Clastic Rocks Associated with the Midcontinent Rift System in Iowa

U.S. GEOLOGICAL SURVEY BULLETIN 1989–I

Chapter I

Clastic Rocks Associated with the Midcontinent Rift System in Iowa

By RAYMOND R. ANDERSON and ROBERT M. McKAY

U.S. GEOLOGICAL SURVEY BULLETIN 1989

STRATEGIC AND CRITICAL MINERALS IN THE MIDCONTINENT REGION, UNITED STATES

WARREN C. DAY and DIANE E. LANE, Editors

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

Published in the Central Region, Denver, Colo.
Manuscript approved for publication October 20, 1996.
Photocomposition by Norma J. Maes.

UNITED STATES GOVERNMENT PRINTING OFFICE: 1997

For sale by
U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Anderson, Raymond R.
Clastic rocks associated with the Midcontinent Rift System in Iowa / by Raymond R. Anderson and Robert M. McKay.
p. cm. — (Strategic and critical minerals in the midcontinent region, United States ; ch. I) (U.S. Geological Survey bulletin ; 1989)
Includes bibliographical references (p. –).
Supt. of Docs. no. : I 19.3 : 1989–I
1. Geology, Stratigraphic—Proterozoic. 2. Geology—Iowa. 3. Keweenawan Rift. I. McKay, Robert M. II. Title. III. Series. IV. Series: U.S. Geological Survey bulletin ; 1989.
QE75.B9 no.1989–I
[QE653.5]
557.3 s—dc21 96–50394
[551.7’15’09777] CIP

CONTENTS

Abstract **I1**
Introduction **I1**
The Midcontinent Rift System (MRS) in Iowa **I3**
MRS clastic rock data **I4**
- The well record in Iowa **I4**

Geophysical data **I4**
- Gravity anomaly data **I4**
- Magnetic anomaly data **I4**
- Reflection seismic data **I5**

Clastic units associated with the MRS **I7**
- Reagan Sandstone **I7**
- Mount Simon Sandstone **I7**
- Red clastics **I7**
  - History of the term “Red clastics” **I7**
  - The M.G. Eischeid #1 deep petroleum test well **I9**
    - Stratigraphy of the M.G. Eischeid #1 Red clastics **I10**
      - Upper Red clastics sequence **I10**
      - Lower Red clastics sequence **I12**
  - Red clastics basins flanking the Iowa Horst **I16**
    - Western flanking basins **I16**
      - Duncan Basin **I16**
      - Defiance Basin **I16**
    - Eastern flanking basins **I16**
      - Wellsburg Basin **I17**
      - Ankeny Basin **I18**
      - Shenandoah Basin **I18**
  - Clastic basins on the Iowa Horst **I19**
    - Stratford Basin **I19**
    - Jewell Basin **I19**
    - Mineola Basin **I19**
    - Ames Block **I20**
- Summary of Red clastics in Iowa **I23**
- Depositional history of MRS clastic rocks in Iowa **I24**
  - MRS lower Red clastics sequence **I24**
  - MRS upper Red clastics sequence **I24**
- Problems associated with differentiation of clastics **I25**
  - Investigation of the UPH–2 core **I25**
  - Reinterpretation of the #1 Wilson well **I26**
    - Petrographic analysis **I26**
    - Examination of fossils **I26**
    - Examination of chip samples **I29**
    - Conclusions **I31**
  - Re-examination of the #1 Huntley well **I31**
- Evaluation of criteria for picking the Mount Simon–Red clastics contact **I32**

Metallic mineral potential of MRS clastic rocks in Iowa **I35**
Petroleum resources **I35**
- Petroleum potential studies of Eischeid samples **I35**
  - Source-rock potential **I35**

Porosity **I36**
Conclusions **I36**
Petroleum potential of MRS clastic rocks **I36**
Conclusions **I37**
Acknowledgments **I38**
References cited **I38**
Appendix I1. Results of petrographic analyses of thin-sectioned samples collected from basal Mount Simon Sandstone and Red clastics interval of the M.G. Eischeid #1 well in Carroll County, Iowa **I43**
Appendix I2. Results of petrographic analyses of thin-sectioned samples collected from Mount Simon Sandstone and Red clastics intervals of several wells in Iowa and Illinois **I44**

FIGURES

I1.–I2. Maps showing:
I1. Location and major lithologies of the Midcontinent Rift System **I2**
I2. Structural components of the Midcontinent Rift System in Iowa **I3**
I3. Chart showing comparative Keweenawan stratigraphy of the Midcontinent Rift region **I5**
I4.–I6. Maps showing:
I4. Major features of the Midcontinent Rift System in Iowa displayed on the "Bouguer Gravity Anomaly Map of Iowa" **I6**
I5. Major features of the Midcontinent Rift System in Iowa displayed on a modified version of the "Aeromagnetic Anomaly Map of Iowa" **I8**
I6. Locations of Petty-Ray Geosource, Inc., reflection seismic profiles on a map of major features of the Midcontinent Rift System in Iowa **I9**
I7–I8. Generalized lithologic logs of:
I7. Upper Red clastics sequence from M.G. Eischeid #1 deep petroleum test well, Carroll County **I11**
I8. Lower Red clastics sequence from M.G. Eischeid #1 deep petroleum test well, Carroll County **I13**
19. Quartz–feldspar–lithic grain (QFL) diagrams for Keweenawan Supergroup clastic rocks from Lake Superior area and M.G. Eischeid #1 well, Carroll County **I15**
I10.–I13. Maps showing thickness of:
I10. Red clastics preserved in basins flanking Iowa Horst **I18**
I11. Lower Red clastics sequence in Stratford and Jewell Basins **I20**
I12. Upper Red clastics sequence in Mineola Basin **I21**
I13. Upper Red clastics sequence, lower Red clastics sequence, and total Red clastics on Ames Block **I22**
I14. Diagram of depositional environment of unit B and lower Oronto Group equivalent rocks **I23**
I15.–I16. Charts showing:
I15. Stratigraphy and construction history of #1 Wilson oil exploration well, Page County **I27**
I16. Historical interpretations of stratigraphy near base of #1 Wilson oil exploration well, Page County **I28**
I17. Lithic log and quartz–feldspar–lithic grain (QFL) diagram for part of #1 Wilson oil exploration well, Page County **I29**
I18. Photographs of selected microfossils recovered from chip samples from #1 Wilson oil exploration well, Page County **I30**

I19. Back-scattered electron photomicrograph of Cryptostome bryozoan from #1 Wilson oil exploration well, Page County **I31**
I20. Chart showing stratigraphy and construction history of #1 Huntley oil exploration well, Butler County **I33**
I21. Lithic and gamma logs and quartz–feldspar–lithic grain (QFL) diagram for part of #1 Huntley oil exploration well, Butler County **I34**
I22. Quartz–feldspar–lithic grain (QFL) diagram of analyses of Mount Simon Sandstone and Red clastics from selected Iowa wells **I35**

TABLES

I1. Iowa wells penetrating the Midcontinent Rift System Red clastic rocks **I10**
I2. Dimensions of Red clastics basins in Iowa **I17**

METRIC CONVERSION FACTORS

Multiply	By	To obtain
feet	0.3048	meters
miles	1.609	kilometers
square miles	2.590	square kilometers
cubic miles	4.168	cubic kilometers

Clastic Rocks Associated with the Midcontinent Rift System in Iowa

By Raymond R. Anderson[1] *and* Robert M. McKay[1]

Abstract

The Middle Proterozoic Midcontinent Rift System (MRS) of North America is a failed rift that formed in response to region-wide stresses about 1,100 Ma. In Iowa, the MRS is buried beneath 2,200–3,500 ft of Paleozoic and Mesozoic sedimentary rocks and Quaternary glaciogenic deposits. An extremely large volume of sediments was deposited within basins associated with the rift at several stages during its development. Although the uplift of a rift-axial horst resulted in the erosional removal of most of these clastic rocks from the central region of the MRS in Iowa, thick sequences are preserved in a series of horst-bounding basins. Recent studies incorporating petrographic analysis, geophysical modeling, and other analytical procedures have led to the establishment of a preliminary stratigraphy for these clastic rocks and interpretations of basin geometries. This information has allowed the refinement of existing theories and history of MRS formation in Iowa. Additionally, drill samples previously interpreted as indicating the existence of early Paleozoic basins overlying the Proterozoic MRS basins were re-examined. Samples previously interpreted as deep-lying Paleozoic rocks are now known to have caved from upper levels of the drillhole and were out of stratigraphic position. No deep Paleozoic basins exist in this area. These investigations led to the development of petrographic parameters useful in differentiating the Proterozoic MRS Red clastics from Paleozoic clastic rocks having similar lithologies.

INTRODUCTION

The Middle Proterozoic Midcontinent Rift System (MRS) extends from eastern Lake Superior, south and west across northwestern Wisconsin, southeastern Minnesota, central and southwest Iowa, southeastern Nebraska, and northeastern Kansas, with related dikes continuing into Oklahoma (fig. I1). Over most of its length the MRS is dominated by a series of axial horsts, composed primarily of mafic volcanic rocks, and flanked by clastic-filled basins. Related clastic rocks are also locally preserved on the central horsts. MRS clastic rocks are exposed in the Lake Superior region of Minnesota, Wisconsin, and Michigan, but are buried beneath Phanerozoic strata south of that region.

In Iowa the MRS is dominated by a central horst primarily composed of mafic igneous rocks (the Iowa Horst) flanked by five clastic-filled basins (Anderson, 1988). The rocks of the MRS in Iowa are buried beneath [2]2,200–3,500 ft of Phanerozoic marine and terrestrial sedimentary rocks and glacial drift. MRS rocks are known only from sparse drill samples and interpretation of their geophysical signatures. Drill samples in Iowa include only 14 penetrations of MRS clastic rocks, most of which are shallow. These rocks have historically been called Red clastics (Norton, 1912). Most of these drill penetrations are shallow, and three include cored intervals.

Modeling of gravity and magnetic data over the MRS led to the interpretation of clastic-filled basins flanking the Iowa Horst (fig. I2). They include on the west (north to south) the Duncan and Defiance Basins and on the east the Wellsburg, Ankeny, and Shenandoah Basins (Anderson, 1988). Two basins preserving Red clastics were also modeled on the Iowa Horst, the Stratford and Mineola Basins (Anderson, 1988). Recently, two additional areas of Red clastics were identified on the Iowa Horst, the Jewell Basin and Ames Block (Anderson, 1992). Additionally, new modeling of a series of gravity profiles, controlled by reflection seismic and magnetic data, has led to the delineation of the geometries of these basins and estimation of the volumes of clastics preserved in each (Anderson, 1988).

---

[1]Iowa Department of Natural Resources, Geological Survey Bureau, 109 Trowbridge Hall, Iowa City IA 52242–1319.

[2]Measurements of drill holes on which most thicknesses are based were in feet.

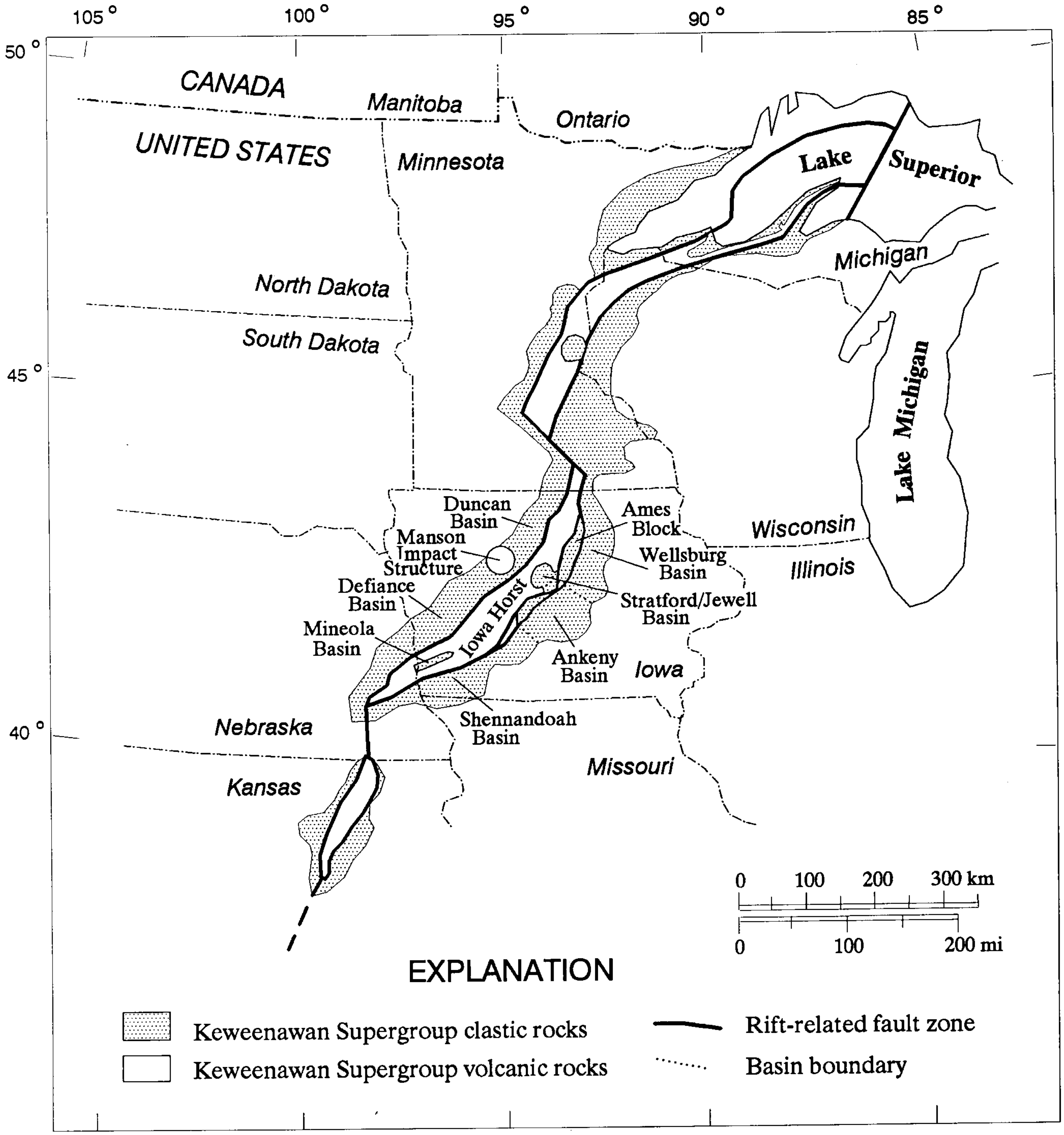


Figure I1. Location and major lithologies of the Midcontinent Rift System (MRS) (from Palacas and others, 1990).

