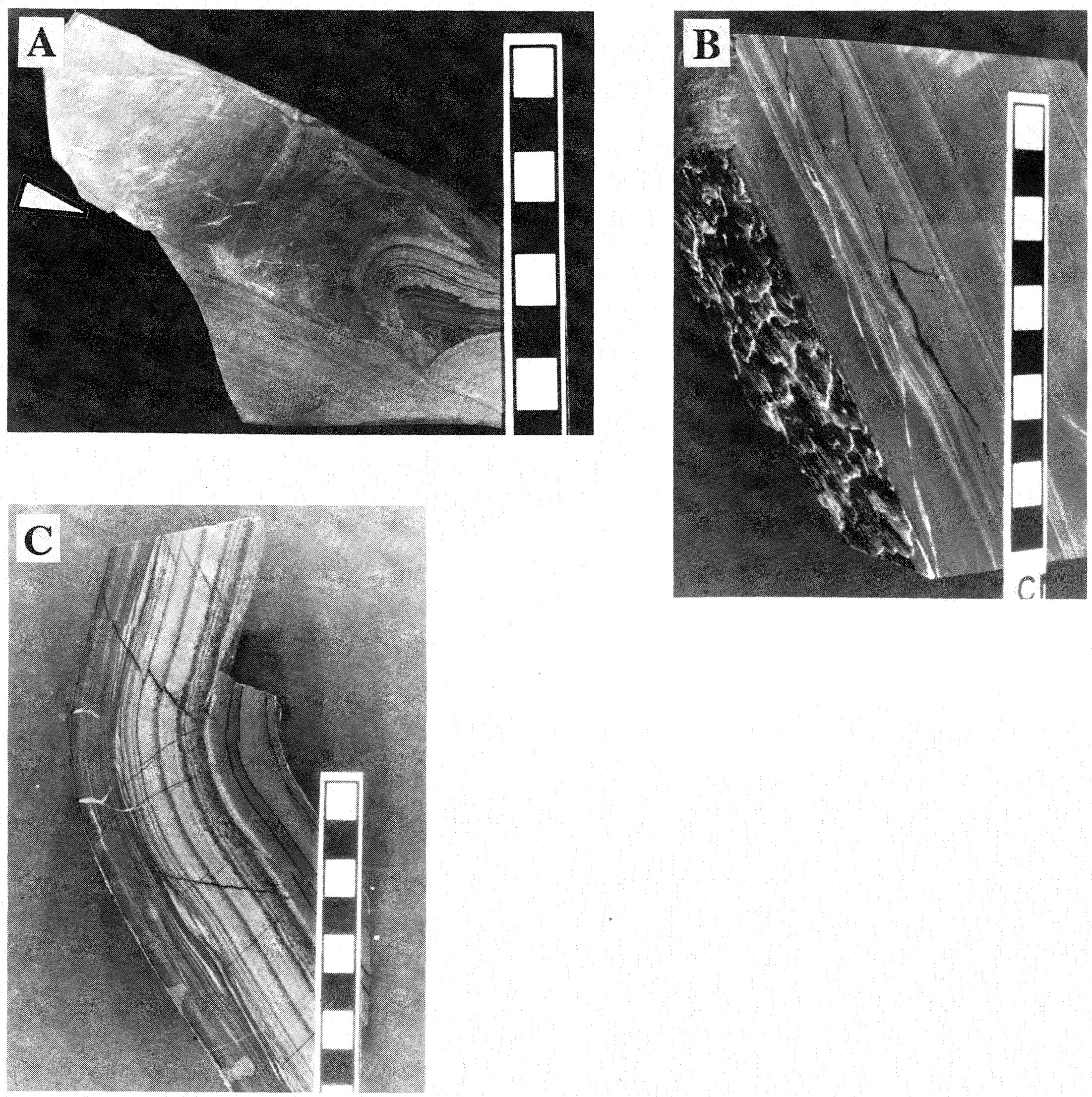


Figure 1. Photographs of deformational fabrics in cored sedimentary rocks from the Amoco M.G. Eischeid #1 drillhole. All samples are oriented vertically with respect to the core axis. A) Small-scale reverse fault (arrow) in Unit D-4, centimeter scale, 11,394 feet. B) Small-scale bedding-parallel reverse faults and slickensides with rough facets, unit C-1, centimeter scale, 16,043.3 feet. C) Horizontal fold hinge in deformed shale/silstone of Unit C-1; the upper limb is overturned, centimeter scale, 16,045.5 feet.

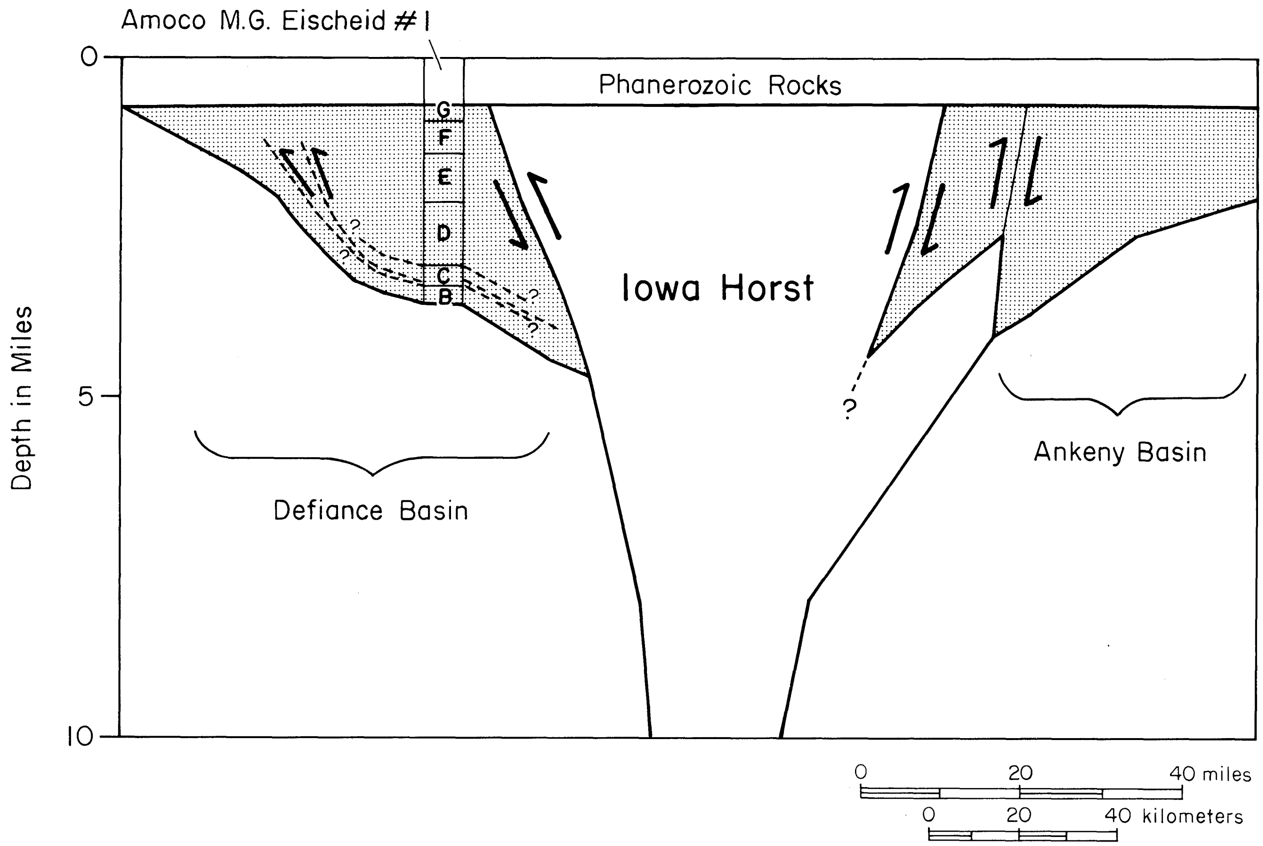


Figure 2. Schematic east-west cross section of the Midcontinent Rift System near the Amoco M.G. Eischeid #1 drillhole, modified from Anderson (this volume). Lettered units in the drillhole are those of Witzke (this volume). A structural detachment surface in the Defiance Basin is illustrated in Unit C, with tectonic transport of superjacent strata to the northwest, away from the Iowa Horst. The vertical scale is approximate.

transport of superposed stratigraphic units (Fig. 2).

Petrography of tectonic carbonate veinlets

As noted by Ludvigson and others (this volume), tectonic carbonate veins are especially abundant in the highly-strained rocks of Unit C. Petrographic, stable isotopic, and fluid inclusion studies of these veinlets were undertaken to elucidate the subsurface environments of deformation. Two core intervals with abundant carbonate veinlets were sampled at 15,097.6 and 15,118.6 feet.

A noteworthy feature of the veinlets is an abundance of inclusion trails of wallrock material suspended within the calcite veinlets (Fig. 3A). These features indicate that the structures are compound veinlets that developed by the crack-seal mechanism outlined by Ramsey (1980). Many of the smaller veinlets are discontinuous, and are linked by microfaults (Fig. 3B). The veinlets have sigmoid outlines, and parallelism between the vein walls and internal inclusion trails show that they developed incrementally as pull-apart veins along shear fractures (Hancock, 1985). Equant calcite crystals within the veins characteristically are cut by multiple intersecting sets of deformational glide twins. These features show that the calcites in the veins have been strained, and confirm that the compound pull-apart veinlets developed during incremental microfault strains. Similar features have been described from the Douglas Fault of northwest Wisconsin, a Keweenawan reverse fault bounding the Saint Croix Horst (Ludvigson and

Anderson, 1986). Differences in the density and number of sets of glide twins between different veinlet increments require that development of the glide twins was coeval with vein growth.

Some larger veinlet complexes in the MGE core have late-generation veins that developed by symmetric crustiform crystal growths on vein walls, with acicular euhedral crystal terminations merging toward a medial suture (Fig. 3C). These veins formed by crystal growth in large, open fractures, and typically have a late-stage filling of unstrained quartz. Some veins contain an early generation of strain-shadowed quartz cut by calcite veinlets with glide twins.

Shale and siltstone units bordering the veinlet complexes show evidence of considerable bedding-parallel shear strain, including isoclinal folding of bedding (Fig. 3D). Fracture-fills of microbrecciated wall-rock and vein material bordering some veinlet complexes provide convincing evidence that cataclasis was associated with the development of the veinlet complexes (Fig. 3E).

Stable Isotopic Data

Powdered samples of 2-3 mg size were drilled with a 0.75 mm carbide dental burr from polished slabs of cored intervals at 15,097.6 and 15,118.6 feet in Unit C-2. In order to further evaluate the setting of the veins in the MGE drillhole, pull-apart calcite veinlets from the Douglas Fault at Amnicon Falls State Park, Wisconsin were also sampled for comparison. Three replicate samples were drilled from each rock sample to evaluate internal variations within each veinlet complex. Calcite samples were vacuum-roasted for three hours at 200° C to remove volatile contaminants, and two samples selected for organic carbon analyses of enclosing shales were reacted with reagent grade hydrochloric acid to remove contaminant carbonate phases. Samples were analyzed at the laboratory of Dr. E.M. Ripley at Indiana University, using a Finnigan Delta-E mass spectrometer with a 9 cm deflection radius. Carbon and oxygen isotopic analyses are reported in per mil values relative to the PDB (Pee Dee belemmite) standard. Calculated oxygen isotopic compositions for pore fluids are discussed in per mil relative to the SMOW (standard mean ocean water) standard. Analytical precision for $\delta^{13}C$ and $\delta^{18}O$ values are considered to be better than ±0.05 per mil.

The results of the isotopic analyses are shown in Figure 4. The isotopic composition of calcite veinlets from the MGE core are relatively invariant, with $\delta^{13}C$ ranging from -3.41 to -4.46 $^{o}/oo$, and $\delta^{18}O$ from -16.21 to -16.52$^{o}/oo$. Calcite veinlets from the Douglas Fault show larger internal variations, with $\delta^{13}C$ ranging from -2.22 to -3.59 $^{o}/oo$, and $\delta^{18}O$ ranging from -11.23 to-13.58 $^{o}/oo$. Veinlets from the Douglas Fault show larger internal variations, and are isotopically enriched relative to their counterparts in the MGE cores. The most likely explanation for the oxygen isotopic enrichment in the calcites from the Douglas Fault is that they were precipitated at lower temperatures than those in the MGE cores.

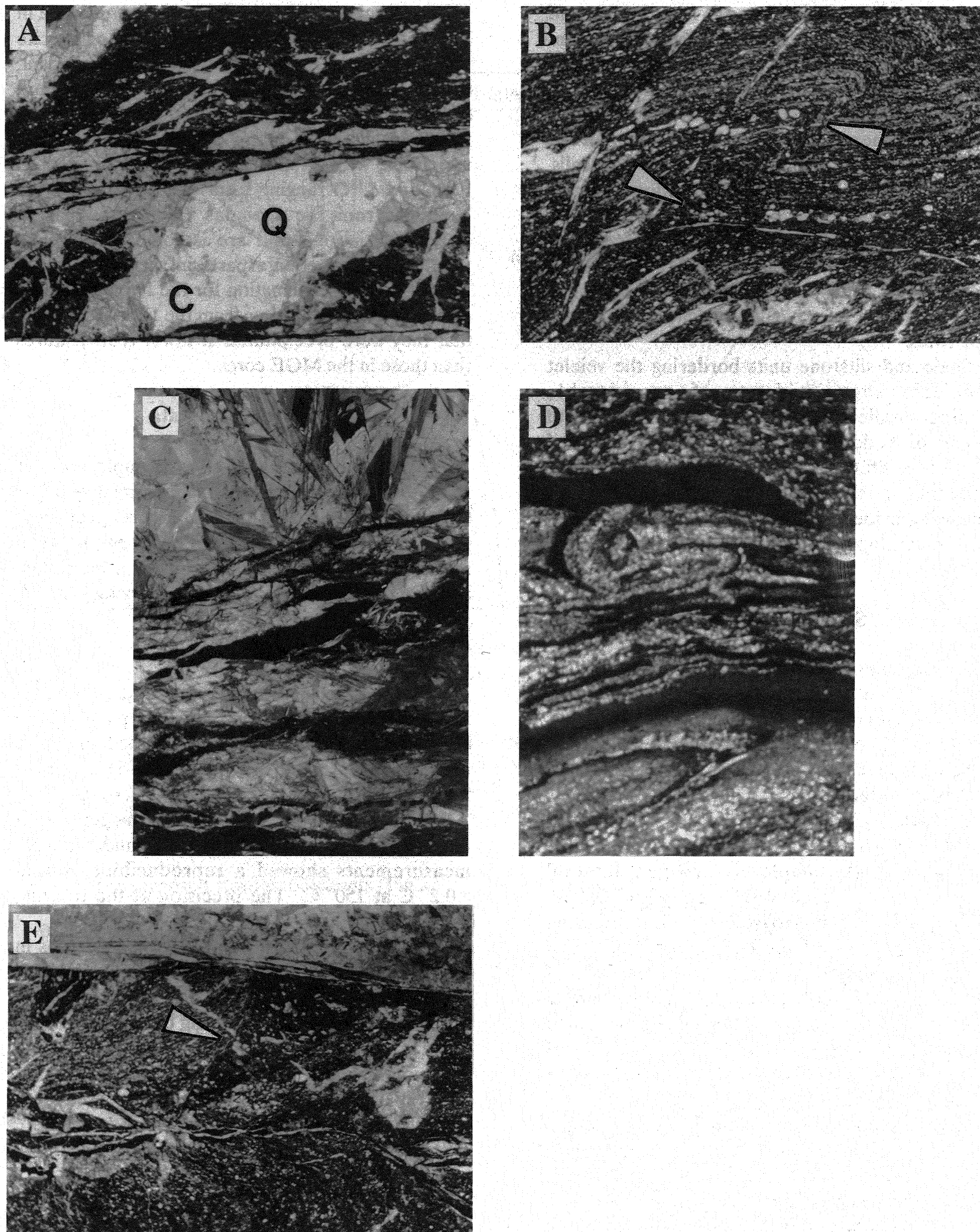
Fluid Inclusion Data

Two doubly-polished wafers (samples MGE1 15,097.6 and MGE1 15,118.6), approximately 0.2 to 0.4 mm thick, of calcite veins were prepared. Homogenization and freezing temperature measurements were determined using a Fluid, Inc. adapted U.S.G.S. gas-flow heating/freezing system.

Nature of fluid inclusions

Most fluid inclusions that were studied occur in isolated areas or along discontinuous planes. Two or three heating runs were performed on every measured inclusion. The individual homogenization and freezing data are given in Table 1. The precision of the homogenization temperature was ±0.2° C or better and replicate measurements showed a reproducibility within ±0.2° C at 150° C. The precision of the freezing runs was ±0.2° C.

Three fluid inclusion types, up to 40 microns in size, were identified. Type 1 inclusions are CH_4 and CH_4-H_20 inclusions in which CH_4 homogenizes into the liquid state upon heating between -86.8° to -92.7° C. Melting of the solid phase of one inclusion at -179.6° C (close to the melting of point of CH_4 of -182.5° C) suggests the presence of almost pure CH_4. Further evidence for the presence of CH_4 is indicated by the high clathrate melting temperatures (19.6° to 21.4° C). Type 2 inclusions are believed to be CO_2-rich inclusions. It is unclear why melting of solid CO_2 was not visible under the microscope. However, CO_2 homogenized into the liquid state between 9.4° to 29.3° C. Type 1 and 2 inclusions occur in isolated patches and are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believed to be primary in origin. Type 3 inclusions are aqueous liquid-vapor inclusions that occur in planes and are likely to be secondary in origin. Liquid-to-vapor volume ratios appear to be consistent; at room temperature, the vapor phase usually occupies approximately ten volume percent. Homogenization temperatures range from 125.1° to 179.8° C. Initial ice melting temperatures as low as -30° C suggest the presence of $CaCl_2$, and possibly $MgCl_2$, in addition to NaCl. Type 2 inclusions are present in sample MGE1 15,118.6 and type 1, 2, and 3 inclusions are present in sample MGE1 15,097.6.

One doubly-polished thin section of calcite veinlets from the Douglas Fault at Amnicon Falls in northwest Wisconsin was examined. At room temperature, the calcite contains aqueous liquid-filled inclusions with very small volumes of vapor phase. Vapor bubbles migrate randomly by Brownian motion through the inclusions, and thus were not studied further. The small volume percentages of the vapor phase indicate, however, that the inclusions were trapped at near sedimentary temperatures, perhaps ranging from 25° to 50° C.

Discussion

The presence of CH_4 and CO_2 is hardly surprising in view of the high organic content of both samples. The relative timing between the formation of the CH_4- and CO_2-rich inclusions is unclear because they occur in different fluid inclusion sections of two different compound vein complexes. Because of their secondary nature, the aqueous inclusions formed after the CH_4- and CH_2-rich inclusions. The aqueous inclusions appear to to have originated from warm, dilute fluids that were probably meteoric in origin. Low salinities of the primary fluids are also indicated by the range of clathrate melting. The variable homogenization temperature for CO_2 (i.e., variable densities) reflect multiple of CO_2 trapping events.

IMPLICATIONS FOR FLUID MIGRATION IN KEWEENAWAN SEDIMENTARY BASINS

The combined isotopic and fluid inclusion data have the potential to yield insights into fluid circulation in the sedimentary basins of the Midcontinent Rift System. Filling temperatures from aqueous liquid-vapor inclusions and $\delta^{18}O$ values can be employed with the calcite paleotemperature equation (Craig, 1965) to calculate possible ranges of oxygen isotopic fluid compositions from the veinlets in the Douglas Fault and the MGE drillhole.

This practice must be exercised with caution, particularly with respect to calcite, because of the relative ease with which fluid inclusions may be reequilibrated (Goldstein, 1986). Even though the two-phase liquid-vapor inclusions from which the homogenization temperature was determined come from secondary inclusions that are probably aligned along glide twin planes, there are good reasons to believe that they may accurately represent the actual filling temperatures during vein formation. Microscopic fabric observations of glide twin densities in successive growth increments show that the twins are coeval with the development of the compound veins. Furthermore, the lack of isotopic heterogeneity in the veinlets from the MGE core point toward calcite precipitation from a fluid of similar composition. Therefore, even though the fluid inclusion filling temperatures may represent samples of later-generation fluids captured in earlier-generation calcites, it is unlikely that the physico-chemical environment changed

Figure 3. Photomicrographs of deformational fabrics in cored sedimentary rocks from the Amoco M.G. Eischeid #1 drillhole. All samples are oriented vertically with respect to the core axis. All micrographs have a 6.4 mm field of view. A) Complex of compound calcite veinlets, with opaque inclusion trails of wallrock bracketing successive increments of fracture opening. Blocky calcite crystals (C) in the veins are cut by closely-spaced glide twins. The large vein in the center of the figure is filled by a late phase of unstrained quartz (Q), plane polarized light. B) Pull-apart calcite veinlets (white) filling microfaults in shale. Note that a silt-rich lamina (arrows) is offset along a reverse microfault with small drag folds, plane polarized light. C) Compound vein complex with a late generation vein (top) of void-filling by acicular calcite, cross-polarized light. D) Isoclinal recumbent folds in shale laminae bordering a compound veinlet complex, plane polarized light. E) Fracture filling of microbrecciated shale and vein calcite (arrow) bordering a compound veinlet, plane polarized light.

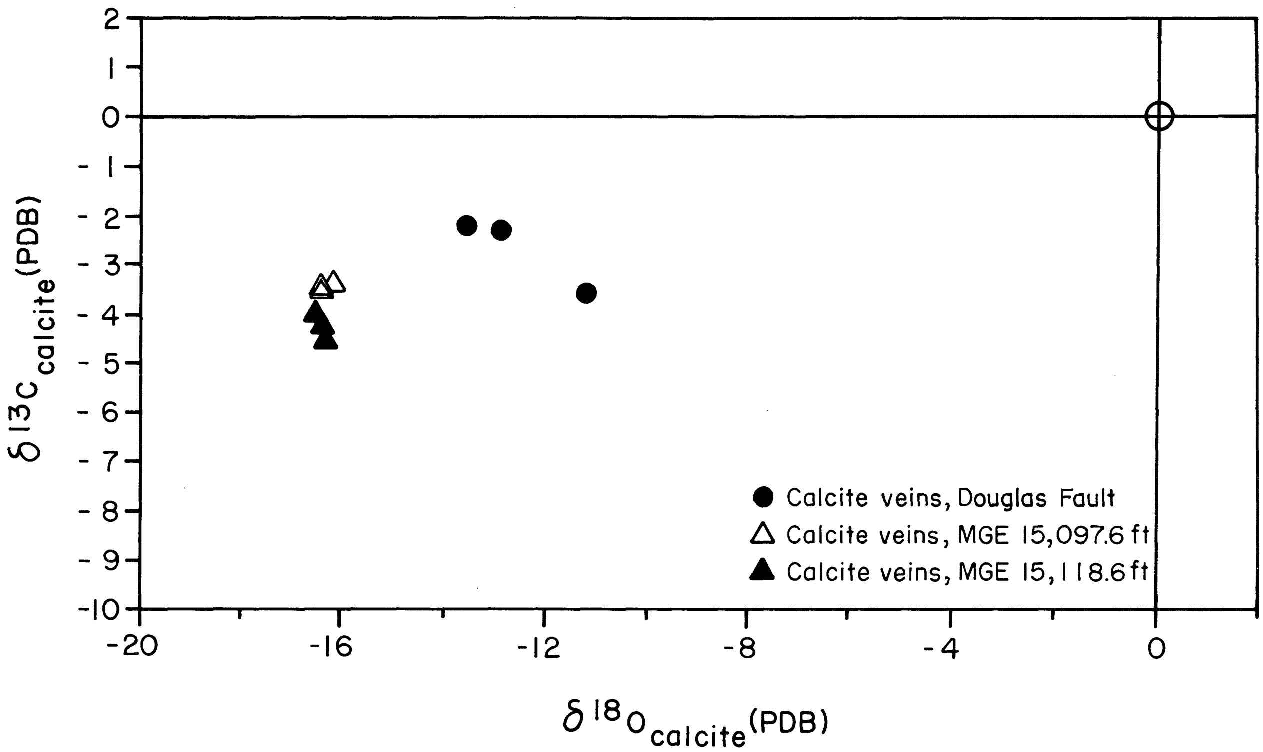

Figure 4. Cross-plot of carbon and oxygen isotopic ratios in vein-filling calcites from the Douglas Fault and the Amoco M.G. Eischeid #1 drillhole.

substantially during compound vein growth. The isotopic and fluid inclusion data are interpreted to record a stable environment of precipitation that prevailed throughout the growth history of the compound veinlets in the MGE core. While the same textural arguments can be advanced for the veinlets from the Douglas Fault, the isotopic heterogeneity of the veinlets does suggest changing fluid compositions during the growth of these veins. The significance of these variations will be discussed in a later section.