Drilling of the M.G. Eischeid #1 deep petroleum test well by the Amoco Production Company in 1987 produced a suite of chip samples and cores that allowed the erection of an informal stratigraphy for the Red clastics. This included the identification of two "groups" and seven "formations" (McKay, 1990; Witzke, 1990). A series of studies of these samples and associated logs (see Anderson, 1990a) also provided a wealth of information about the depositional history, thermal maturity, hydrocarbon potential, and diagenetic history of these rocks.

Study of chip samples collected during the drilling of the #1 Wilson and #1 Huntly oil tests suggested the presence of thick sequences of basal Paleozoic clastic rocks (Bunker, 1982; Bunker and others, 1988; Sims, 1990). The presence of these thick sequences was interpreted as evidence of Middle Cambrian reactivation and subsidence of

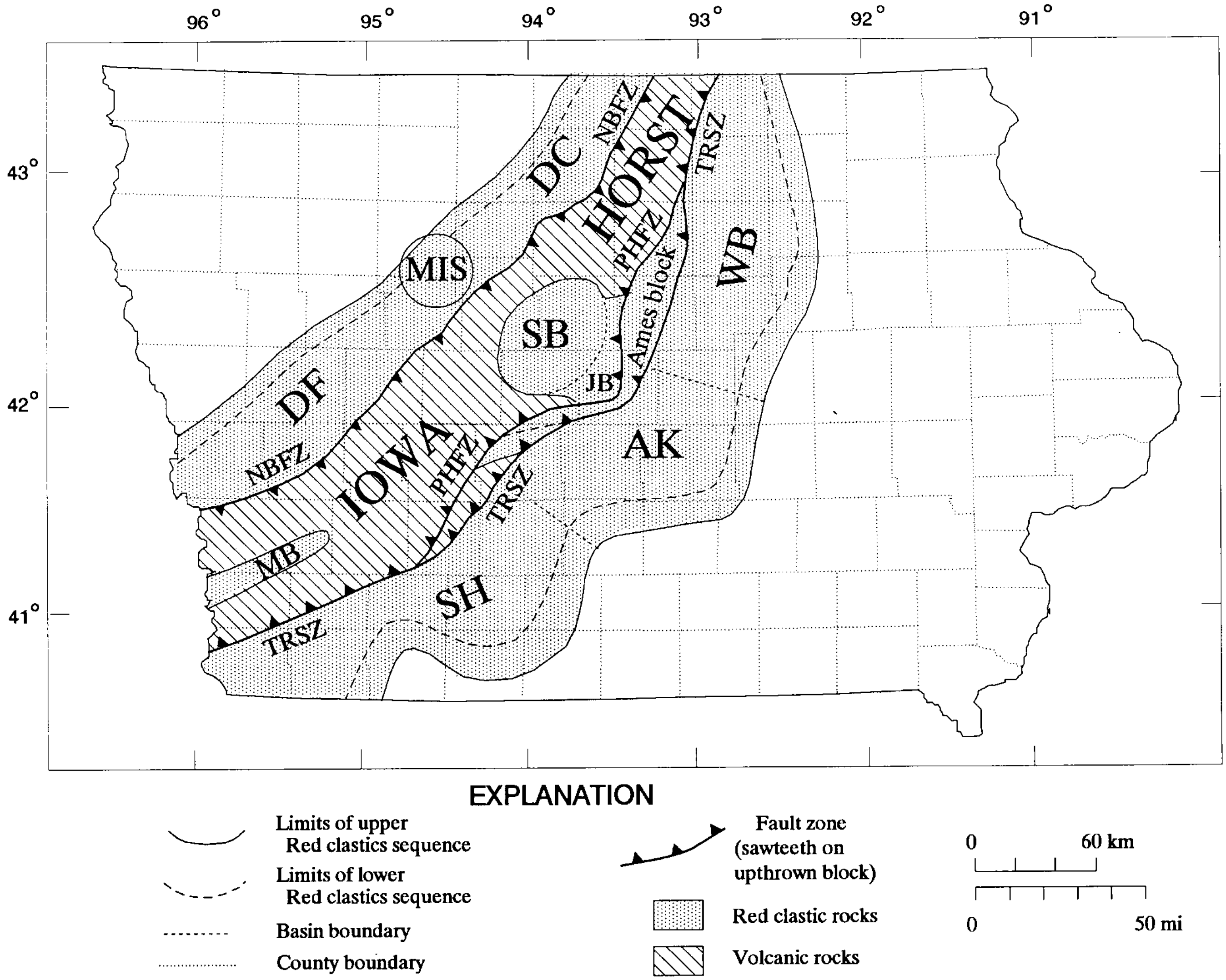


Figure I2. Structural components of the Midcontinent Rift System (MRS) in Iowa (modified from Anderson, 1992; and Anderson, 1995, fig. 1, p. 56, copyright ©1995 Kluwer Academic Publishers, used with kind permission from Kluwer Academic Publishers). NBFZ, Northern Boundary Fault Zone; TRSZ, Thurman-Redfield Structural Zone; PHFZ, Perry-Hampton Fault Zone; DF, Defiance Basin; DC, Duncan Basin; SH, Shenandoah Basin; AK, Ankeny Basin; WB, Wellsburg Basin; SB, Stratford Basin; JB, Jewell Basin; MB, Mineola Basin; MIS, Manson Impact Structure.

the Red clastics basins. These samples were re-examined using petrographic and SEM techniques to evaluate the earlier interpretations. Additionally, samples of basal Paleozoic clastic rocks from many areas of Iowa and Illinois were petrographically examined to determine their characteristics. This included a study of the thick sequence of Cambrian Mount Simon Sandstone recovered in the Consolidated Edison UPH–2 core from northwestern Illinois.

THE MIDCONTINENT RIFT SYSTEM (MRS) IN IOWA

The Iowa segment of the MRS extends about 300 mi southwestward from the southern end of the Belle Plaine Fault Zone just north of the Iowa border to eastern Nebraska, where it is truncated by a second major transfer fault, a north- to northeast-trending structure having a trend apparently coincident with the Big Blue River. The Iowa segment is dominated by the Iowa Horst (Anderson, 1988), which is bounded by the Thurman-Redfield Structural Zone on the southeast and the Northern Boundary Fault Zone (Anderson, 1988) on the northwest, and flanked by basins that contain clastic sedimentary rocks as much as 30,000 ft thick, including a denser basal and a less-dense upper sequence. The three clastic basins identified east of the Iowa Horst in Iowa (fig. I2), the Wellsburg, Ankeny, and Shenandoah Basins, and the two basins west of the horst, the Duncan and Defiance Basins, are identified by their pronounced gravity minima. They are interpreted as depressions filled with clastic sedimentary rocks of relatively low density (Anderson, 1992). The three basins southeast of the Iowa Horst apparently are interconnected, forming a continuous sequence of clastic rocks. The two basins northwest of the Iowa Horst are connected in a similar fashion. The areal extent of the eastern basins appears to be slightly greater than that of the western basins, but the MRS is nearly symmetrical in cross section normal to the strike of the feature.

The igneous and sedimentary rocks that were emplaced during the formation of the MRS in Iowa display pronounced gravity and magnetic anomalies that extend continuously to the Lake Superior region; in the Lake Superior region these rocks are assigned to the Keweenawan Supergroup (King, 1978). MRS rocks sampled during drilling in Iowa are very similar to rocks exposed in the Lake Superior area (fig. I3). Therefore, the name "Keweewnawan Supergroup" also was applied to all igneous and sedimentary rocks associated with the Midcontinent Rift System in Iowa by Anderson (1992). Most of the MRS clastic sedimentary rocks that were deposited in the axial areas of the structure were subsequently erosionally removed during uplift of the Iowa Horst. These clastic rocks were, however, preserved on a step-faulted block on the eastern edge of the horst in central Iowa (the Ames block), in the Stratford and Jewell Basins in the center of the horst, and in the Mineola Basin on the axis of the horst at the Nebraska border (Anderson, 1992).

MRS CLASTIC ROCK DATA

The clastic rocks associated with the MRS in Iowa—informally called Red clastics—are buried beneath 2,200–5,500 ft of Phanerozoic strata. Since they are not known to contain economic levels of mineralization and are not used as aquifers in Iowa, few wells penetrate them. Study of the few well samples of Red clastics and analysis of geophysical data provide the only data on these rocks.

The Well Record in Iowa

Fourteen wells are known to penetrate Red clastic strata in Iowa (table I1). Petroleum exploration wells account for five of these penetrations (total of 19,197 ft) and water wells for four penetrations (total of 1,064 ft); three drillholes (total of 75 ft) were drilled during the development of underground natural gas storage structures, and one hole was a research core into the Manson Impact Structure (370 ft). Cores of Red clastics in Iowa include the three gas storage structure wells (total 75 ft), four short intervals of the M.G. Eischeid #1 oil test (totaling 63 ft), and the M–4 research core into the Manson Impact Structure (370 ft). The deepest and most significant Red clastics penetration in Iowa is the M.G. Eischeid #1 deep petroleum test well, drilled by the Amoco Production Company in 1987. The Eischeid well penetrated more than 14,898 ft of MRS clastics from which chip samples were collected at intervals of 20–30 ft. The M–4 core encountered a Red clastics section that was stratigraphically thinned and overturned by the impact.

GEOPHYSICAL DATA

Much of our current understanding of the volume and areal distribution of Red clastics in Iowa is based on interpretation of geophysical data. These data include gravity data, with a 6-mi grid of points covering almost all of Iowa, supplemented by areas of 1-mi-spaced coverage. Analog aeromagnetic data was collected over the entire state of Iowa between 1953 and 1972. This data was obtained along 1-mi-spaced flightlines, most at an altitude of 500 ft. The final set of geophysical data over the MRS is reflection seismic data, collected over the MRS in the early to mid-1980's by exploration and geophysical companies as a part of programs to explore MRS clastics. Data collected along seven lines of profile by Petty-Ray Geosource, Inc., was made available for investigations, as was one short line from the the AMOCO Production Company.

Gravity Anomaly Data

The "Bouguer Gravity Anomaly Map of Iowa" (Anderson, 1981) clearly displays anomalies produced by the major lithologies that characterize the MRS in Iowa (fig. I4). Ranging from north-central Iowa to the southwest corner of the state, the strongly positive axial anomaly is the result of the thick sequence of dense, mafic-dominated volcanic and plutonic rocks that dominate the Iowa Horst and its shallow location at the Precambrian surface. The flanking gravity minima are produced by the thick sequences of less dense, rift-related clastic sedimentary rocks that are preserved in the basins marginal to the horst. The clastic rocks associated with the MRS have modeled densities ranging from 2.40 to 2.75 g/cm^3, much lower than associated crustal rocks whose densities range from 2.67 to 2.79 g/cm^3 (Anderson, 1992). Five clastic-filled flanking basins are defined by closed contours of gravity minima along the flanks of the Iowa Horst. The very steep gravity gradient between the axial high and the flanking lows attests to the abrupt contact between the two features, their density contrast, and the very large volumes of the disparate lithologies.