Figure 5 shows the ranges of possible $\delta^{18}O_{water}$ values that can be calculated from the calcite veinlets in the MGE core and the Douglas Fault. The vein-precipitating waters from the Douglas Fault range from less than -4 to slightly greater than -12 per mil relative to SMOW, whereas the waters from the MGE veinlets range from slightly greater than 0 to greater than 6 per mil relative to SMOW. The values from the Douglas Fault are consistent with isotopically-depleted meteoric waters that condensed at low to middle latitudes, provided it can be safely assumed that SMOW approximates the composition of Keweenawan seawater. Conversely, the isotopic values from the MGE cores are suggestive of evolved basin fluids enriched in ^{18}O as a consequence of protracted rock-water isotopic exchanges, again assuming that Keweenawan seawater $\delta^{18}O$ values approximated SMOW.

Secular variation in oxygen isotope ratios of up to several per mil are known to have occurred in the composition of Phanerozoic seawater, and also are believed to extend back into the Proterozoic Era (Veizer et al., 1986; Veizer, 1985). Although accurate estimation of the isotopic composition of ancient seawater can be frought with interpretive difficulties, some data are available with which to estimate the possible ranges of variation during Keweenawan time. Early Cambrian marine carbonates are reported to be depleted in ^{18}O by about 4 per mil relative to the PDB standard, suggesting that coeval seawater was depleted by about 4 per mil relative to SMOW (Veizer et al., 1986; Lohmann, 1988). Zempolich and others (1988) reported that Late Proterozoic marine carbonate cements are depleted in ^{18}O by 0.5 ± 2 per mil relative to PDB, suggesting that coeval

Table 1. Fluid inclusion data for samples MGE1 15,097.6 and 15,118.6. Temperatures are in degrees Celsius.

Inclusion No.	$T_{m\ CH_4}$	$T_{h\ CH_4}$	$T_{h\ CO_2}$	$T_{i\ ice}$	$T_{fdp\ ice}$	$T_{h\ H_2O}$	$T_{m\ clath}$
15,097.6							
1	-197.6	-89.2	20.1				20.1
2			20.6				20.6
3		-86.8					
4		-92.7					
5			21.4				21.4
6		-88.2	19.6				19.6
7		-90.0					
8		-90.8					
9		-87.4					
10		-90.0					
11				-30	-0.6		
12					-0.6		
13					-0.4		
14					-1.0	159.7	
15					-2.2	179.8	
16						125.1	
17					-1.7	176.5	
18					-1.7		
19					-2.0	172.3	
20					-1.9		
15,118.6							
1			9.4				
2			24.3				
3			12.1				
4			29.3				
5			12.2				
6			27.2				
7			28.1				
8			20.7				
9			28.2				

$T_{m\ CH_4}$ - melting point of CH_4-rich inclusions;

$T_{h\ CH_4}$ - homogenization temperature of CH_4 (into the liquid phase);

$T_{h\ CO_2}$ - Homogenization temperature of CO_2 (into the liquid phase);

$T_{i\ ice}$ - initial temperature of ice melting;

$T_{fpd\ ice}$ - freezing point depression of final ice melting;

$T_{h\ H_2O}$ - homogenization temperature of aqueous inclusions (into the liquid phase);

$T_{m\ clath}$ - clathrate melting point.

seawater was similarly depleted with respect to SMOW. Finally, Beeunas and Knauth (1985) reported that "unaltered" Middle Proterozoic (1200 Ma) marine dolomites stabilized by early meteoric diagenesis have values that are depleted relative to PDB by as little as 5 per mil. This would suggest that 1200 Ma seawater had $\delta^{18}O$ values greater than -5 per mil relative to SMOW. These three published estimates suggest that between 1200 and 570 Ma, the oxygen isotopic composition of seawater varied between -5 to -0.5 per mil relative to SMOW (Fig. 6).

The preceding discussion adressed the possible limits of variation in the oxygen isotopic composition of Keweenawan marine carbonates. This information is needed not only to specify the expected range of values for Keweenawan seawater, but also the ranges that could be reasonably expected from coeval meteoric waters in various climatic settings (Fig. 6; also see Lohmann, 1988). Depositional interpretations of Keweenawan sedimentary sequences along the MRS are in general agreement that the units accumulated in a nonmarine setting in the continental interior (see Witzke, this volume). Thus, infiltrating meteoric groundwaters can be presumed to have controlled sediment diagenesis and fluid evolution in these rocks. This presumption is consistent with the observation that the calculated $\delta^{18}O_{water}$ values for calcite vein fluids indicated in Figure 5 do not overlap with the expected values for Keweenawan seawater (Fig. 6). Although the veinlets generally are interpreted to have precipitated from fluids derived from meteoric infiltration, further information can be drawn from their geochemistry. Critical evaluation of the precipitational environments of veinlets from the Douglas Fault and the MGE drillhole follow.

Calcite veinlets from the Douglas Fault

The waters responsible for the precipitation of calcite veins in Keweenawan basalts from the Douglas Fault were isotopically depleted in ^{18}O with respect to coeval seawater by as little as 0.5 to perhaps as much as 12 per mil (Fig. 6). Not only are these values indicative of meteoric water, but their relatively small depletions with respect to marine water are further suggestive of meteoric origin at low latitudes, especially since the locality was probably some appreciable distance from any large body of seawater. Rainwater in continental interiors is further depleted from coeval coastal rainwaters by Rayleigh distillation processes ascribed to orographic and "land" effects (Drever, 1982). Independent confirmation for a low-latitude setting for the MRS during the deposition of the sedimentary Oronto and Bayfield groups was reported by Halls and Pesonen (1982, p. 180), in a collation of paleomagnetic data for Keweenawan rocks. Accordingly, the veinlets are interpreted to record rock deformation in near-surface environments saturated by pore fluids that were little altered from fresh, low-latitude meteoric groundwater.

Other geochemical lines of evidence are in accord with this interpretation, and add further useful constraints. While ferric oxide phases are abundant in the rock matrix of the microbrecciated basalts and in the inclusion trails of wallrock suspended within the compound calcite veins, wavelength dispersive microprobe analyses of the vein calcites show that Fe and Mn are below detection limits ($\approx$ 100 ppm). This indicates that despite abundant local supplies of these transition metals, Fe^{2+} and Mn^{2+} were not stable in solution, and that the veins formed in oxidizing groundwaters. The depth of formation of the calcite veinlets is not known, but linear and planar fabrics developed in the enclosing cataclasites point toward deformation under sufficient confining pressures to exclude formation immediately at the land surface. Factors which may have favored the development of deep oxidizing groundwater environments along the Douglas Fault Zone would include: 1) a probable lack of high levels of organic productivity in Middle Proterozoic weathering zones; 2) a lack of sources of organic carbon in the basaltic protolith would further retard the activity of aerobic, oxygen-consuming microorganisms in the pore fluid; and 3) topographic relief along rising frontal fault scarps bordering the uplifted Keweenawan axial horsts may have induced rapid, gravity-driven, meteoric infiltration through fracture permeability along the fault systems. Deep oxygenated groundwaters are known in modern high-relief settings (Winograd and Robertson, 1982).

These interpretations may have important implications regarding the subsurface fluid flow dynamics in the flanking Keweenawan sedimentary basins. The geochemistry of the late vein-filling calcites at Amnicon Falls State Park indicate that deformation along the Douglas Fault occurred

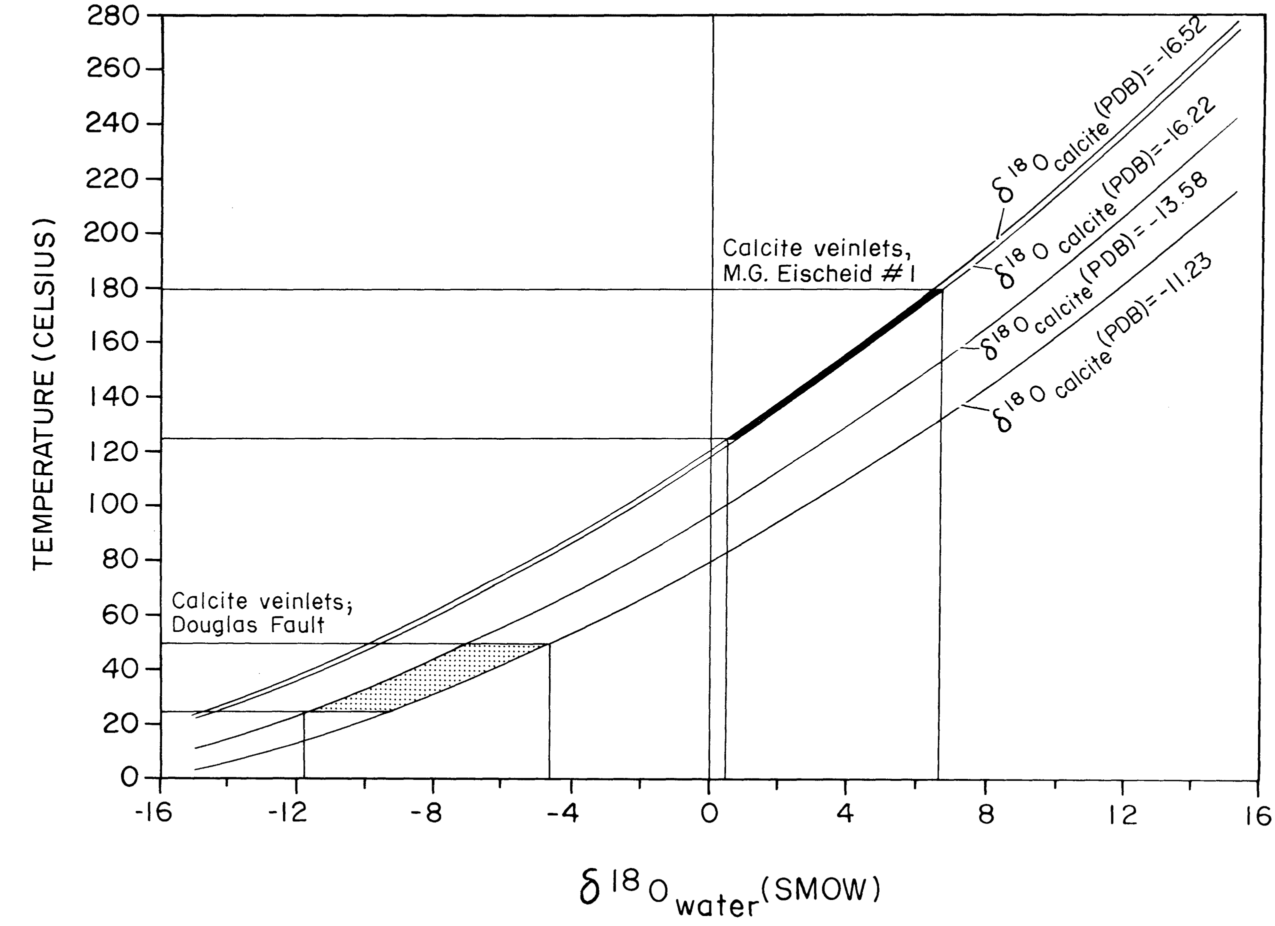

Figure 5. Calculated ranges of possible oxygen isotopic fluid compositions for vein-filling calcites from the Douglas Fault and the Amoco M.G. Eischeid #1 drillhole, using fluid inclusion filling temperatures and the calcite paleotemperature equation (Craig, 1965).

while the rocks were saturated with oxidizing meteoric groundwaters at sedimentary temperatures. This suggests that the frontal fault system along the St. Croix Horst would have to be at a proximal (ie. recharging) position in any integrated fault-basin fluid-flow system. The degrees of hydrologic connection between basinal fluid circulation and that along the frontal fault systems are currently a matter of conjecture. However, the calcite data from Amnicon Falls provide convincing evidence against the presence of upwardly discharging basinal fluids along the frontal fault system. The paleothermometry of earlier deformed generations of calcite and zeolite veinlets at Amnicon Falls have not been investigated, so some earlier high-temperature phases might be present. If so, they could be viewed as recording information on the uplift history of the St. Croix Horst.

Calcite Veinlets from the MGE Drillhole

The waters responsible for the precipitation of the calcite veinlets in Unit C of the MGE drillhole were enriched in ^{18}O with respect to coeval seawater by as little as one to as much as 12 per mil (Fig. 6). This data set is consistent with vein growth in formation fluids from deep sedimentary basins. Linear trends of ^{18}O enrichment are well documented from covariate plots of hydrogen and oxygen isotopic ratios of evolved meteoric groundwaters in the interiors of sedimentary basins

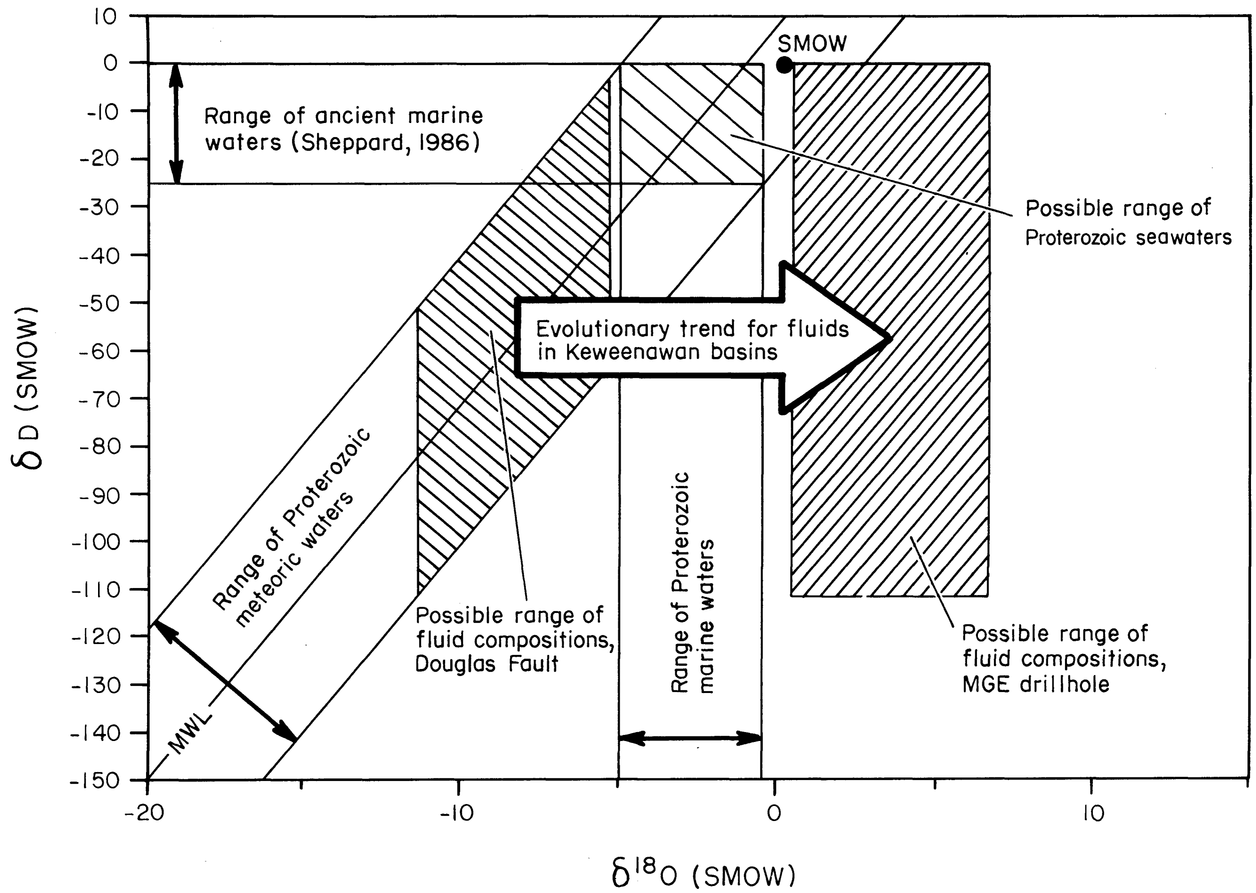

Figure 6. Possible ranges of hydrogen and oxygen isotopic fluid compositions for vein-filling calcites from the Douglas Fault and the Amoco M.G. Eischeid #1 drillhole. The $\delta^{18}O$ ranges for vein fluids are from Figure 5, and the $\delta^{18}O$ range of Proterozoic marine waters are from discussions in the text. The range of ancient δD compositions for marine water are from Sheppard (1986). The range of possible isotopic compositions of Proterozoic meteoric waters is derived from the envelope of possible isotopic compositions of Proterozoic marine waters, modified from Lohmann (1988). The δD ranges of the vein-filling calcites are based on the premise that the vein fluids are of meteoric derivation.

(Drever, 1982). These linear trends intercept the meteoric water line at the local mean annual composition of rainwater, and from that point record an evolutionary progression of increasing $\delta^{18}O$ with relatively invariant δD values (Fig. 6). This so-called "oxygen isotope effect" has been attributed to isotopic exchanges between groundwaters and rock-forming minerals (Clayton et al., 1966). This relationship suggests that the fluids that precipitated the veinlets in the Douglas Fault and Unit C in the MGE could be viewed as representing different parts of an integrated fault-basinal fluid flow system. The fluids that precipitated tectonic veinlets in the Douglas Fault were essentially near-surface groundwaters, whereas the fluids that precipitated the tectonic veinlets in Unit C of the Defiance Basin were evolved basinal fluids. From these two points of observation, a hypothesis can be advanced that during the late phase of compressive deformation of the MRS, gravity-driven groundwater flow systems, recharging along the frontal faults that bound axial horsts of the MRS, controlled fluid circulation in the flanking sedimentary basins (Fig. 7). This scenario would be comparable to the combined tectonic/hydrologic setting used by Garven (1985) to explain fluid transport and Mississippi Valley Type ore deposition in a foreland

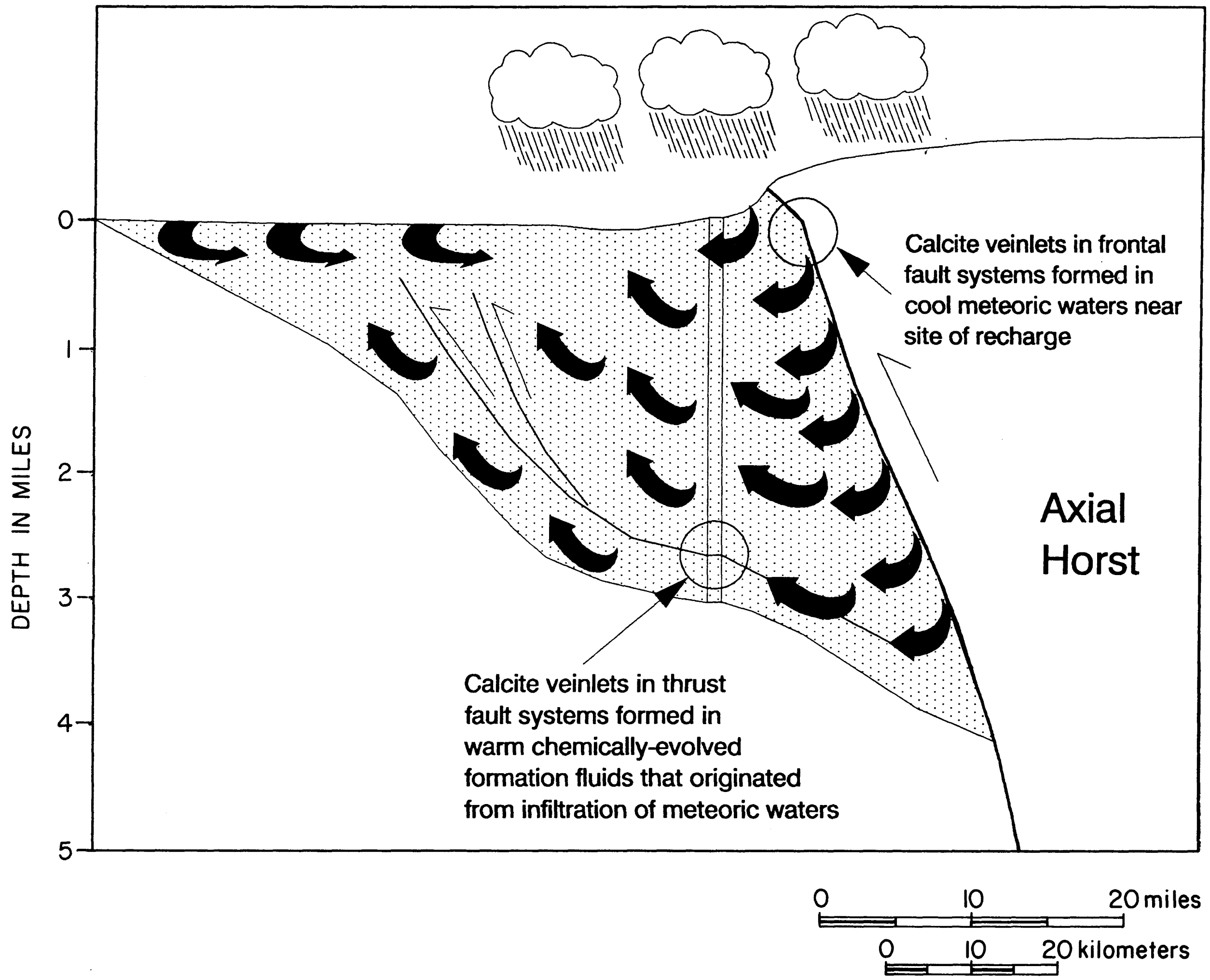

Figure 7. Proposed regional fluid flow system in Keweenawan clastic sedimentary basins, using the Defiance Basin of western Iowa and the Amoco M.G. Eischeid #1 drillhole as examples. Modified from Anderson (this volume). Points of observation used in the synthesis are the vein systems from Unit C in the Eischeid drillhole, and the vein systems exposed along the Douglas Fault, shown here in their analogous position at the boundary of the axial horst. Gravity-driven meteoric recharge at the edge of the uplifted horst is interpreted to dominate regional fluid transport in the basin.

basin setting. Interpretations of relationships between the carbon isotopic ratios in the vein systems are deferred until further data are collected on the carbon isotopic ratios of sedimentary carbonate and organic carbon preserved in Unit C of the MGE drillhole.

Implications for Petroleum Migration in Keweenawan Sedimentary Basins

Petroleum source rock studies of Unit C in the MGE drillhole (Palacas et al., this volume) indicate that organic-rich units in the Defiance Basin are thermally matured past the "dry gas window." Questions remain about the timing of thermal maturation, although Keweenawan expulsion has been implicated (Witzke, this volume; Palacas et al. this volume). The presence of distinct generations of CH_4- and CO_2-filled inclusions in the tectonic veinlets from Unit C of the MGE drillhole strongly suggests that petroleum generation and migration may have coincided with Late Keweenawan compressive deformation in the Defiance Basin. If so, potential may exist for large structural traps related to thrust faulting in the sedimentary basins of the MRS.