Magnetic Anomaly Data

Over most of its trend in Iowa, the magnetic signature of the MRS (fig. I5) is characterized by a series of linear anomalies following the trend of the gravity anomaly. Magnetic intensities are generally within a few hundred gammas (nanoteslas) of regional values, as compared to anomalies for typical intrusions, which can exceed 1,000

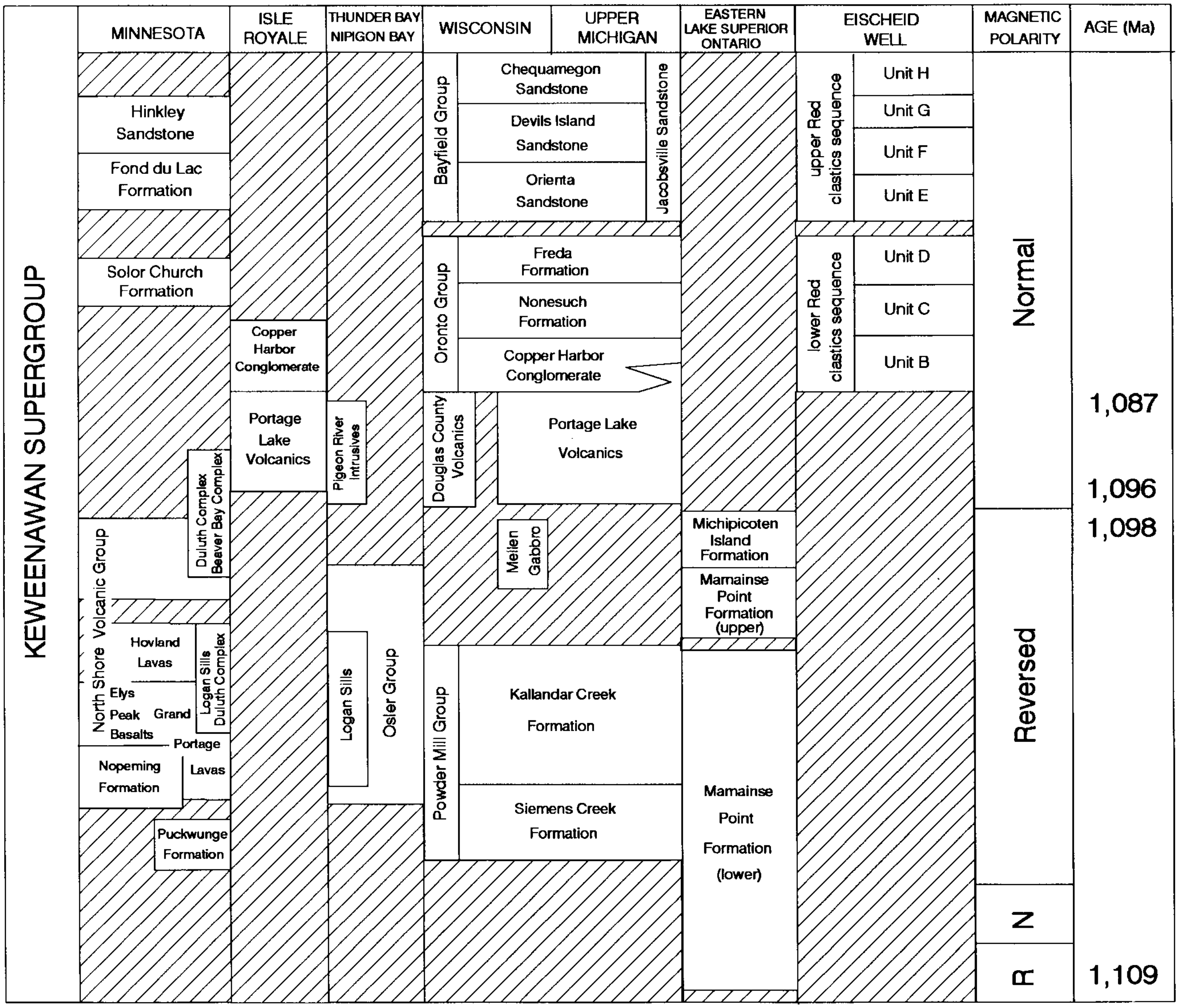


Figure I3. Comparative Keweenawan stratigraphy of the Midcontinent Rift region. Modified from Green (1982), Anderson (1992), and Anderson (1997, fig. 5, modified with permission of the publisher, the Geological Society of America, Boulder, Colo., U.S.A., copyright © 1997 Geological Society of America).

gammas (Carmichael and Black, 1986). The lack of a strong magnetic signature associated with the generally highly magnetic mafic igneous rocks of the Iowa Horst can probably be attributed to a combination of the strong remanent components in these rocks and the vertical sequence of normal and overlying reversely polarized rocks. The clastic rocks that fill the flanking basins are magnetically transparent. The increase in the depth of the underlying magnetic basement results in a lowering of the magnetic surface and observed aeromagnetic field intensity. This creates, in effect, a filtering out of the shorter wavelength components of the field. On the magnetic map of Iowa (Zietz and others, 1976), this filtering produces a series of smooth, low-intensity magnetic minima having a general trend parallel to the rift axis and flanking the Iowa Horst. A close examination of the more detailed (20-gamma contour interval) “Aeromagnetic Map of Central Iowa” (Henderson and Vargo, 1965) clearly shows the contact of the magnetic (igneous) rocks of the Iowa Horst with the nonmagnetic (clastic) rocks of the flanking basins. The shallow depth of the magnetic rocks of the Iowa Horst produces a high-relief anomaly surface, characterized by closely spaced, tightly curving contours. Off the horst, the greater depth of the magnetic basement beneath the clastics produces much more subdued relief having more widely spaced, smoothly curving contours.

Reflection Seismic Data

Reflection seismic data originally collected by Petty-Ray Geophysical Geosource, Inc., were released by

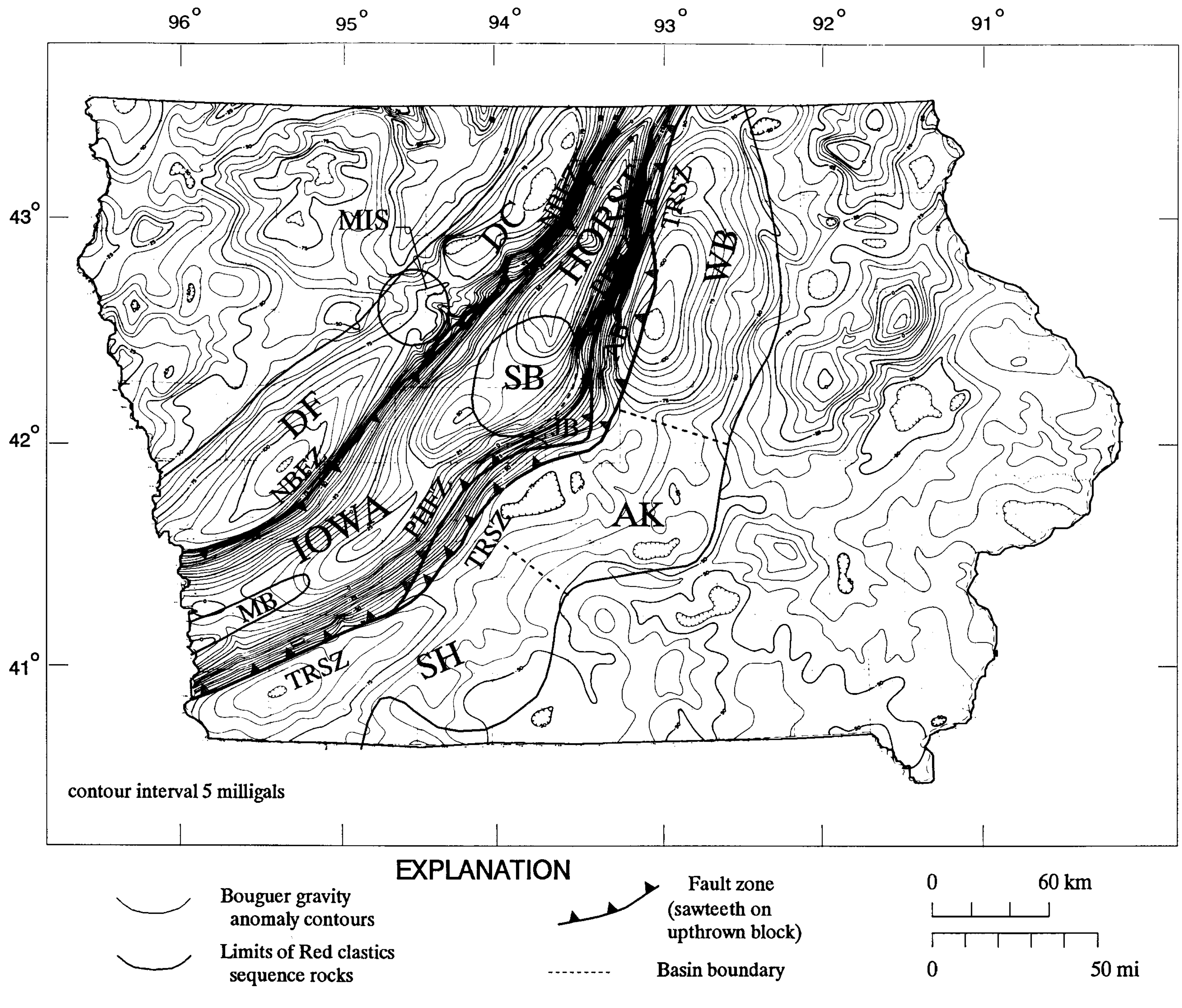

96°
95°
94°
93°
92°
91°
43°
42°
41°
MIS
DC
HORST
TRSZ
WB
SB
DF
NBEZ
IOWA
PHFZ
TRSZ
AK
MB
SH
TRSZ
contour interval 5 milligals
EXPLANATION
Bouguer gravity anomaly contours
Limits of Red clastics sequence rocks
Fault zone (sawteeth on upthrown block)
Basin boundary
0
60 km
0
50 mi

Figure I4 (previous page). Major features of the Midcontinent Rift System (MRS) in Iowa displayed on the "Bouguer Gravity Anomaly Map of Iowa" (from Anderson, 1992; and Anderson, 1997, fig. 8, modified with permission of the publisher, the Geological Society of America, Boulder, Colo., U.S.A., copyright © 1997 Geological Society of America). NBFZ, Northern Boundary Fault Zone; TRSZ, Thurman-Redfield Structural Zone; PHFZ, Perry-Hampton Fault Zone; DF, Defiance Basin; DC, Duncan Basin; SH, Shenandoah Basin; AK, Ankeny Basin; WB, Wellsburg Basin; SB, Stratford Basin; JB, Jewell Basin; MB, Mineola Basin; AB, Ames Block; MIS, Manson Impact Structure.

Halliburton Geophysical Services, Inc., for investigation by Anderson (1992). These seismic lines are currently available from the Wisconsin Geologic and Natural History Survey in Madison, Wisc. Data released included final stack and migrated profiles and profile location maps along seven lines (fig. I6). Three east-west lines (profiles 7, 12, and 9) completely cross the Iowa Horst and extend over both flanking basins (although profile 7 displays no useful information below Phanerozoic reflectors). One more east-west line (profile 11) and three north-south lines (profiles 8, 10, and 13) extend from on the Iowa Horst over one flanking basin. In his study, Anderson (1992) utilized interpretive stick diagrams that were manually constructed from the migrated profiles. Interpretations were constrained by general rift geometry, lithologies, and seismic velocities described by earlier workers in the Lake Superior outcrop belt, Iowa drill data (especially information from the M.G. Eischeid #1 well), magnetic data displayed on maps by Henderson and Vargo (1965) and Zietz and others (1976), the "Bouguer Gravity Anomaly Map of Iowa" (Anderson, 1981), and by co-modeling with two-dimensional gravity data along extended seismic profiles.

CLASTIC UNITS ASSOCIATED WITH THE MRS

The Middle Proterozoic Red clastics were deposited in two stages during formation of the MRS in Iowa, between about 1.1 and 1.0 Ma. Similar-appearing clastic rocks of the Cambrian Mount Simon and Reagan Sandstones overlie the Red clastics in Iowa. These units have traditionally been very difficult to differentiate in hand specimen or under a binocular microscope.

Reagan Sandstone

Taft (1902) assigned the name "Reagan Sandstone" to the Cambrian-aged basal Phanerozoic sandstone in southern Oklahoma. The term is also used to identify similar strata in Kansas. The Reagan Sandstone overlies sandstones of the Proterozoic Rice Formation in some area of Kansas. The Reagan Sandstone is generally considered younger than the Mount Simon (Kurtz and others, 1975). Recent research (Carlson and others, 1990) suggests that the basal Cambrian sandstone in southeastern Nebraska and extreme southwestern Iowa is younger than the Mount Simon and should be assigned to the Reagan.