Migration pathways for petroleum are governed by regional aqueous fluid and heat transfer in sedimentary basins, and the generalized relationships shown in Figure 7 pertain to these phenomena. This paper proposes that gravity-driven meteoric recharge from the margins of the uplifted axial horsts dominated fluid flow in the flanking sedimentary basins. Accordingly, petroleum accumulations would be expected to most likely occur near the updip margins of the basins. In the event that future petroleum exploration is undertaken in this province, research results reported here suggest that the thinner, shallower sedimentary sequences of the basin margins should be tested by drilling.

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RECONNAISSANCE FLUID INCLUSION STUDY, AMOCO EISCHEID #1 WELL, DEFIANCE BASIN, MID-CONTINENT RIFT SYSTEM, IOWA

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ABSTRACT

Uncorrected homogenization temperatures measured on bitumen-free, fracture-bound (secondary) fluid inclusions occurring in calcite and quartz veins from 15,000 to 16,000 feet in the Amoco M.G. Eischeid #1 well (MGE) fall into two groups clustered near 200° C and at 140° C. Crushing stage studies show that both groups of inclusions have a significant portion of non-condensible gas (probably CH_4 and CO_2). Consequently, a pressure correction is not applied to the homogenization temperature, and it is interpreted as the inclusion trapping temperature. Therefore, the fluid inclusion data indicates the minimum paleotemperature was about 200° C.

Organic matter in other fluid inclusions, in some pores and microfractures in the matrix, and in the veins appears to be a non-fluorescent pyrobitumen. No fluorescent oil fluid inclusions were observed. Reflected light observations of the pyrobitumen on whole rock samples of the veins indicate many reflectance populations are present. Most particles are too small for quantitative measurement, but populations with reflectance less than 1.0%, about 1.5%, and 2 to 2.5% are present. The peak bitumen reflectance indicates a vitrinite reflectance equivalent (VRE) of about 1.5 to 1.7%. This VRE range, when converted to peak burial temperature using an empirical geothermometer, overlaps with the minimum paleotemperature from fluid inclusion measurements.

INTRODUCTION

Fluid inclusions are common in calcite, or in calcite and quartz veins in cores recovered from the MGE well. Geothermometry of fluid inclusions is employed here to estimate the minimum burial temperature recorded by fluid inclusions trapped during diagenesis of the host sandstone. The veins cut Middle Proterozoic (about 1,000 Ma) rocks at depths of 15,118, 16,044 and 16,058 feet.

Measurement of the phase transition temperatures in a fluid inclusion can give information on temperature, pressure, and the composition of fluids present during diagenesis. The homogenization temperature (T_h) marks a phase transition that is a quantitative property of the closed chemical system in the fluid inclusion. Ignoring complications, T_h can be directly interpreted as the minimum temperature of inclusion entrapment (see review by Roedder, 1984; Shepard and others, 1985).

Primary inclusions are formed by trapping of fluid during deposition of cement or fracture-filling minerals. Secondary fluid inclusions occur in healed microfractures and are younger than the host mineral. Usually, all that is known is that secondary inclusions formed sometime after crystal growth. The utility of fluid inclusions is that they indicate the thermal and fluid conditions at the time they formed. However, the timing of the trapping of inclusions is resolved only by determining superposition or crosscutting relationships. The absolute timing is usually not measurable directly. The paleotemperature data from fluid inclusions must be fixed by analysis of burial history in order to use T_h data in reconstructing the rocks' thermal history.

If only a minimum burial temperature estimate for a rock is required, then the constraints on inclusion origin and timing are not important. Primary or secondary inclusions can produce an estimate of the minimum burial temperature, if complicating factors are not significant.

The most common characteristics which limit the usefulness of fluid inclusions are: (1) fluid inclusions that have necked and closed with two phases present (e.g., liquid and vapor), resulting in the trapping of variable phase ratios; (2) trapping of a heterogeneous fluid in an inclusion (e.g., noncondensible gas and water); and (3) post-trapping reequilibration of the inclusion vacuole or liquid contents (such as the bitumen problem, described below).

All of these complicating factors affect the MGE samples. However, most changes in a fluid inclusion that make geothermometry invalid result in microscopically detectable variability in the vapor to liquid ratio; these inclusions should not be used to estimate minimum temperature of formation. In the MGE samples all inclusion types with a homogenization temperature measurable within a reasonable sedimentary temperature range were analyzed, with the restriction that inclusions within the same paragenetic population must have consistent vapor to liquid ratios.

SAMPLE SETTING

Three core samples were available that contained material that appeared suitable for fluid inclusion study. The shallowest sample at 15,118.6 feet (4608 m) contains a 1-2 cm wide calcite and quartz vein subparallel to the medium-gray sandstone bedding. The timing of quartz crystallization relative to calcite is complex (Ludvigson and Spry, this volume); while quartz both predates and postdates calcite, the latter is most common. The quartz is locally replaced by, and therefore, appears to predate some calcite. However, the quartz fills medial vein positions relative to calcite and postdates most of the calcite.

The other core samples at 16,044 and 16,058 feet contain simple-subplanar to complex-braided 1-3 mm calcite veins that crosscut the bedding planes of a medium-gray sandstone that generally are subparallel to the core's long axis. No orientation data are available, their relationship to regional stress patterns is unknown.

Crosscutting all these veins are abundant planes of secondary fluid inclusions suggesting that primary fluid inclusions may be replaced by the later fluids, so the mineral paragenesis may be misleading as to the relative timing of the fluid inclusions. Consequently, the fluid inclusion data are interpreted by grouping into temperature ranges rather than paragenetic sequence.

FLUID INCLUSION PETROGRAPHY

All the vein samples contained some usable fluid inclusions. Most of the inclusions range from sub-rectangular or negative crystal forms to irregular substellate forms, 5-15 μm in largest dimension. The typical occurrence is as a two-phase, aqueous-vapor- or natural-gas-bearing inclusion that is fracture-bound and of secondary origin. These fractures cut the crystals in complex multiple trail patterns to isolated subplanar trails. Uncommonly, fluid inclusions are clustered in three dimensional arrays, appearing as cloudy portions of crystals. These arrays may be primary crystal growth zones or shattered portions of crystals healed with numerous secondary inclusions. Finally, rare orphan fluid inclusions occur as isolated individuals without any notable relation to other inclusions or crystal features.

Trails or clusters of vapor or natural gas-rich inclusions are common in these samples, especially in the quartz host. These portions of the veins had extremely variable vapor to liquid ratios, ranging from nearly all liquid to essentially all gas. The irregular vacuole shape with narrow umbilicals extending towards other inclusions suggest formation by necking or post-trapping reequilibration.

Many of these inclusions, whether liquid or vapor rich, contain very small (about 1 μm) blebs of opaque black to translucent brown material which is interpreted to be bitumen. This bitumen is non-fluorescent rough-granular textured to smooth wall-coating material with no distinguishable crystalline outline suggesting that it is not an opaque daughter mineral. Much of the bitumen is attached to the vacuole wall or to the vapor bubble (which may oscillate by pseudobrownian motion). This bitumen is thought to form by the breakdown of petroleum trapped in the inclusion. Petroleum is thermodynamically metastable in crustal temperature and pressure conditions. Thus, petroleum trapped in an inclusion is susceptible to alteration with increasing burial and/or temperature. This possible change is important because fluid inclusion geothermometry assumes that the fluid in the mineral chamber has not changed molar volume after trapping. Petroleum fluid inclusions may isochemically react to form high-molecular-weight solid bitumen, or with increasing temperature may crack to smaller molecular weight hydrocarbons. Changes of fluid density within inclusions will change T_h by altering the vapor to liquid ratio, which may invalidate the assumption that T_h indicates the minimum entrapment temperature. This post-trapping alteration presents a severe constraint on the use of the fluid inclusion data.

Some planes of secondary fracture-bound inclusions do not contain bitumen, perhaps including other non-petroleum-bearing fluids trapped in the veins. In estimating minimum burial temperature, no inclusion that contained bitumen was used, although several were measured and fell into the T_h range of the low temperature group.

HEATING STAGE OBSERVATIONS

Phase transition temperatures in fluid inclusions were determined in a U.S. Geological Survey-designed gas-flow heating/freezing stage. Repeated calibration measurements using synthetic fluid inclusions indicate the accuracy of the temperature determinations is ±1° C in heating mode and ±0.2° C in freezing mode. Doubly polished sections suitable for fluid inclusion analysis were prepared using the method of Barker and Reynolds (1984). Because of the problems with fluid inclusions that contain bitumen or variable vapor-liquid volume ratios, the groups of inclusions that displayed these characteristics were either not measured or were excluded from calculation of mean homogenization temperature.

Homogenization

Repeated homogenization temperature determinations by cycling method shows homogenization occurs over a wide range (124-220° C) but falls into two distinct groups. The low temperature group between 124-155° C is found in all of the samples. The average T_h for this group was 140° C (mode =150° C; n=17; s=9° C). Most or all of these secondary inclusions are fracture-bound. These inclusions were generally well behaved, showing the expected sudden renucleation of a vapor bubble after about 20-30° C cooling from homogenization. Generally, no reequilibration was apparent during heating; as this would have been evidenced by increasing T_h during repetition of the measurements.

In the 15,118 foot sample, a high temperature fluid inclusion group ranging between 170-220° C was found. This group occurs, when the origin is determinable, as fracture-bound secondary inclusions. The average T_h for this group was 194° C (mode = 190° C, n=12, s=14° C)

Freezing

The formation of methane clathrates upon cooling complicates estimates of salinity and major cation composition in fluid inclusions (Hanor, 1980). Because this type of information was not the thrust of this investigation, these measurements were not made.

CRUSHING STAGE OBSERVATIONS

Fragments of the polished sections of all vein samples were opened in a crushing stage (Roedder, 1984). Only the sample at 15,118 feet gave useful results. The cleavage fragments were immersed in glycerin to check for noncondensible gas such as CO_2 and then in kerosene to check for petroleum gas. These samples contained rare to abundant fracture-bound, secondary planes of two-phase fluid inclusions. Bubbles that evolved from these samples when cracked on the crushing stage, did not dissolve in glycerin and many but not all of the bubbles rapidly disappeared in kerosene. The gas bubbles that rapidly dissolved in the kerosene are qualitatively identified as methane (Shepard and others, 1985). Some of the bubbles were not readily soluble in kerosene, requiring several hours to dissolve. This suggests that the inclusions contain two or more gases. The two common gases with the properties displayed on the crushing stage are methane and carbon dioxide.

LUMINESCENCE MICROSCOPY OBSERVATIONS

No fluorescent hydrocarbon inclusions were observed under blue light or peak UV (346 μm) excitation, although extensive searches of the polished rock sections were made. Cathodoluminescence microscopy was not available.

Bitumen Reflectance

Reflected light observation of the pyrobitumen in whole rock samples of the veins indicates it occurs throughout the samples as well as filling pores and microfractures in the enclosing rock. Most particles are too small for quantitative measurement, but three general ranges of material are present: at less than 1.0% reflectance, at about 1.5%, and at 2.3%. The highest bitumen reflectance group indicates a vitrinite reflectance equivalent (VRE) of about 1.5 to 1.7 % (Jacob, 1985). This VRE range, when interpreted as a peak burial temperature using an empirical geothermometer (Barker and Pawlewicz, 1986) overlaps the minimum paleotemperature estimated from fluid inclusions (200° C). The other groups apparently represent a later bitumen migration event into the rocks at less than peak temperature.

INTERPRETATION

To reiterate, the most direct use of fluid inclusion homogenization temperature data is to assume they represent a minimum temperature of entrapment (or host mineral formation) and therefore, not apply a pressure correction. Several conditions must be known if T_h is to be used as the inclusion trapping temperature (T_t). Common methods to correct T_h to T_t require knowledge of the phases present in an inclusion, pressure-volume-temperature properties of this system, and depth of inclusion formation (pressure correction method) or similar physico-chemical data from a different composition inclusion (intersecting isochore method). These requirements make pressure correction of fluid inclusion data a difficult, error-prone procedure. This is particularly true of the MGE well where the burial history, and consequently the depth of formation of the crystals, is speculative. However, calculations based on using the present depth as the depth of formation, hydrostatic pressure conditions with a low to moderate salinity, and ignoring the influence of non-condensible gases present, suggest the pressure correction would be on the order of 50° C (Potter, 1977).

All of these inclusions are suspected to contain natural gas because of their association with the gas-bearing aqueous inclusions in quartz and calcite veins at 15,118 feet. The T_h data from these inclusions were not corrected for pressure. The presence of natural gas can produce a large error in the pressure correction of T_h data to trapping temperature (Hanor, 1980). However, Hanor concludes that T_h of natural-gas-bearing aqueous inclusions can be used as the minimum temperature of entrapment if no post-entrapment leakage of gas and liquid has occurred. The conclusion of this fluid inclusion study is that these samples attained a minimum burial temperature of about 200° C, as indicated by the high-temperature-group average T_h without pressure correction.

The bottom hole (BHT) is 95° C at 17,851 feet (5,441 m). Adding a correction of 12.2° C to the BHT (AAPG, 1976) the estimated equilibrium formation temperature is about 105° C. Measured temperatures in the well are much lower than the estimates of minimum burial temperature from fluid inclusions. Therefore, the well has cooled markedly from the minimum burial temperature estimate of 200° C.

The distinctly different mean T_h of 140° C and 194° C for the fluid inclusion groups suggests that two thermal events have affected the rocks at about 15,000-16,000 feet. The 140° C event appears to follow the 200° C event. Fluid inclusions in calcite tend to reequilibrate to a higher T_h if exposed to temperatures higher than the original trapping temperature (Goldstein, 1986; Burruss, 1987; Prezbindowski and Larese, 1987). Therefore, the low temperature inclusions may have been trapped during cooling in the system to the present-day measured temperature of about 100° C at 15,000-16,000 feet. This cooling could occur by uplift and erosion, reduction in heat flow, and/or ebbing of the hydrothermal system that deposited the veins.

CONCLUSION

The minimum paleotemperature for rocks in the MGE well was about 200° C at 15,000-16,000 feet, based upon fluid inclusion geothermometry and bitumen reflectance.

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REVIEW OF CURRENT STUDIES OF PROTEROZOIC ROCKS IN THE AMOCO M.G. EISCHEID #1 PETROLEUM TEST WELL, CARROLL COUNTY, IOWA

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INTRODUCTION

The M.G. Eischeid #1 petroleum exploration test was drilled in 1987 by the Amoco Production Company to test the hydrocarbon potential of the clastic rocks of the Midcontinent Rift System (MRS) in Carroll County in west-central Iowa. The well reached a total depth of 17,851 feet, far surpassing the 5305-foot depth of the previous deepest well in the state, and making it one of the deepest in the midcontinent.

The Eischeid well penetrated 2802 feet of Phanerozoic strata overlying 14,898 feet of Keweenawan Supergroup clastic rocks before encountering a gabbroic crystalline basement at a depth of 17,700 feet. Preliminary investigation of samples of the Keweenawan clastic rocks from the well led to the differentiation by Witzke (this volume) of two informal groups and seven informal formations. The lower group is compositionally similar to and probably correlative with the Oronto Group of Wisconsin; the upper group is similar to the Bayfield Group of Wisconsin and was probably deposited in a similar setting.

Amoco Production Company granted permission for Iowa Department of Natural Resources Geological Survey Bureau (GSB) geologists and selected additional researchers to examine cores, cuttings, and logs from the Eischeid well prior to their release from confidential status for the production of this volume. The stratigraphy of all rock units (Phanerozoic and Proterozoic) encountered during the drilling of the Eischeid well were investigated, and the units identified by Witzke (this volume). The dificulties in identifying the contact between the lithologically similar Cambrian Mt. Simon Sandstone and the Upper "Red Clastic" Sequence were reviewed and rationale for picking the contact in the Eischeid well was discussed by McKay (this volume). The petroleum source rock potential of the thick sequences of dark gray to black shales and siltstones encountered in the Lower "Red Clastic" Sequence was investigated (Palacas et al., this volume) as was the porosity of sandstone dominated units above and below the dark, fine-grained rocks (Schmoker and Palacas, this volume). Preliminary petrographic studies (Ludvigson et al., this volume; Barnes, this volume), clay mineralogy investigations (Pollastro et al., this volume), and fluid inclusion studies (Barker, this volume; Ludvigson and Spry, this volume) have provided a basic understanding of the post-depositional history of the Keweenawan clastic units. Finally, the gabbro at the bottom of the Eischeid well was investigated and its age determined by Van Schmus (this volume).

A PRELIMINARY INVESTIGATION OF THE M.G. EISCHEID #1 SAMPLES AND LOGS

Samples and logs from the M.G. Eischeid #1 deep petroleum test well were studied by a number of scientists from the GSB, U.S. Geological Survey, and the academic community. These preliminary investigations were primarily directed toward the evaluation of the petroleum potential of the Proterozoic clastic units encountered during the drilling.

Stratigraphy of the M.G. Eischeid #1 "Red Clastic" Rocks

Beneath the Phanerozoic sequence, the M.G. Eischeid #1 well encountered 14,898 feet of clastic rocks associated with the Midcontinent Rift System, here assigned to the Keweenawan Supergroup. These clastic rocks were divided into two groups, informally named the Upper "Red Clastic" Sequence, subdivided into four formations, and the Lower "Red Clastic" Sequence, divided into three formations (Witzke, this volume).

The petrography of the Eischeid well was examined by point-counting 51 thin-sections produced by mounting cuttings in blue-dyed epoxy and stained to aid in the identification and discrimination of feldspar grains. The cuttings were sampled at 500-foot intervals and at additional intervals of interest as determined from the mud log. Also, studied were 16 thin sections prepared from five cored intervals. The results of these petrographic analyses are reported by Ludvigson and others (this volume) and Barnes (this volume).

Upper "Red Clastic" Sequence

The clastic rock sequences encountered at depths from 2802 to 10,510 feet in the M.G. Eischeid well were designated the Upper "Red Clastic" Sequence. The lithologies of the sequence, as interpreted from the mud log, down-hole geophysical logs, and petrographic and other studies, were described by Witzke (this volume). He divided the sequence into four formations, informally called (from the top) units H, G, F, and E (see Witzke, this volume, Figs. 2 and 3). Unit H was initially interpreted as a part of the Cambrian Mt. Simon Sandstone. However, studies by McKay (this volume), completed after the the preparation of several articles in this volume, described features of the sandstone-dominated strata between 2802 and 3615 feet that were not characteristic of the Mt. Simon in this region. McKay concluded that the interval was pre-Mt. Simon (pre-Dresbachian).

Witzke (this volume) concurred and informally named the interval Unit H. However, he noted that the interval was poorly consolidated and coarser-grained than "Red Clastics" strata typically encountered in deep wells in Iowa. He concluded that several possible interpretations of the stratigraphic position of Unit H were possible, but that a late Keweenawan age for the unit presents the simplest stratigraphic solution. Consequently Unit H is considered a part of the Upper "Red Clastics" Sequence for the purpose of the discussions presented in this paper.

Unit H. Unit H (2802-3615 feet) is poorly consolidated and dominated by two primary lithologies, a clear to light reddish-brown, fine- to very coarse-grained, arkosic sandstone, and a reddish-brown, micaceous, shaley to sandy siltstone (McKay, this volume). Petrographic study of thin-sections produced from cuttings collected from Unit H yielded a mean framework composition of $Q_{79}F_{17}L_4$ and documented all of the feldspars grains to be potassium feldspar (Ludvigson et al., this volume). McKay (this volume) also reported the presence of trace amounts of microbrecciated rock fragments, identical to those found downhole throughout a large part of the "Red Clastics" section. The presence of microbreccia chips probably implies that Unit H strata were affected by structural movements similar to those which created these tectonized fabrics throughout much of the Eischeid drillhole sequence (Ludvigson and Spry, this volume). This provides additional evidence for assignment of this unit to the Upper "Red Clastic" Sequence.

Unit H was divided into two formations by Witzke (this volume). He described an upper coarse sandstone interval, H-2 (2802-3100 feet), overlying H-1 (3100-3615 feet), a large-scale fining-upward sequence ranging from a coarse-grained basal unit to fine sandstones, siltstones, and shales near its top. He noted that the lithologies suggested an alluvial environment of deposition for Unit H.

Unit G. Unit G, encountered at depths from 3615 to 4690 feet, is dominated by pale gray (clear) to red-brown, fine- to medium-grained sandstone with interbedded red-brown and minor green siltstone and shale (Witzke, this volume). The sandstones are dominated by quartzose grains, with a mean framework grain composition of $Q_{76}F_{17}L_7$. The volcanic rock component of the lithic grain population in this interval (35%) is the highest observed in any clastic unit in the Eischeid well (Ludvigson et al., this volume).

Unit F. Unit F (4690-7020 feet) was subdivided into three generally fining-upwards sequences labeled (top down) F-3, F-2, and F-1 by Witzke (this volume). These sequences grade upward from basal red-brown to pale gray (clear), very fine- to fine-grained sandstones, to red-brown (in part, mottled light green to gray-green) shales and siltstones (Witzke, this volume). The sandstones have a mean framework grain composition of $Q_{69}F_{22}L_9$ (Ludvigson et al., this volume).

Unit E. The basal unit of the Upper "Red Clastic" Sequence, Unit E (7020-10,510 feet), is a thick, sandstone-dominated unit that is characterized by the highest percentage of lithic fragments in the Eischeid well, with a mean of

$Q_{67}F_{20}L_{13}$ (Ludvigson et al., this volume). The unit was subdivided into two descriptive intervals, E-2 (upper) and E-1 by Witzke (this volume).

Interval E-2 (7020-9740 feet) is dominated by red to brown, generally very fine- to fine-grained sandstones with red to brown (some mottled grayish-green) interbedded siltstones and shales (Witzke, this volume). Core #1 (8834-8844 feet), which sampled 10 feet of this interval, displayed horizontal bedding. Two facies were observed, a well stratified sandstone with low-angle cross-stratification and red mudstone rip-up clasts, and a massive, non-stratified sandstone with smaller mud clasts (Ludvigson et al., this volume).

Interval E-1 (9740-10,510 feet) contains more shale than E-2 and is composed of four relatively thin, fining-upward sequences, each grading upward from a basal very fine- to fine-grained sandstone to a red to dark brown shale and siltstone (Witzke, this volume).

Discussion of the Upper "Red Clastic" Sequence. The Upper "Red Clastic" Sequence occupies the same relative stratigraphic position as the Bayfield Group in the Lake Superior region. Both units are apparently dominated by fluvial deposition, with the possible exception of the Devils Island Sandstone of the Bayfield Group which may be a lacustrine deposit. There are, however, some compositional differences between the clastic rocks of the Bayfield Group and the Upper "Red Clastic" Sequence. The Bayfield Group is more mature, both in texture and mineralogy, than the underlying Oronto Group (Ojakangas, 1986), whereas the rocks of the Upper "Red Clastic" Sequence are mineralogically less mature than the Lower "Red Clastic" Series. Volcanic rocks fragments contribute less to Bayfield Group rocks than to the Oronto Group (Ojakangas and Morey, 1982). However, in the Eischeid well volcanic rock fragments are more common in the Upper "Red Clastic" Sequence than the Lower "Red Clastic" Sequence (Ludvigson et al., this volume). Finally, Eischeid drilling did not penetrate any Proterozoic quartz arenites, such as those seen in the Devils Island and Hinckley sandstones in the Lake Superior area.

The Bayfield Group and Upper "Red Clastic" Sequence do, however, share many characteristics. Both groups apparently overlie the initial MRS clastic sequence (Oronto Group and Lower "Red Clastic" Sequence). The Bayfield Group, as described by Ojakangas and Morey (1982), is dominated by fluvial deposition (excluding the possible lacustrine Devils Island Sandstone). The lithologies present in the Upper "Red Clastic" Sequence, as described by Witzke (this volume), and the petrology and sedimentary structures, as interpreted from the cored intervals by Ludvigson and others (this volume), also suggest a fluvial origin. The differences in the composition of the units of the Upper "Red Clastic" Sequence and the Bayfield Group can be explained by differences in the lithologies of source terranes.