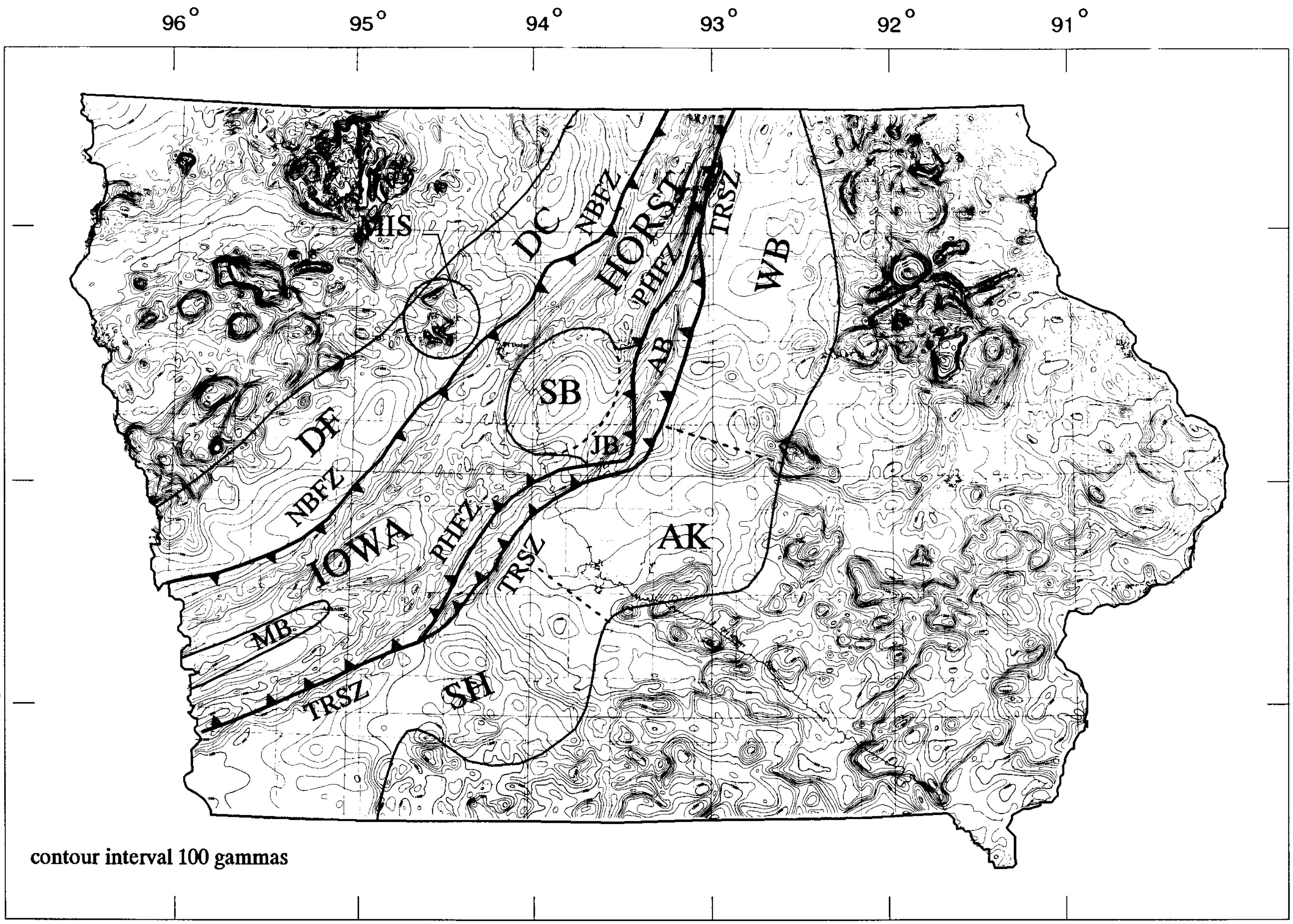
Mount Simon Sandstone

The Mount Simon Sandstone, named by Ulrich (Walcott, 1914), is the basal Cambrian sandstone over much of the region, including Wisconsin, Minnesota, Iowa, Illinois, and Nebraska. The Mount Simon is consistently less than 300 ft thick over much of Wisconsin, Minnesota, Iowa, and Nebraska, but in northern Illinois it reaches a maximum thickness of about 2,600 ft (Buschbach, 1964). Previous interpretations of thick half-graben basins of Mount Simon clastic rocks in central Iowa (Bunker, 1981; Bunker and others, 1988) are now considered incorrect on the basis of results from this study. The Mount Simon sandstone is correlative with the Lamotte Sandstone of Missouri.

Red Clastics

History of the Term "Red Clastics"

The term "Red clastic series" was first applied to red shales and sandstones beneath Paleozoic rocks in the subsurface of Minnesota by Hall and others (1911). The related term "Red clastics" was used by Norton and others (1912) to describe the red sandstones encountered beneath Cambrian strata in Iowa drillholes. At the time, these rocks were differentiated from the overlying white Cambrian sandstones by their red to pink coloration. He correlated the Iowa strata to similar rocks in the subsurface of Minnesota and suggested an Algonkian age for the rocks. Thiel (1944) described the Red clastics of the southern Minnesota subsurface as making up the lower part of the Lake Superior series and applied the name "Fond du Lac beds" to them in Minnesota. The term "Red clastics" is still used in Iowa to define the post-volcanic MRS clastic rocks in Iowa (for example, Anderson, 1990a), although their contact with the overlying Cambrian sandstones is now defined by lithologic and textural criteria instead of coloration, as will be detailed later in this report. The Nebraska Geological Survey uses the term "Red clastics" or "Cornhusker clastics" to refer to similar rocks in Nebraska.



EXPLANATION

Aeromagnetic anomaly contours

Limits of Red clastics sequence rocks

Fault zone (sawteeth on upthrown block)

Basin boundary

0 60 km

0 50 mi

Figure I5 (previous page). Major features of the Midcontinent Rift System (MRS) in Iowa displayed on a modified version of the "Aeromagnetic Anomaly Map of Iowa" (Zietz and others, 1976). NBFZ, Northern Boundary Fault Zone; TRSZ, Thurman-Redfield Structural Zone; PHFZ, Perry-Hampton Fault Zone; DF, Defiance Basin; DC, Duncan Basin; SH, Shenandoah Basin; AK, Ankeny Basin; WB, Wellsburg Basin; SB, Stratford Basin; JB, Jewell Basin; MB, Mineola Basin; AB, Ames Block; MIS, Manson Impact Structure.

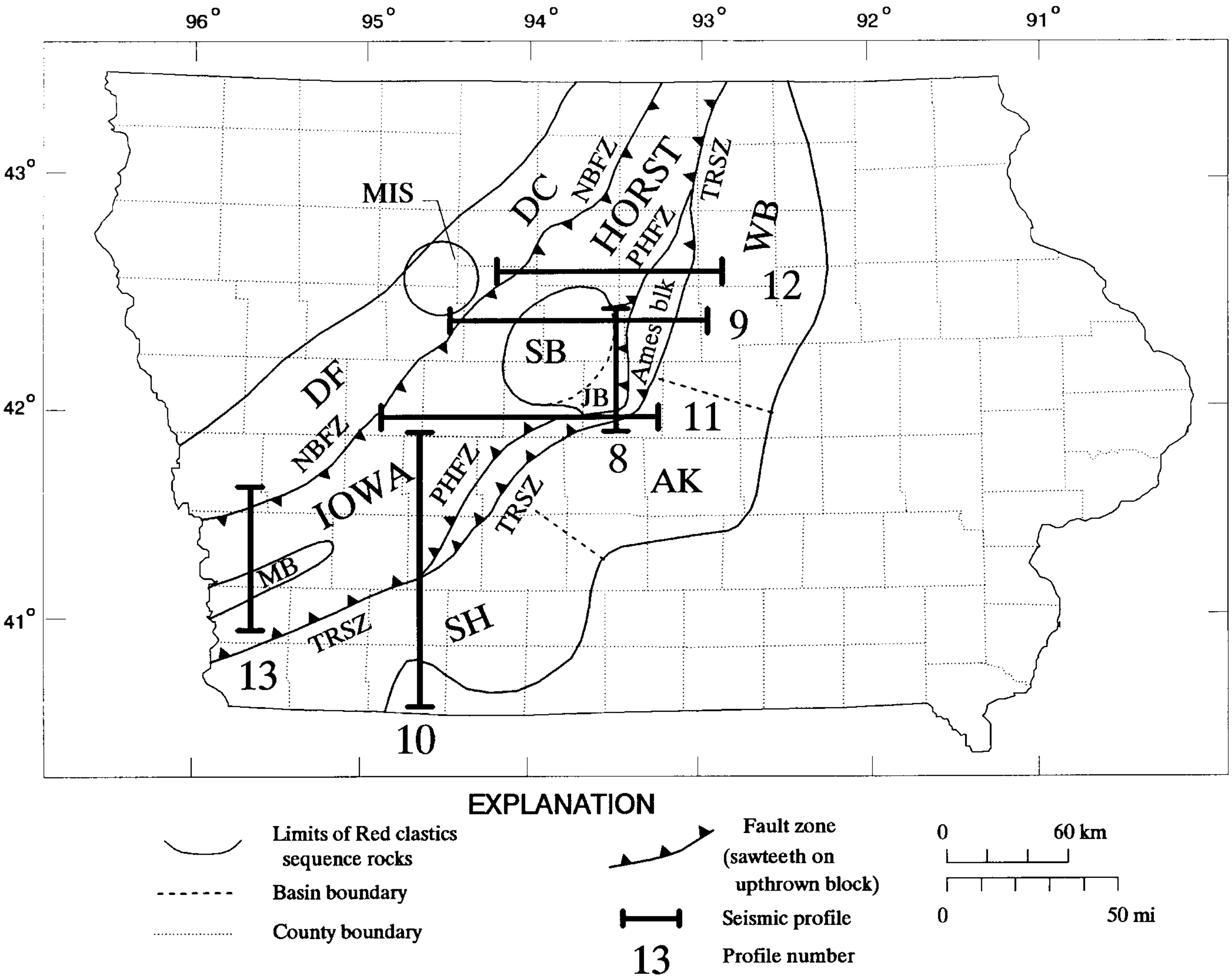


Figure I6. Locations of Petty-Ray Geosource, Inc., reflection seismic profiles on a map of major features of the Midcontinent Rift System (MRS) in Iowa (from Anderson, 1997, fig. 9, modified with permission of the publisher, the Geological Society of America, Boulder, Colo., U.S.A., copyright © 1997 Geological Society of America). NBFZ, Northern Boundary Fault Zone; TRSZ, Thurman-Redfield Structural Zone; PHFZ, Perry-Hampton Fault Zone; DF, Defiance Basin; DC, Duncan Basin; SH, Shenandoah Basin; AK, Ankeny Basin; WB, Wellsburg Basin; SB, Stratford Basin; JB, Jewell Basin; MB, Mineola Basin; MIS, Manson Impact Structure.

The M.G. Eischeid #1 Deep Petroleum Test Well

In the mid-1980's, the Amoco Production Company was engaged in a program to investigate the petroleum potential of the MRS. Their geological and geophysical studies led to the identification of a site for a deep petroleum test well, which was drilled in 1987 in southwestern Iowa on the M.G. Eischeid farm near the town of Halbur, in Carroll County. It reached a total depth of 17,851 ft, penetrating 14,898 ft of MRS clastic rocks, the deepest penetration of MRS clastic rocks anywhere along the trend of the rift, and the entire succession of the clastic rocks in the Defiance Basin, the basin north of the Iowa Horst in western Iowa (fig. I1). An excellent suite of sample chips was recovered (generally at 10-ft intervals), and cores of the clastic rocks were recovered at four intervals (8,834–8,844, 11,381–11,395, 15,096–15,120, and 16,043–16,058 ft). Splits of the sample chips and cores were reposited at the Iowa Geological Survey Bureau (IGSB) Sample Repository and were held confidential until October 26, 1989.

Table I1. Iowa wells penetrating the Midcontinent Rift System (MRS) Red clastic rocks.

IGSB well number	Name (county)	Location	Depth of MRS clastics penetrated (ft)	Depth of MRS clastics cored (ft)
W–03463	A. Luebke* (Calhoun)	Sec. 35, T. 89 N., R. 31 W.	843–1,380	1,223–1,270
W–33109	Manson M–4* (Pocahontas)	Sec. 23, T. 90 N., R. 30 W.	586–956	586–956
W–27933	Eischeid #1 (Carroll)	Sec. 6, T. 83 N., R. 35 W.	2,802–17,700	8,834–8,844 11,381–11,395 15,096–15,120 16,043–16,058
W–14428	#1 Huntley (Butler)	Sec. 15, T. 90 N., R. 15 W.	2,305–3,595	None
W–0005	Ogden City #2 (Boone)	Sec. 32, T. 84 N., R. 27 W.	2,815–2,852	None
W–32431	Boone City #1 (Boone)	Sec. 22, T. 84 N., R. 26 W.	2,700–3,000[@]	None
W–4909	Nevada City (Story)	Sec. 26, T. 83 N., R. 22 W.	3,107–3,342	None
W–26850	M.H. Augustine (Crawford)	Sec. 35, T. 85 N., R. 38 W.	2,505–3,860	None
W–27272	McCallum A–1 (Dallas)	Sec. 5, T. 79 N., R. 27 W.	3,014–3,030	3,014–3,030
W–23106	B. Lehman #1 (Dallas)	Sec. 18, T. 79 N., R. 27 W.	2,924–2,967	2,924–2,967
W–8171	State Center #5 (Marshall)	Sec. 10, T. 83. N., R. 20 W.	3,120–3,310	None
W–23289	Rhinehart A–1 (Dallas)	Sec. 28, T. 80 N., R. 27 W.	3,066–3,082	3,066–3,082
W–00017	Wilson #1 (Page)	Sec. 25, T. 68 N., R. 37 W.	3,700–5,305	None
W–26582	#16–13 Poetker (Fremont)	Sec. 16, T. 67 N., R. 40 W.	3,880–3,929	None

*Well drilled into the Manson Impact Structure.
[@]No samples available.