Although no quartz arenites were encountered in the Eischeid well, Unit F displays the highest content of siltstone and shale of any unit in the Upper "Red Clastic" Sequence. These lower energy deposits may be related to the interpreted lacustrine deposits in the Devils Island Sandstone of the Bayfield Group, perhaps deposited by a low gradient river that flowed into a nearby lake.

Several trends are evident in the composition of the sandstone component of the Upper "Red Clastic" Sequence. First, the quartzose grain content increases upward in the sequence, from 67% in Unit E to 79% in Unit H. The QFL composition of the framework grains are comparable to compositions of units in the Lake Superior area (see Fig. 7, Anderson, "Review of the Precambrian ...," this volume.) Second, the average lithic rock fragment percentage decreases up-section from 13% in Unit E to 4% in Unit H. Finally, the volcanic rock component of the lithic rocks increased from 22% in Unit E to 62% in Unit G and the sedimentary and metamorphic rock component decreased from 65% in Unit E to 37% in Unit G. The compositions of the lithic fragments in the two intervals examined in Unit H were quite disparent and additional analyses are needed.

The relative increase in the concentration of volcanic rock fragments up-section through Unit G in the Upper "Red Clastic" Sequence of the Eischeid well may record the local, proximal, erosional unroofing of the basalts on the Iowa Horst. Well data and seismic interpretations from the trend of the MRS in Iowa indicate that Keweenawan sedimentary rocks were erosionally removed from most areas of the Iowa Horst, exposing underlying volcanic rocks prior to Phanerozoic sedimentation (Anderson, 1988). The lithic component of Unit H is dominated by sedimentary rock fragments unlike any known MRS clastic rock unit in the Lake Superior area.

Lower "Red Clastic" Sequence

The rocks encountered between 10,510 and 17,700 feet in the Eischeid well were informally named the Lower "Red Clastic" Sequence by Witzke (this volume). He divided the sequence into three informal units, (from the top) units D, C, and B (see Witzke, this volume, Fig. 4).

Unit D. The upper-most unit in the Lower "Red Clastic" Sequence, Unit D (10,510-14,980 feet), was described by Witzke (this volume) as a thick, generally fining-upward sequence that is dominated by sandstones in the lower half and siltstone to shale in the upper half. He subdivided the unit into four intervals, (from the top) D-4, D-3, D-2, and D-1. The sandstones in Unit D are quartz dominated (with a mean framework grain composition of $Q_{76}F_{21}L_3$) and the lithic component includes the highest average percentage of sedimentary and metamorphic rock fragments (74%) observed in any unit in the Eischeid well (Ludvigson et al., this volume).

Interval D-4 (10,510-11,960 feet) is dominated by red to brown (with minor light green to gray) shales in the upper half and red-brown siltstones in the lower half (Witzke, this volume). Core #2 (11,381-11,395 feet) was recovered from this interval and was described by Ludvigson and others (this volume). Two facies are displayed, the first composed of red, very fine- to fine-grained, cross-stratified sandstones; the second, a very fine-grained, horizontally-stratified sandstone with minor mudstone. These sediments are interpreted as representative of a fluvial setting with shallow channel fills, subaerial exposure, over-bank deposits, and then a return to shallow channel deposition (Ludvigson et al., this volume). The cored interval also displays fault-related deformation.

The underlying interval, D-3 (11,960-12,600 feet), is siltstone-dominated with minor interbedded sandstone and shale. This interval also contains gray to dark gray siltstones and shales and the first occurrences of black siltstones and black carbonaceous specks. The lower portion of this interval is dominated by light gray, fine- to medium-grained sandstones with minor shales and siltstones (Witzke, this volume).

The upper portion of interval D-2 (12,600-14,450 feet) as described by Witzke (this volume) is dominated by varicolored siltstone with some dark gray to black shaley laminations (some pyritic). The majority of the interval is sandstone-dominated with minor red-brown to gray-green siltstone and shale interbeds. Coarse sand grains are abundant in the basal portions of interval D-2.

The basal interval in Unit D, D-1 (14,450-14,498 feet), is a sandstone-dominated sequence with an upper varicolored shale and siltstone package Witzke (this volume). The sandstone is dominantly light gray to red-brown and fine- to medium-grained with minor coarse grains. Shales are red-brown to gray (some black) and contain siltstone interbeds. Down-hole logs indicated traces of methane and ethane in this interval. Witzke (this volume) reported the presence of intergranular black residues, possibly hydrocarbon residues.

Unit C. Unit C (14,980-16450 feet) is the most distinctive Keweenawan Supergroup clastic unit encountered in the M.G. Eischeid well. It is unique in its abundance of gray to black siltstones and shales, calcite cements, calcite vein-fills, and structural deformation. The unit is also the most thoroughly cored, with two cores totaling 39 feet taken during the drilling. The unit was subdivided into two intervals, an upper interval, C-2, and a lower interval, C-1.

Interval C-2 (14,980-15,700 feet) is an interbedded sequence of sandstones, siltstones, and shales, with gray to black siltstones and shales more common in the upper portion of the interval and red-brown to green-gray colors more common in the basal portion (Witzke, this volume). Methane and ethane were detected throughout the interval and black intergranular residues, possibly relict hydrocarbons, were reported. Also reported on the mud log in this interval (15,440 feet), were traces of chalcopyrite or native copper. A careful examination of samples from this interval, however, failed to confirm the presence of copper or chalcopyrite. Core #3 (15,096-15,120 feet), taken in the upper part of the interval, consists of horizontally laminated, millimeter to decimeter thick, interlayered, medium to dark gray shales and lighter gray siltstones to fine-grained sandstones (Ludvigson et al., this volume). These strata were interpreted to have been deposited in a lake or other body of standing water with a fluctuating water depth and intermittent influxes of coarse detritus (Ludvigson, this volume). Petrologic study of two samples of coarse detritus from interval C-2 yielded a mean of $Q_{72}F_{24}L_3$ (Ludvigson et al., this volume). The 24% feldspar observed in this interval is the greatest concentration observed in any interval in the Eischeid well.

Interval C-1 (15,700-16,450 feet) is dominated by light to dark gray siltstones and shales with dark brown to black shaley interbeds (Witzke, this volume). Calcite cements, spar, and vein fills are common in this interval and a carbonate-rich region near the bottom of the interval was identified as limestone on the mud log. Core #4 (16,043-16,058 feet) showed a high angle, tectonically-derived dip ranging from 65° to vertical and slightly overturned. The cored interval is composed of well laminated, interbedded, light gray, micaceous siltstone and medium gray to black shale (Ludvigson et al., this volume). Calcite veinlets and slickensided fault surfaces with calcitic rough facets are common in the core providing evidence of deformation in a reverse faulting mode, requiring lateral compression (Ludvigson and Spry, this volume).

Unit B. The basal clastic unit in the Eischeid well (16,450-17,700 feet) was informally called Unit B by Witzke (this volume) who described it as dominated by white to light gray and red, very fine- to fine-grained sandstone with possible siltstone and shale partings. Petrographic studies of Unit B sandstones by Ludvigson and others (this volume) indicates that it contains the highest percentage of quartzose grains observed in the "Red Clastic" sequence $Q_{87}F_{12}L_1$, with a small lithic component dominated by sedimentary and metamorphic clasts (74%).

Discussion of the Lower "Red Clastic" Sequence. The Lower "Red Clastic" Sequence is very closely similar to, and may correlate with, the Oronto Group in the Lake Superior area. The biggest difference between the two groups is the presence of a conglomerate facies in the Copper Harbor Conglomerate, the basal unit of the Oronto Group, and the lack of this facies in Unit B, the basal unit of the Lower "Red Clastic" Sequence. The Copper Harbor is dominated by the conglomeratic facies, composed primarily of mafic and felsic volcanic rock clasts. Associated sandstone facies also are dominated by volcanic rock fragments. Unit B is dominated by a sandstone facies that displays the highest quartzose grain content (87%) of any "Red Clastic" unit in the Eischeid well with no volcanic rock fragments observed.

This disparity can be explained by the positions of the two units relative to the central horst of the Midcontinent Rift. The Copper Harbor Conglomerate exposures are located on the central horst, which was an axial graben at the time of Copper Harbor deposition. The volcanic clast-dominated rocks of the Copper Harbor apparently were deposited by alluvial fans that were sourced from erosion of Keweenawan volcanic rocks capping the foot walls of normal faults that bounded the graben. The Eischeid well, and Unit B, is located in one of the clastic basins that flank the central horst, and was, therefore, outside of the central graben at the time of its deposition. The dominant quartzose grains in the unit suggest that it was sourced from an area of weathered granitic rocks, the most common lithology in the area around the MRS. The unit was probably deposited by rivers that flowed towards the axis of the rift. These rivers may have continued into the axial graben, cutting through foot-wall capping volcanics and incorporating volcanic rock fragments in their sediment load, and then depositing these materials, with Copper Harbor-like lithologies, on alluvial fans in the graben.

Unit C is lithologically and sedimentologically very similar to the Nonesuch Formation of the Oronto Group. The fine-grained components of Unit C display unidirectional, bi-directional, symmetrical, and trough cross-stratification and small-scale, amalgamated, hummocky cross-stratification. Shrinkage cracks are also present in this interval (Ludvigson et al., this volume). Milavec (1986) identified similar features in the Nonesuch Formation.

The Nonesuch has been interpreted as a lake deposit by most workers (e.g., Elmore, 1981; Daniels, 1982; Milavec, 1986) although some workers have suggested that it may have been deposited in a marine environment (Burnie et al., 1972; Hieshima, 1989, pers. com.). In either case the Nonesuch appears to have been deposited in a standing body of water. Sedimentary structures observed in cores of Unit C also suggest deposition in a standing body of water (Ludvigson et al., this volume). The presence of these lake deposits indicate that the body of water was not confined to the central horst, the position where correlative Nonesuch deposits are observed. Confidential petroleum industry seismic data suggest that Unit C may extend at least seven miles, and perhaps as much as 15 miles or more, west of the Iowa Horst in the Defiance Basin (Anderson, in preparation).

The black coloration in Unit C, like the Nonesuch Formation, is primarily the product of disseminated organic carbon, along with minor pyrite. Palacas and others (this volume) reported total organic carbon (TOC) values as high as 1.4% (averaging 0.6%) in the dark shales and siltstones of Unit C. The Nonesuch Formation has yielded maximum TOC values of almost 4% (Hieshima et al., 1989). The petroleum source-rock potential of Unit C is discussed later in this paper.

Unit D occupies the same stratigraphic position in the Eischeid well as the Freda Formation in the Oronto Group. Interpretation of Core #1 from Unit D suggested to Ludvigson and others (this volume) that the unit was deposited in a fluvial environment. A similar interpretation has been proposed for the Freda Formation (e.g., Daniels, 1982; Morey and Ojkangas, 1982). Petrographic studies of Unit D revealed a mean detrital composition of $Q_{76}F_{21}L_{3}$ compared to a mean composition of $Q_{52}F_{18}L_{30}$ for seven Freda samples reported by Daniels (1982). The lithic component of the Freda is dominated (72%) by volcanic rock fragments. The higher volcanic rock lithic component indicates that volcanic rocks were exposed in the Freda source area, however similar lithologies were apparently not exposed extensively in the source area of Unit D.

Unit A

The M.G. Eischeid #1 well encountered the Proterozoic crystalline basement at a depth of 17,700 feet. The rock, informally named Unit A (Witzke, this volume), is a virtually undeformed, medium-grained metagrabbro, consisting of relatively fresh augite, altered plagioclase, lesser amounts of hypersthene partially altered to chlorite or serpentine, and a minor amount of opaque minerals (Van Schmus et al., this volume).

This unit was probably intruded as a post-orogenic dike, sill, or pluton into the rocks of the Penokean Orogenic Belt. U-Pb analysis of zircons collected from Core #5 (17,733-17,742 feet) by Van Schmus and others (this volume) yielded an age of 1281 ± 50 Ma, significantly older than the igneous rocks of the Keweenawan Supergroup (ca. 1086-1108 Ma--U-Pb analysis). This age suggests a possible correlation with the mafic intrusive rocks of the Mackenzie dike swarm, a suite of mafic intrusives (ca. 1267-1270 Ma) that trend southwards from the northern regions of the Northwest Territories (NWT) of Canada, across portions of the District of Kewatin, and Manitoba, and also includes the Muskox layered mafic intrusion in the NWT (Van Schmus et al., this volume). If Unit A is a part of the Mackenzie swarm it would represent the southern-most known representative, about 2300 miles south of the northern end of the zone, and suggest possible correlation with the Corson diabase of southeastern South Dakota and/or the mafic dikes in the St. Francois Mountains of southeast Missouri.

The presence of a pre-Keweenawan rock at the crystalline surface in the Eischeid well indicates that Keweenawan extrusive rocks are presently confined to the region of the central graben of the MRS, and do not extend more than about 5 miles west of the gra)en-bounding fault in this area. If Keweenawan extrusive rocks were emplaced in this area they were lost to erosion prior th the deposition of Unit B. The presence of 1281 Ma, coarse-grained intrusive rocks at the basement surface directly below the sedimentary rocks of Keweenawan Supergroup Unit B, requires a period of erosion between 1281 Ma and about 1086-1108 Ma (the approximate age of Keweenawan volcanism) at which time the Unit A gabbro was unroofed.

Petroleum Potential of Eischeid Samples

Since the target of the Amoco drilling was to encounter economic deposits of petroleum and/or to learn more about petroleum potential of the sedimentary rocks of the Keweenawan Supergroup, core and cuttings samples from the M.G. Eischeid #1 well were examined by several workers who evaluated various aspects of past or present petroleum potential. Logs of the well did not indicate any oil shows, however trace amounts of methane and ethane were detected in units B, C, and D-1, and intergranular black residues (suggestive of oil movement) were reported in units B, C-2, and D-1. Black shales were reported by Witzke (this volume) in units B, C, and D-1, with Unit C being dominated by black to dark gray shales and siltstones; all were formerly organic-rich and potential petroleum source-rocks but are now overmature (Palacas et al., this volume). Finally, the large sandstone component of the the Upper and

Lower "Red Clastics" sequences, although showing little (Schmoker and Palacas, this volume) or no (Ludvigson et al., this volume; Barnes, this volume) porosity in the Eischeid well, may offer the potential for petroleum accumulation in other areas of the basin. Ludvigson and Spry (this volume) reported the presence of gaseous hydrocarbons, preserved in inclusions trapped in calcite that filled fractures, which they interpreted as the product of compressional stresses on Unit C rocks. This implies that gasseous (and liquid?) hydrocarbons were mobilized during the period of compression, probably associated with the development of the Iowa Horst. Structural traps would no doubt have also been produced during this late compressional phase of MRS history. Therefore, since there were apparently structural, and probably stratigraphic, traps available at the time that the petroleum was mobilized and if Keweenawan sandstones were locally more porous than was observed in the Eischeid samples, then petroleum may have been trapped. Because the stable midcontinent has undergone very litte tectonism, this trapped petroleum may still be present.

Source-Rock Potential

The source-rock potential of samples collected from 53 intervals, including Paleozoic and Proterozoic units, in the Eischeid well were analyzed for total organic carbon (TOC) content by Palacas and others (this volume). Selected samples were also analyzed for the maximum pyrolysis temperatures (T_{max}), the hydrogen index (HI), the oxygen index (OX), the production index (PI), free hydrocarbons (S_1), and the pyrolytic yield (S_3). Samples from the Upper "Red Clastic" Sequence all contained less than 0.1% TOC with most values in the 0.03%-0.05% range. The Lower "Red Clastic" Sequence showed higher levels of TOC, with Unit D values all less than 0.1% and some intervals as high as 0.08%. Unit C was the most organic rich, reaching a maximum value of 1.4% and averaging 0.6%. The only analysis from unit B displayed a TOC of 0.4%. These TOC values are low, but many petroleum geologists consider a TOC of 0.5% a minimum for a source rock (Palacas, 1989, pers. comm.). By this definition the carbonaceous rocks of Unit C can be considered a marginal source rock.

Although the TOC content of Unit C might suggest that it is a marginal source rock, determinations of T_{max} for samples collected from six intervals of Unit C core by Palacas and others (this volume) indicate that the organic material in the unit is over mature with respect to oil generation. They identified T_{max} values ranging from 497° to 508° C (averaging 503° C), considerably higher than the 460-465° C considered the maximum temperature at which liquid petroleum is produced. The 503° C T_{max} values for Unit C samples places the unit in the lower end of the wet gas zone and possibly the dry gas (metagenetic) zone (Palacas et al., this volume).

This advanced stage of thermal maturity was corroborated by several other studies including Barker (this volume), who measured homogenization temperatures of two-phase fluid inclusions in calcite and quartz veins in Unit C. He identified two populations of temperatures, indicating an earlier 200° C event and a later 140° C event, which he attributed to deep burial, elevated heat flow, or hydrothermal activity. He verified the 200° C event by measuring the peak bitumin reflectance (vitrinite reflectance equivalent) of Unit C rocks. Ludvigson and Spry (this volume) measured homogenization temperatures ranging from 125° to 178° C of two phase liquid-vapor fluid inclusions in calcite veins near the top of Unit C. Pallastro and others (this volume) used clay geothemometry to calculate a minimum paleotemperature of 175° -180° C for samples from the top of Unit C, and estimate a minimum bottom hole (17,851 feet) paleotemperature of 192° -197° C. Reflectance measurements on vitrinite-like particles, thermal alteration index measurements, and chloroform extractable organic matter indices, determined by Palacas and others (this volume), all indicated that the organic matter in unit C has advanced well into the gas generation zone. Palacas and others (this volume) also calculated genetic potentials of 0.1-0.4 HG/g and hydrogen indices from 20 to 80 mg HC/g TOC leading them to conclude that "at present, these shale beds have no potential of generating commercial petroleum..." They concluded, however, that significant amounts of hydrocarbon may have been generated in the geologic past.

Porosity

The porosity of the Proterozoic "Red Clastic" rocks in the M.G. Eischeid #1 well was investigated by Schmoker and Palacas (this volume), Ludvigson and others (this volume), and Barnes (this volume). Schmoker and Palacas utilized a variety of down-hole geophysical logs to calculate the porosity of sandstones between 11,450 and 17,340 feet (units B and C and the lower portion of Unit D). They determined porosity ranging from 1 to 6% (averaging 2.3%) in this interval, with greater porosity (3.5% or more) in about 14% of the section and distributed in the upper (in Unit D) and lower (in Unit B) zones. The mud log noted the detection of methane and ethane gases in these two zones and reported intergranular black residue, possibly a bitumin or pyrobitumin-like material (Schmoker and Palacas, this volume), in the lower zone.

Ludvigson and others (this volume) and Barnes (this volume) noted, however, that optically-resolvable porosity was not observed in samples below 8000 feet. The disparity between the low porosity reported by Schmoker and Palacas (this volume) and the virtual absence of porosity noted by Ludvigson and others (this volume) and Barnes (this volume) may be the presence of microporosity (not observable by optical microscopic techniques) or porosity as gas and/or liquid filled inclusions in calcite and quartz veins and calcite cements. Also, drill-cutting samples from many intervals included abundant loose (not cemented) grains, possible areas of incomplete cementation and higher porosity.

Conclusions

It appears that some intervals of the Lower "Red Clastic" Sequence, especially Unit C, in the M.G. Eischeid #1 well once contained high levels of organic carbon and probably produced large volumes of petroleum. However, hydrocarbon production probably reached its peak relatively early in the rocks' history, about 800 Ma (Palacas et al., this volume). Black intergranular residue reported on the Eischeid mud log may identify paths of petroleum migration through over- and underlying rocks, but no areas of past petroleum accumulations were identified. The organic rich rocks in the Eischeid well have realized most of their petroleum potential and are presently over mature and retain no potential for producing commercial petroleum. Porosity is also very low in the Proterozoic clastic rocks in the Eischeid well. Much of the original porosity may have been destroyed by compaction and the precipitation of intergranular cements.

Petroleum Potential of MRS Clastic Rocks

The absence of commercial petroleum, or even a petroleum potential in the Proterozoic clastic rocks in the M.G. Eischeid #1 well does not preclude the possible presence of commercial quantities of petroleum in other areas of the Midcontinent Rift System. The advanced state of maturity observed in Unit C by Palacas and others (this volume) is the result of high temperatures experienced by the unit, probably early in its history. The methane-filled fluid inclusions in tectonic veinlets described by Ludvigson and Spry (this volume) indicate that late Keweenawan deformation was coeval with petroleum migration in the Defiance Basin. Palastro and Finn (this volume) estimated minimum paleotemperatures between 175° and 197° C for this thermal event, considerably higher than the present estimated bottom-hole temperature of 105° C (Barker, this volume). It seems unlikely that this thermal regime was the product of deep burial alone. The source was probably elevated heat flow produced by the igneous activity along the trend of the Midcontinent Rift, and possibly hydrothermal activity associated with later stages of the magmatism. This elevated heat flow and geothermal activity would have been most pronounced nearest the axis of the central graben area of the rift. At more distal areas the maximum temperatures would probably not have been as high. Interpretations of seismic data acquired over the Defiance Basin by Anderson (in preparation) suggest that Unit C lithologies may continue for as far as 15 miles from the Iowa Horst (originally the central graben). If Unit C also contained significant amounts of organic carbon away from the central graben, these organic-rich strata may not have been exposed to the high paleotemperatures experienced by rocks closer to the axis of the rift. Consequently, these rocks might not have released their petroleum as early as rocks closer to the center of the MRS, and petroleum may still remain in stratigraphic and/or structural traps. Citing fluid inclusion and isotopic evidence, Ludvigson and Spry (this volume) suggested that during uplift of the axial horst, fluid transport in the Keweenawan sedimentary basins was away from the rift axis. The petroleum would have migrated up dip, generally away from the axis of the rift, and the best potential exploration targets may exist on the outer flanks of the Midcontinent Rift System (Ludvigson and Spry, this volume).

CONCLUSIONS

The Amoco M.G. Eischeid #1 petroleum test penetrated a "normal" Phanerozoic rock sequence, dominated by Paleozoic marine carbonates, shales, and sandstones, to a depth of 2802 feet. Below the Phanerozoic section, 14,898 feet of Middle Proterozoic Keweenawan Supergroup clastic rocks were encountered. Two informal groups were differentiated and subdivided into seven informal formations. The upper group is characterized by fining upward sequences, dominated by reddish sandstones interpreted as fluvial in origin, and probably representing deposition in an environment similar to most of the Bayfield Group of Wisconsin. The lower group includes upper and lower sandstone-dominated sequences interpreted as fluvial in origin, separated by a formation dominated by dark gray to black siltstones and shales, interpreted as the product of deposition in a standing body of water, probably a lake. This lower group is closely similar to the Oronto Group of Wisconsin.

Source rock investigations of the dark gray and black siltstones and shales identified an average TOC of 0.6%, with a high value of 1.40% detected. The organic material in these rocks is apparently overmature (in the lower "wet gas" to upper "dry gas" phase) and has an average genetic potential of 0.22 mg/g, hydrogen indices of about 40 mg/g, and chloroform extractable bitumens of 30 ppm. The rocks presently retain no potential for generating commercial quantities of petroleum. Study of down-hole logs indicated average porosities of 2.3% in sandstones above and below the dark siltstones and shales, however, no porosity was microscopically observed in samples from this interval.

Although the dark shales and siltstones presently have no potential for generating large quantities of petroleum, it is likeky that they generated large volumes of petroleum in the geologic past, probably relatively soon after their deposition. Black, intergranular residue in sandstones above and below the dark, fine-grained units may record petroleum movement following this early release. The early petroleum generation was probably related to elevated crustal heat flow levels and possible hydrothermal activity following late rift magmatism. Organic-rich units further from the rift axis may not have experienced the same high heat conditions and may have yielded petroleum later in their histories. Such petroleum might still exists in traps in these distal areas.

At a depth of 17,700 feet the M.G. Eischeid well penetrated into gabbro at the crystalline basement surface. This gabbro, probably a dike or sill, yielded a zircon age of about 1280 Ma, suggesting that the unit is probably associated with the Mackenzie dike swarm of Canada, the southern-most known occurrence of a Mackenzie dike.

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