At the request of the IGSB, the Eischeid samples were released about two months prior to the end of the period of confidentiality for study by IGSB and external researchers in advance of preparation of a report on the well. The report, "The Amoco M.G. Eischeid #1 Deep Petroleum Test, Carroll County, Iowa—Report of Preliminary Investigations" (Anderson, 1990a) was published by the Iowa Department of Natural Resources, Geological Survey Bureau as Special Report Series #2. The IGSB (supported in part by the U.S. Geological Survey's Midcontinent Strategic and Critical Minerals Program) produced 51 thin sections from chips collected at about 500-ft intervals and from additional intervals of interest, and 16 thin sections from selected core samples. All thin sections were stained to aid in the identification and differentiation of potassium feldspar and plagioclase and analyzed petrographically. The results of this petrographic examination were discussed and interpreted by Ludvigson and others (1990), McKay (1990), and Witzke (1990) (see appendix I1). Additionally, thin sections from the cored intervals were analyzed (Barnes, 1990). Core and chip samples and logs were sent to U.S. Geological Survey geologists for evaluation of their potential as source rocks (Palacas and others, 1990), clay mineralogy and bulk rock composition (Pollastro and Finn, 1990), porosity (Schmoker and Palacas, 1990), and fluid inclusions (Barker, 1990). Additional samples were sent to Iowa State University for calcite veinlet studies (Ludvigson and Spry, 1990) and to the University of Kansas for age determination (Van Schmus and others, 1990).

Stratigraphy of the M.G. Eischeid #1 Red Clastics

Beneath the Phanerozoic sequence, the M.G. Eischeid #1 well encountered 14,898 ft of clastic rocks associated with the MRS and assigned to the Keweenawan Supergroup (Anderson, 1990b). These clastic rocks were divided into two sequences, informally named the upper Red clastics sequence and lower Red clastics sequence (Witzke, 1990). These units are group-level stratigraphic subdivisions (Anderson, 1992) but will be referred to as informal sequences in this paper. The upper Red clastics sequence has been subdivided into four informal units, from the top down, H, G, F, and E (fig. I7). The lower Red clastics sequence (fig. I8) is divided into three informal units. In the Eischeid well these informal subdivisions are units D, C, and B (Witzke, 1990). The informal units of both sequences are formation-level subdivisions (Anderson, 1992).

Upper Red Clastics Sequence

The clastic rock sequences encountered at depths of 2,802–10,510 ft in the M.G. Eischeid #1 well are designated the upper Red clastics sequence. The lithologies of the sequence, as interpreted from the mud log, down-hole logs,

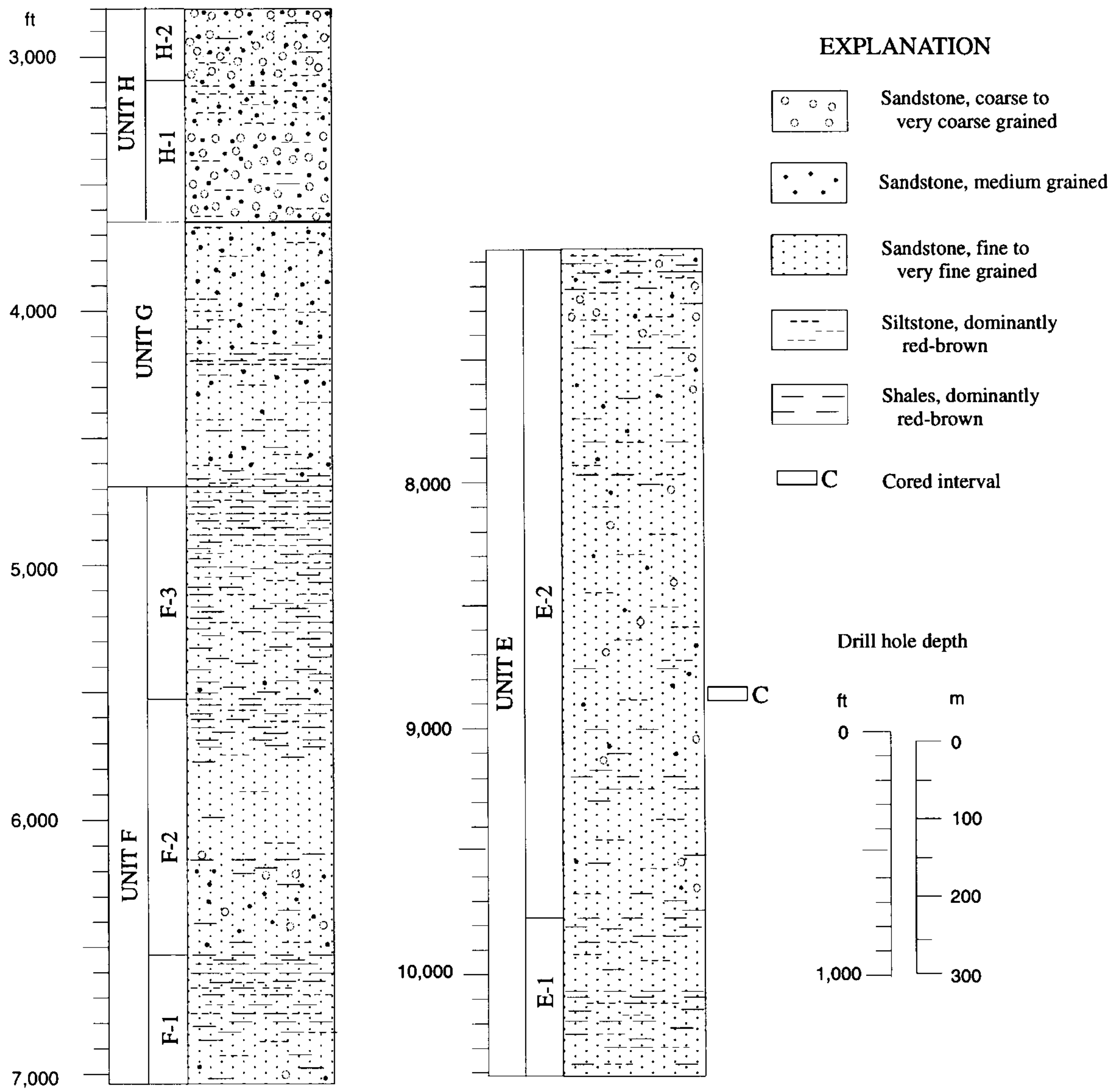


Figure I7. Generalized lithologic log of upper Red clastics sequence from M.G. Eischeid #1 deep petroleum test well (modified from Witzke, 1990), Carroll County, Iowa.

and petrographic and other studies, was described by Witzke (1990). He divided the sequence into four formation-level units (from the top): unit H, unit G, unit F, and unit E.

Unit H (2,802–3,615 ft) (fig. I7) is dominated by two primary lithologies a clear- to light-reddish-brown, fine-grained to very coarse grained arkosic sandstone, and a reddish-brown, micaceous, shaly to sandy siltstone (McKay, 1990). The common occurrence of loose quartz and feldspar grains in the chip samples indicates that much of the unit is poorly indurated. Petrographic study of 11 thin sections produced from chips collected from the upper half of unit H yielded a mean framework composition of [3]$Q_{78.5}F_{13.8}L_{7.7}$ and documented all the feldspar grains to be potassium feldspar. The study also revealed the presence of trace amounts of microbrecciated rock fragments, identical to those found down-hole throughout a large part of the Red clastics section. The presence of microbreccia chips probably implies that the uppermost preserved part of the Red clastics section was affected by structural movements similar to those that created similar tectonized fabrics throughout much of the Eischeid well sequence (Ludvigson and others, 1990).

Unit G, encountered at depths of 3,615–4,690 ft (fig. I7) is dominated by pale-gray (clear) to red-brown, fine- to

---

[3]In $Q_{78.5}F_{13.8}L_{7.7}$, Q=quartz, F=feldspar, and L=lithic fragments; numbers are percentages by volume.

medium-grained sandstone interbedded with red-brown (and minor green) siltstone and shale (Witzke, 1990). The sandstone is dominated by quartzose grains and has 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 percent) is the highest observed in any clastic unit in the Eischeid well (Ludvigson and others, 1990).

Unit F (4,690–7,020 ft), the third Red clastics unit encountered in the Eischeid well (fig. I7), was subdivided by Witzke (1990) into three intervals that generally fine upwards, F–3, F–2, and F–1 (from the top down). These intervals grade from basal red-brown to pale-gray (clear), very fine grained to fine-grained sandstones upward to red-brown (in part mottled light green to gray-green) to red (in part mottled light green to gray-green) shales and siltstones (Witzke, 1990). The sandstones have a mean framework grain composition of $Q_{69}F_{22}L_9$ (Ludvigson and others, 1990).

Unit E (7,020–10,510 ft), the basal unit of the upper Red clastics sequence (fig. I7), is a thick, sandstone-dominated unit that is characterized by the highest percentage of lithic fragments, having a mean of $Q_{67}F_{20}L_{13}$, in the Eischeid well (Ludvigson and others, 1990). The unit was subdivided by Witzke (1990) into two descriptive intervals, E–2 (upper) and E–1.

Interval E–2 is the uppermost of the sub-units that make up unit E. It is dominated by red to brown, generally very fine grained to fine-grained sandstones interbedded with red to brown (some mottled grayish-green) siltstones and shales (Witzke, 1990). Core 1 (8,834–8,844 ft) sampled 10 ft of this interval and displays horizontal bedding and two facies, one well stratified with low-angle cross-stratification and containing red mudstone rip-up clasts, the second a massive, nonstratified sequence containing smaller mud clasts (Ludvigson and others, 1990).

Interval E–1 contains more shale than E–2 and is composed of four relatively thin, fining-upward sequences, each grading from a basal very fine grained to fine-grained sandstone upward to a red to dark-brown shale and siltstone (Witzke, 1990).

The upper Red clastics sequence occupies the same relative stratigraphic position as the Bayfield Group in the Lake Superior region (fig. I3). Both units are apparently dominated by fluvial deposits, 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 two sequences. 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 clastics sequence are mineralogically less mature than the lower Red clastics sequence. Volcanic rock fragments contributed less to Bayfield Group rocks than to the Oronto Group (Ojakangas and Morey, 1982b). However, in the Eischeid well volcanic rock fragments are more common in the upper Red clastics sequence than the lower. Finally, Eischeid drilling did not penetrate any Proterozoic quartz arenites, such as in the Devils Island and Hinckley Sandstones in the Lake Superior area.

The Bayfield Group and upper Red clastics sequence do, however, share many characteristics. Both sequences apparently overlie the initial MRS clastic units (Oronto Group and lower Red clastics sequence). The Bayfield Group, as described by Ojakangas and Morey (1982b), is dominated by fluvial deposition (excluding the possible lacustrine Devils Island Sandstone). The lithologies present in the upper Red clastics sequence, as described by Witzke (1990), and the petrology and sedimentary structures, as established from the cored intervals by Ludvigson and others (1990), also suggest a fluvial origin. The differences in the composition of the units of the upper Red clastics sequence and the Bayfield Group can be explained by differences in the lithologies of source terranes.

Although quartz arenites were not encountered in the Eischeid well, unit F of the upper Red clastics sequence displays the highest content of siltstone and shale. These lower energy deposits may be related to the possible lacustrine deposits observed in the middle unit (Devils Island) 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 clastics sequence. The QFL composition of the framework grains is compared to the composition of units in the Lake Superior area in figure I8. Quartzose grain content increases upward in the sequence, from 67 percent in unit E to 79 percent in unit H. At the same time, the average percentage of lithic grains decreased up section from 13 percent in unit E to 4 percent in unit H; the volcanic rock component of the grains increased from 22 percent in unit E to 62 percent in unit G, and sedimentary and metamorphic grains decreased from 65 percent in unit E to 37 percent in unit G. The compositions of the lithic fragments in the two intervals examined in unit H were quite disparate, and additional analyses are needed.

The relative increase in the concentration of volcanic rock grains moving up section in the upper Red clastics sequence in the Eischeid well may record the local proximal erosional unroofing of the basalts on the Iowa Horst. Well data from the trend of the MRS in Iowa and seismic interpretations indicate that Keweenawan sedimentary rocks were erosionally removed from most areas of the Iowa Horst, exposing underlying volcanic rocks (Anderson, 1988).

Lower Red Clastics Sequence

The rocks encountered at depths between 10,510 and 17,700 ft in the Eischeid well are informally called the lower Red clastics sequence (fig. I8). The sequence was divided by Witzke (1990) into three component units (from the top downward): units D, C, and B.

The uppermost unit in the lower Red clastics sequence, unit D (10,510–14,980 ft), was described by Witzke (1990) as a thick, generally upward-fining sequence that is dominated by sandstones in the lower half and siltstone to shale

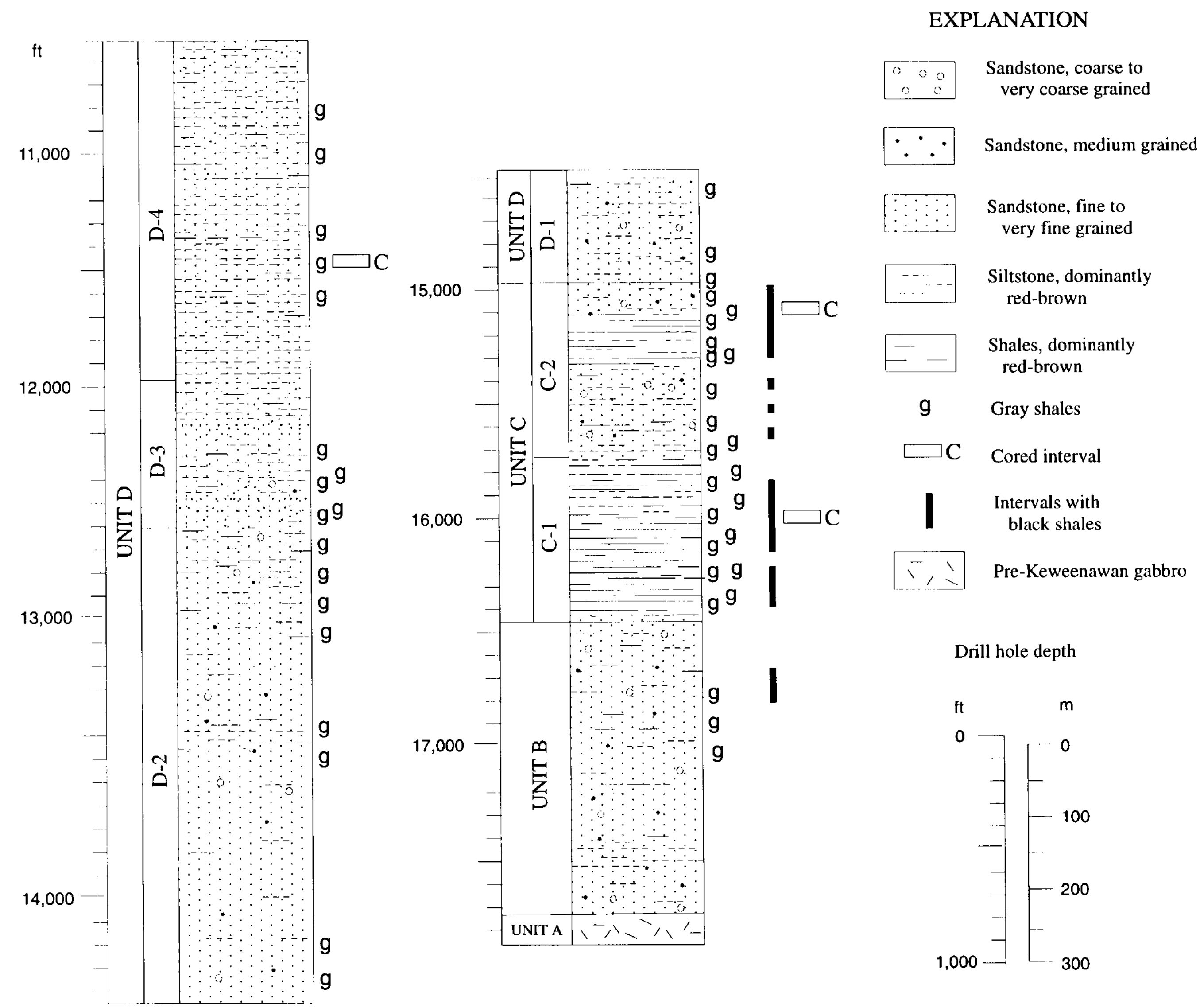


Figure I8. Generalized lithologic log of lower Red clastics sequence from M.G. Eischeid #1 deep petroleum test well (modified from Witzke, 1990), Carroll County, Iowa.

in the upper half. He subdivided the unit into four intervals (from the top downward): D–4, D–3, D–2, and D–1. The sandstones in unit D are dominated by quartz (having a mean framework grain composition of $Q_{76}F_{21}L_3$), and the lithic component includes the highest percentage of sedimentary and metamorphic rock fragments (average 74 percent) observed in any unit in the Eischeid well (Ludvigson and others, 1990).

Interval D–4 is dominated by red to brown (with minor, light-green to gray) shale in its upper half and red-brown siltstone in the lower half (Witzke, 1990). Core 2 (11,381–11,395 ft) was recovered from this interval and was described by Ludvigson and others (1990) as displaying two facies, one composed of red, very fine grained to fine-grained, cross-stratified sandstone, and the second a very fine grained, horizontally stratified sandstone containing minor interbedded mudstone. These sediments are interpreted as representative of a fluvial setting characterized by shallow channel fills, subsequent subaerial exposure, inundation by over-bank deposits, and then a return to shallow channel deposition (Ludvigson and others, 1990). The cored interval also displays fault-related deformation.

The underlying interval, D–3, is dominated by siltstone containing minor sandstone and shale. This interval also contains gray to dark-gray siltstone and shale and the uppermost occurrences of black siltstone and black carbonaceous specks. The lower part of this interval is dominated by light-gray, fine- to medium-grained sandstone interbedded with minor shales and siltstone (Witzke, 1990).

The upper part of interval D–2, as described by Witzke (1990), is dominated by varicolored siltstone containing some dark-gray to black shaly laminations (some pyritic). Most of the interval is dominated by sandstone and minor interbedded red-brown to gray-green siltstone and shale. Coarse sand grains are abundant in the basal parts of interval D–2.

The basal interval in unit D, D–1, was described by Witzke (1990) as a sandstone-dominated sequence conatining varicolored shale and siltstone in the upper part. The sandstone is predominantly light gray to red-brown and fine to medium grained, containing some minor coarse grains. Shales are red-brown to gray (some black) and contain siltstone interbeds. The mud log indicated traces of methane and ethane in this interval, and Witzke (1990) reported intergranular black residues, possibly hydrocarbon residues.

Unit C (14,980–16,450 ft) is the most distinctive Keweenawan Supergroup clastic unit encountered in the M.G. Eischeid #1 well (fig. I8). 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, two cores totaling 39 ft having been 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 is an interbedded sequence of sandstone, siltstone, and shale, gray to black siltstone and shale being more common in the upper part of the interval and red-brown to green-gray rocks more common in the basal part (Witzke, 1990). 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 ft) 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 ft), taken in the upper part of the interval, consists of horizontally laminated, millimeter- to decimeter-thick, interlayered, medium- to dark-gray shale and lighter gray siltstone to fine-grained sandstone (Ludvigson and others, 1990). This stratum was interpreted as having been deposited in a lake or other body of standing water having a fluctuating depth and intermittent influxes of coarse detritus. Petrologic study of two samples of coarse detritus from interval C–2 yielded a mean composition of $Q_{72}F_{24}L_3$ (Ludvigson and others, 1990). The 24-percent feldspar observed in this interval is the greatest concentration observed in any interval in the Eischeid well.

Interval C–1 is dominated by light- to dark-gray siltstone and shale containing dark-brown to black shaly interbeds (Witzke, 1990). 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 ft) 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 and others, 1990). Calcite veinlets and slickensided fault surfaces showing calcitic rough facets are common in the core, providing evidence of deformation in a reverse-faulting mode requiring lateral compression (Ludvigson and Spry, 1990).

Unit B, the basal clastic unit in the Eischeid hole (16,450–17,700 ft), informally named by Witzke (1990), is dominated by white to light-gray and red, very fine grained to fine-grained sandstone possibly containing siltstone and shale partings. Petrographic studies of unit B sandstones by Ludvigson and others (1990) indicated that it contained the highest percentage of quartzose grains observed in the Red clastics sequence, $Q_{87}F_{12}L_1$, and a small lithic component dominated by sedimentary and metamorphic clasts (74 percent).

The lower Red clastics sequence is very similar to, and may correlate with, the Oronto Group in the Lake Superior area (fig. I3). The biggest difference between the two sequences is the coarser grained facies preserved in the Copper Harbor Conglomerate, the basal unit of the Oronto Group, and the lack of the coarse subfacies in unit B, the basal unit of the lower Red clastics sequence. The Copper Harbor is dominated by a 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 percent) of any Red clastics unit in the Eischeid well (fig. I9). 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-rock clasts that predominate in the Copper Harbor were deposited by alluvial fans that were derived by erosion of Keweenawan volcanic rocks capping the foot walls of normal faults that bounded the graben. The Eischeid well, and unit B, are located in one of the clastic basins that flank the central horst and is therefore at a site that was outside of the central graben at the time of its deposition. It is dominated by quartzose sediment derived from granitic rocks, the most common lithology in the region in which the MRS developed, and was deposited by rivers that flowed towards the axis of the rift. As these rivers neared the axial graben they apparently cut through footwall-capping volcanics, depositing the Copper Harbor lithologies 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, bidirectional, symmetrical, and trough cross-stratification and small-scale, amalgamated, hummocky cross-stratification. Shrinkage cracks are also present in this interval (Ludvigson

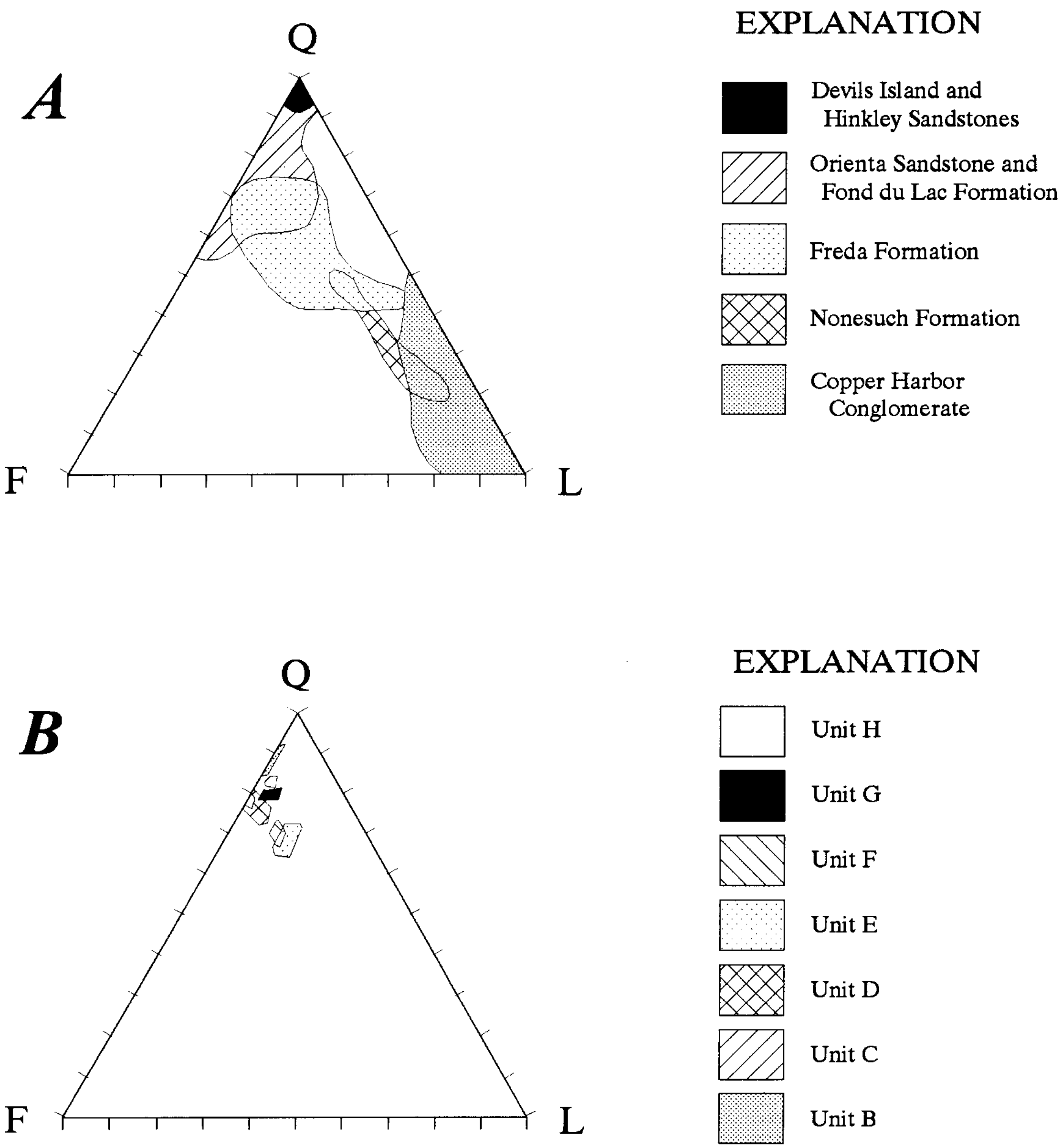


Figure I9. Quartz–feldspar–lithic grain (QFL) diagrams for Keweenawan Supergroup clastic rocks from (*A*) Lake Superior area (from Ojakangas, 1986) and (*B*) M.G. Eischeid #1 well (from Anderson, 1990b; Ludvigson and others, 1990; and Anderson, 1997, fig. 4, modified with permission of the publisher, the Geological Society of America, Boulder, Colo., U.S.A., copyright © 1997 Geological Society of America), Carroll County, Iowa.

and others, 1990). Milavec (1986) identified similar features in the Nonesuch Formation.

The Nonesuch has been interpreted as a lake deposit by most workers (for example, Elmore, 1981; Daniels, 1982; Milavec, 1986), but some workers have suggested that it may have been deposited in a marine environment (Burnie and others, 1972). In either case, the Nonesuch appears to have been deposited in a standing body of water. Structures observed in cores of unit C also suggest deposition in a standing body of water (Ludvigson and others, 1990). The presence of these lake deposits in the Eischeid well indicate that the body of water was not confined to the central horst, the position where correlative Nonesuch deposits are observed. Formerly confidential petroleum industry seismic data suggest that unit C may extend at least 7 mi west of the Iowa Horst in the Defiance Basin, and perhaps as much as 15 mi or more (Anderson, 1992).

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 (1990) reported total organic carbon (TOC) values as high as 1.4 percent (averaging 0.6 percent) in the dark shales and siltstones of unit C. The Nonesuch Formation has yielded maximum TOC values of almost 4 percent (Hieshima and others, 1989). The petroleum source-rock potential of unit C is discussed later in this report.

Unit D occupies the same stratigraphic position in the Eischeid well as the Freda Formation in the Oronto Group of the Lake Superior area. Interpretation of core 1 from unit D suggested to Ludvigson and others (1990) that the unit was deposited in a fluvial environment. A similar interpretation has been proposed for the Freda Formation by many workers (for example, Daniels, 1982; Morey and Ojakangas, 1982). Petrographic studies of unit C 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 exposures reported by Daniels (1982). The lithic component of the Freda is dominated (72 percent) by volcanic rock fragments. The higher volcanic rock lithic component indicates that volcanic rocks were exposed in the Freda source area, and similar lithologies were not exposed in the source area of unit D.

Red Clastics Basins Flanking the Iowa Horst

The Red clastic rocks deposited during the formation of the Midcontinent Rift System in Iowa are most extensive and reach their maximum thickness in the series of basins that flank the Iowa Horst to the west and east (fig. I10). The dimensions of these basins and the volumes of Red clastics preserved in them are given in table I2. The rocks of the flanking clastic basins are buried beneath 2,200–3,500 ft of Phanerozoic strata, and only six drillholes penetrate these rocks, which cover an estimated 13,400 mi^2 of the Iowa Precambrian surface and total more than 34,000 mi^3 (Anderson, 1992). With this limited well control, most of our understanding of these basins is derived from interpretation of geophysical data (Anderson, 1992). A reflector within the clastic sequence as interpreted on the reflection seismic profiles appears to be coincident with the approximate contact between the upper and lower Red clastics sequences. The depth to this reflector was extrapolated over each clastic basin and was used by Anderson (1992) to delineate the limits of each of these clastic sequences.

Western Flanking Basins

The thick sequence of Middle Proterozoic Red clastics that flank the Iowa Horst on the west forms a belt from 22 to 32 mi wide. Although the belt is apparently a continuous blanket of sedimentary rocks covering an estimated 4,400 mi^2 of the Precambrian surface, it is divided into two basins, best delineated on the “Bouguer Gravity Anomaly Map of Iowa” (fig. I4). The central areas of these basins, the Duncan Basin on the north and the Defiance Basin on the south, are located by closed gravity minima. The Manson Impact Structure is located on the saddle that separates the basins. Modeling (Anderson, 1992) suggests that a total of about 12,000 mi^3 of Red clastics is present in the western basins (table I2).

Duncan Basin

The northwesternmost of the MRS clastic basins flanking the Iowa Horst in Iowa, the Duncan Basin, extends in a southwesterly direction for about 70 mi from the Minnesota border (fig. I2). The basin ranges in width from about 17 to 20 mi, an area of about 1,500 mi^2, but the zero edge of the clastics is difficult to define and may extend as much as 10 mi beyond the mapped limits (Anderson, 1992). The basin reaches a maximum modeled depth of 27,700 ft against the Iowa Horst (fig. I10). Modeled overthrusting of the clastic sequence by the volcanic rocks of the Iowa Horst varies from 3 to 8 mi, generally greater on the southern end of the basin. Lower Red clastic sequence rocks and upper Red clastic sequence rocks are preserved in the Duncan Basin. No wells penetrate Duncan Basin clastic rocks in Iowa.

Defiance Basin

The southernmost of the western flanking basins, the Defiance Basin, includes an area of about 2,900 mi^2, extending northwest for about 120 mi from the Nebraska border (fig. I2). The basin ranges in width from about 22 mi in the north to about 33 mi in the south. The zero edge is difficult to define and may extend as much as 10 mi west of its model location. The Middle Proterozoic Red clastic rocks that fill the basin reach a modeled maximum thickness of about 34,600 ft near the Iowa Horst in the southern parts of the basin and total about 7,700 mi^3. The volcanic rocks of the Iowa Horst are thrust 5 to 10 mi over Defiance Basin clastics. Only two wells penetrate into these clastic rocks. One well, the M.G. Eischeid #1, has presently the most complete section of MRS clastic rocks. The second well, the Martin Augustine #1, produced only poor samples (table I1). Rocks of both upper and lower Red clastics sequences are preserved in the Defiance Basin (table I2).

Eastern Flanking Basins

On the eastern side of the Iowa Horst, an apparently continuous belt of flanking Proterozoic Red clastic rocks stretches from Minnesota to Nebraska. It has been divided into three basins, from north to south, the Wellsburg, Ankeny, and Shenandoah Basins, their centers defined by closed isogal minima on the “Bouguer Gravity Anomaly Map of Iowa” (fig. I4). The eastern flanking basin is larger than the western basin, with clastics covering an area of 9,000 mi^2. The total volume of Red clastic rocks in the basins flanking the eastern margin of the Iowa Horst (table I2), based on modeling, is about 23,300 mi^3.

Table I2. Dimensions of Red clastics basins in Iowa.
[n.a., not applicable]

	Maximum values (mi)			Area (mi^2)	Volume (mi^3)
	Length	Width	Depth		
HORST-FLANKING BASINS					
Western basins:					
Duncan Basin:					
Upper Red Clastics sequence	68	20	1.9	1,500	1,600
Lower Red clastics sequence	68	20	3.3	1,470	2,800
Defiance Basin:					
Upper Red clastics sequence	118	35	2.2	2,900	2,900
Lower Red clastics sequence	118	28	4.2	2,200	4,800
Total western basins	185	35	6.5	n.a.	12,100
Upper Red clastics sequence	185	35	2.2	4,400	4,500
Lower Red clastics sequence	185	28	4.2	3,700	7,600
Eastern basins:					
Wellsburg Basin:					
Upper Red clastics sequence	99	47	2.5	2,700	2,500
Lower Red clastics sequence	99	35	4.2	2,350	4,900
Ankeny Basin:					
Upper Red clastics sequence	68	50	2.5	2,500	2,400
Lower Red clastics sequence	68	37	4.4	1,800	2,900
Shenendoah Basin:					
Upper Red clastics sequence	99	43	2.2	3,800	4,600
Lower Red clastics sequence	99	37	3.9	2,800	5,100
Total eastern basins	170	50	6.9	n.a.	22,400
Upper Red clastics sequence	170	50	2.5	9,000	9,500
Lower Red clastics sequence	170	38	4.4	7,000	12,900
Total horst-flanking basins	n.a.	n.a	6.9	n.a.	34,500
Upper Red clastics sequence	n.a.	n.a	2.5	13,400	14,000
Lower Red clastics sequence	n.a.	n.a	4.4	10,700	20,500
SUPERHORST BASINS					
Ames Block:					
Upper Red clastics sequence	130	19	2.2	1,350	1,500
Lower Red clastics sequence	121	19	2.3	1,200	1,900
Stratford Basin:					
Lower Red clastics sequence	35	23	0.6	650	500
Jewell Basin:					
Lower.Red clastics sequence	37	12	0.6	420	410
Mineola Basin:					
Upper Red clastics sequence	40	8.7	0.9	280	120
Total superhorst basins	n.a.	n.a	4.5	n.a.	4,400
Upper Red clastics sequence	n.a.	n.a.	2.2	1,630	1,600
Lower Red clastics sequence	n.a.	n.a.	2.3	2,270	2,800
ALL BASINS					
Grand total Red clastics	n.a.	n.a.	6.9	n.a.	38,900
Upper Red clastics sequence	n.a.	n.a.	2.5	15,000	15,600
Lower Red clastics sequence	n.a.	n.a.	4.4	13,000	23,300

Wellsburg Basin

The northernmost of the three eastern clastic basins, the Wellsburg Basin (fig. I2), extends south from the Minnesota border for about 100 mi to central Marshall County, where it abuts the Ankeny Basin. The basin covers an area of about 2,700 mi^2 and ranges in width from 13 to 47 mi, but its eastern zero edge is poorly constrained and may extend as much as 10 mi farther east than is mapped. The model indicates that about 7,400 mi^3 of MRS upper and lower Red clastics sequences rocks fill the basin (table I2), reaching a maximum thickness of about 36,300 ft. These rocks are penetrated by only one well, the #1 Huntley in Butler County. The Red clastics in the Wellsburg Basin are

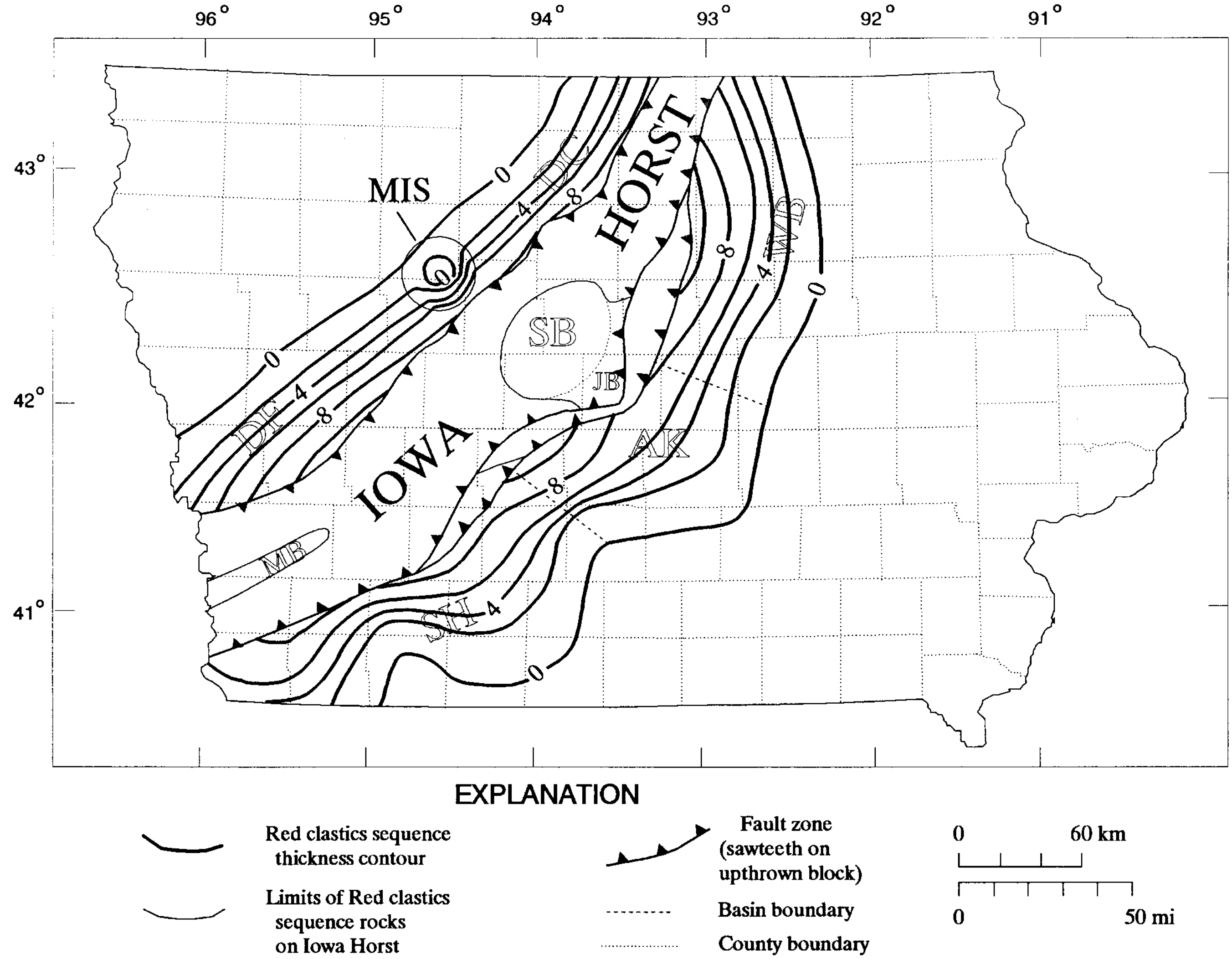


Figure I10. Thickness of Red clastics preserved in basins flanking Iowa Horst (from Anderson, 1992; and Anderson, 1997, fig. 10, modified with permission of the publisher, the Geological Society of America, Boulder, Colo., U.S.A., copyright © 1997 Geological Society of America). MIS, Manson Impact Structure; contour interval 2 km (1.24 mi).

overthrust by the Iowa Horst, from about 3 mi on the north to as much as 8 mi in the area of the Ames Block (fig. I10).

Ankeny Basin

The central one of the three eastern flanking MRS basins in Iowa is the Ankeny Basin (fig. I2). The basin covers an area of about 2,500 mi^2, extending for about 70 mi between the Wellsburg and Shenandoah Basins. It ranges in width from about 23 to 50 mi, but the eastern zero edge of the clastics is poorly defined. Modeling (Anderson, 1992) indicates a maximum thickness in excess of 37,000 ft and a total volume of about 5,300 mi^3 of MRS upper and lower Red clastics sequences rocks are preserved in the Ankeny Basin. The Red clastic rocks are penetrated by only one well, the Story City Town Well #3. The Iowa Horst is thrust from 5 to 8 mi over the Red clastic rocks in the basin.

Shenandoah Basin

The Shenandoah Basin, the southernmost of the eastern flanking basins in Iowa (fig. I2), has two conspicuous lobes. The lobes are separated by an area of positive relief on the crystalline basement, coincident with the Central Iowa Arch pluton (Anderson, 1988). The basin covers an area of about 3,800 mi^2, extending for about 100 mi from the Nebraska border to the Ankeny Basin. The basin displays a maximum width, in the northern lobe, of about 44 mi and a minimum width of 25 mi between the two lobes—but the eastern zero edge is not well constrained. Proterozoic upper and lower Red clastics sequence rocks in the Shenandoah Basin range to as much as about 32,000 ft in thickness (fig. I10), and modeling suggests the presence of about 9,700 mi^3 of the clastic rocks preserved in the basin. The clastic rocks are overthrust from 5 to 10 mi by the Iowa Horst.

Two wells penetrate into the Red clastics of the Shenandoah Basin, the #1 Wilson in Page County, which sampled 1,605 ft of the sequence, and the Gulf Energy 16–13 Poetker in Mills County, which penetrated 49 ft of Red clastics. Additionally, a third well, the Ohio Oil Company Wisnom #1, penetrated 200 ft of quartzarenite at a depth below 3,150 ft. The only quartz arenite in this part of the geologic column is in the basal Cambrian sandstone. This basal sand, however, rarely exceeds 100 ft in thickness in this region. The anomalous quartz arenite in the Wisnom well may represent rocks related to the Bayfield Group Hinckley or Devils Island Sandstone of the Lake Superior region.

Clastic Basins on the Iowa Horst

Stratford Basin

The Stratford Basin (fig. I2) was identified as the “Stratford Geophysical Anomaly” by Osweiler (1982), who interpreted the feature as an elliptical, clastic-filled basin having an area of 650 mi^2 that formed along the axis of the MRS, similar to the Twin City Basin in Minnesota (King and Zietz, 1971). Using a gravity contrast of 0.6 g/cm^3 between the clastics and the underlying mafic volcanic rocks, Osweiler modeled the basin as elongate (about 35 mi long) trending northeasterly (along the axis of the MRS), and about 23 mi wide. The basin reaches a maximum depth of about 3,000 ft below the base of overlying Phanerozoic rocks.

The basin was studied by Anderson (1992) using data from Petty-Ray Geosource, Inc., seismic profile 9. With this data he calculated a maximum depth of about 5,500 ft. To produce a gravity model using this depth required a density of 2.65 g/cm^3 (density contrast of only 0.2 g/cm^3 with the underlying basalts) for the Red clastics. This density is higher than the average 2.55 g/cm^3 density assigned to the lower Red clastics sequence by Anderson (1992) when modeling the horst-flanking basins along profile 9. He suggested that the density of the clastics in the Stratford Basin may be increased by a higher percentage of mafic volcanic rock fragments (similar to clasts in the Copper Harbor Conglomerate) in the clastic rocks of the Stratford Basin. This theory is strengthened by a description (Norton, 1928) of the rocks encountered during the drilling of the Ogden City #2 well in 1929 (table I1). Although no samples exist for the basal 7 ft of the well, the lowest samples, from a depth of 2,845 ft, were described as a litharenite containing abundant feldspar, mafic igneous rock fragments, and mafic minerals. This lithology is similar to the Copper Harbor Formation and in Iowa is part of the lower Red clastics sequence. The well encountered the lower Red clastics at a depth of 2,750 ft and penetrated 102 ft of the clastic sequence. Additionally, the Boone City #1 well also apparently penetrated the clastics of the Stratford Basin.

Boone City #1, drilled in 1890, encountered a sequence of red shales and soft red sandstones, interpreted as the lower Red clastics sequence, at a depth of about 2,700 ft. A total of 300 ft of these rocks was penetrated. Additionally, deep burial along the axis of the MRS and thorough cementation may combine to form an anomalously dense unit, similar to the dense clastic rocks encountered in the Amerada Schroeder well, located in a similar position on the Iowa Horst in Nebraska.

Using a density of 2.65 g/cm^3 for the lower Red clastics, Anderson (1992) modeled the Stratford Basin as having a width and length similar to values determined by Osweiler (1982), but reaching a greater maximum depth (fig. I11), about 12,000 ft. The total volume of lower Red clastics sequence rocks in the Stratford Basin is approximately 500 mi^3.

Jewell Basin

The Jewell Basin was defined by Anderson (1992) as the area of the Iowa Horst that is capped by lower Red clastics sequence rocks between the elliptical Stratford Basin and the Perry-Hampton Fault Zone (fig. I11); it has an area of about 420 mi^2. Seismic profile 8 (fig. I6) crosses the Jewell Basin and displays a continuously thickening clastic sequence, ranging in thickness from about 1,500 ft on the north to 12,500 ft on the south, at its intersection with the Perry-Hampton Fault Zone. Interpretation of available data suggests that the Jewell Basin was never a discrete depositional basin. It is apparently a remnant of lower Red clastics sequence rocks that were originally deposited uniformly within the central graben of the MRS in Iowa, but then were structurally preserved in the area called the Jewell Basin by differential uplift of the Iowa Horst. The Jewell Basin contains approximately 410 mi^3 of lower Red clastics sequence sedimentary rocks.

Mineola Basin

The southernmost of the clastic basins identified on the Iowa Horst in Iowa is the Mineola Basin (fig. I12). It was originally referred to as the “Mineola Graben,” after early gravity modeling suggested a clastic-filled graben having its center near the northern Mills County town of Mineola. However, interpretation of seismic profile 13 (Anderson, 1992) clearly displays a basin structure having no prominent bounding faults. On seismic profile 13 the basin appears to be about 9 mi wide. It proved difficult to match the gravity values observed along profile 13 by modeling using lower Red clastics sequence densities in a basin 6,000 ft deep, as required by the seismic interpretation (Anderson, 1992). However, using upper Red clastics sequence densities, the seismic data show a basin about 5,000 ft deep and yield a gravity model that fits the observed

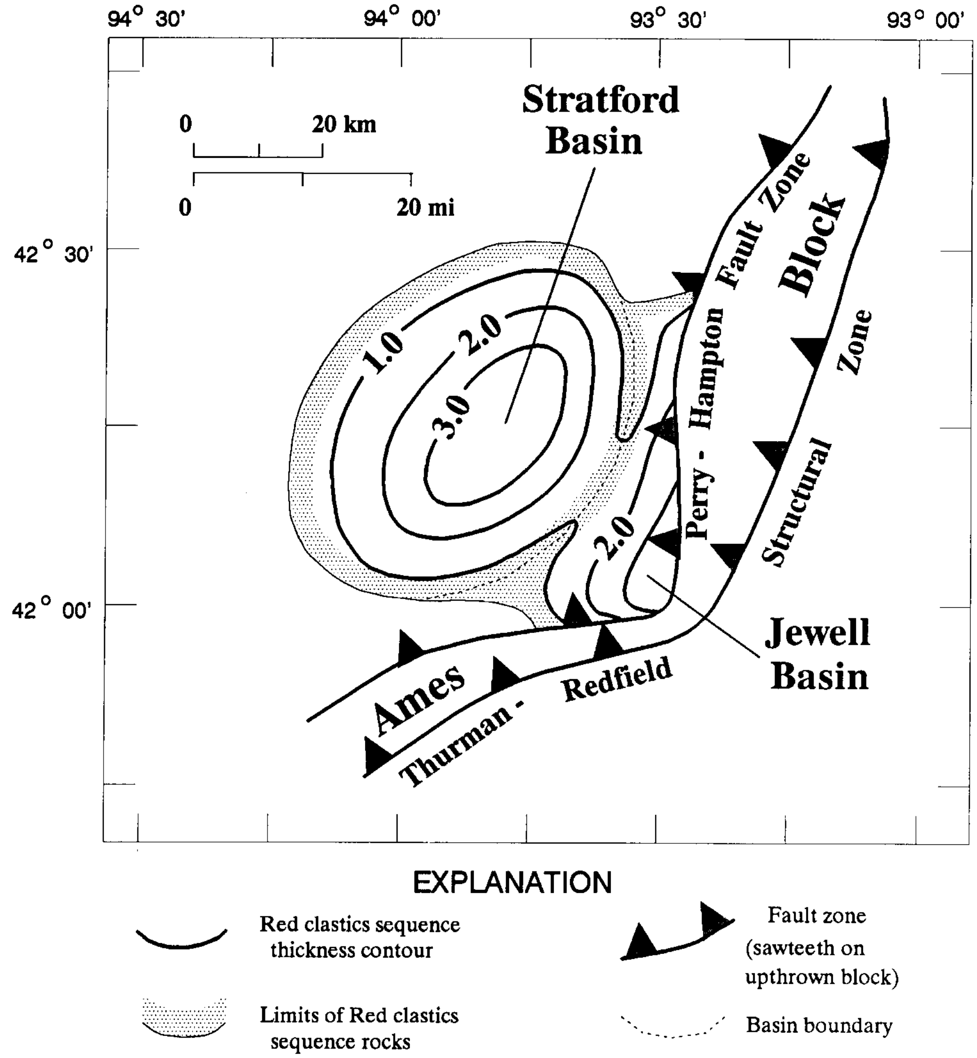


Figure I11. Thickness of lower Red clastics sequence in Stratford and Jewell Basins, Midcontinent Rift System (MRS) of Iowa (from Anderson, 1992; and Anderson, 1997, fig. 14, modified with permission of the publisher, the Geological Society of America, Boulder, Colo., U.S.A., copyright © 1997 Geological Society of America). Contour interval 1 km (0.62 mi).

data very well. Therefore, Anderson concluded that the Mineola Basin is filled with sedimentary rocks displaying upper Red clastics sequence densities.

The limits of the Mineola Basin are best delineated on the "Aeromagnetic Map of Iowa" (Zietz and others, 1976). Interpretation suggests that the basin is about 40 mi long, extending up the axis of the rift from the Nebraska border to eastern Pottawattamie County, Iowa. The basin displays a relatively continuous width of about 9 mi over most of its length and a total area of about 280 mi^2. Having a maximum depth of about 5,000 ft, the basin contains about 120 mi^3 of upper Red clastics sequence sedimentary rocks.

The presence of upper red clastics sequence sedimentary rocks in the Mineola Basin suggests that the feature must have formed after uplifting of the Iowa Horst and the unroofing of horst volcanics by the erosion of lower Red clastics sequence sediments (Anderson, 1992). This implies that the Mineola Basin is the youngest MRS structural feature on the Iowa Horst. The much younger Paleozoic (Pennsylvanian) Glenwood Syncline (Hershey and others, 1960) is nearly coincident with the Mineola Basin and may represent structural reactivation of this feature.

Ames Block

Although the uplift of the Iowa Horst is remarkably uniform, as documented by the long, continuous, horizontal reflectors seen in the seismic profiles of the volcanic rocks, several major structural features were identified on the horst by Anderson (1992). Key among them is the Ames Block, an elongate feature that trends along the eastern edge of the horst (fig. I2) and that was first identified and described by

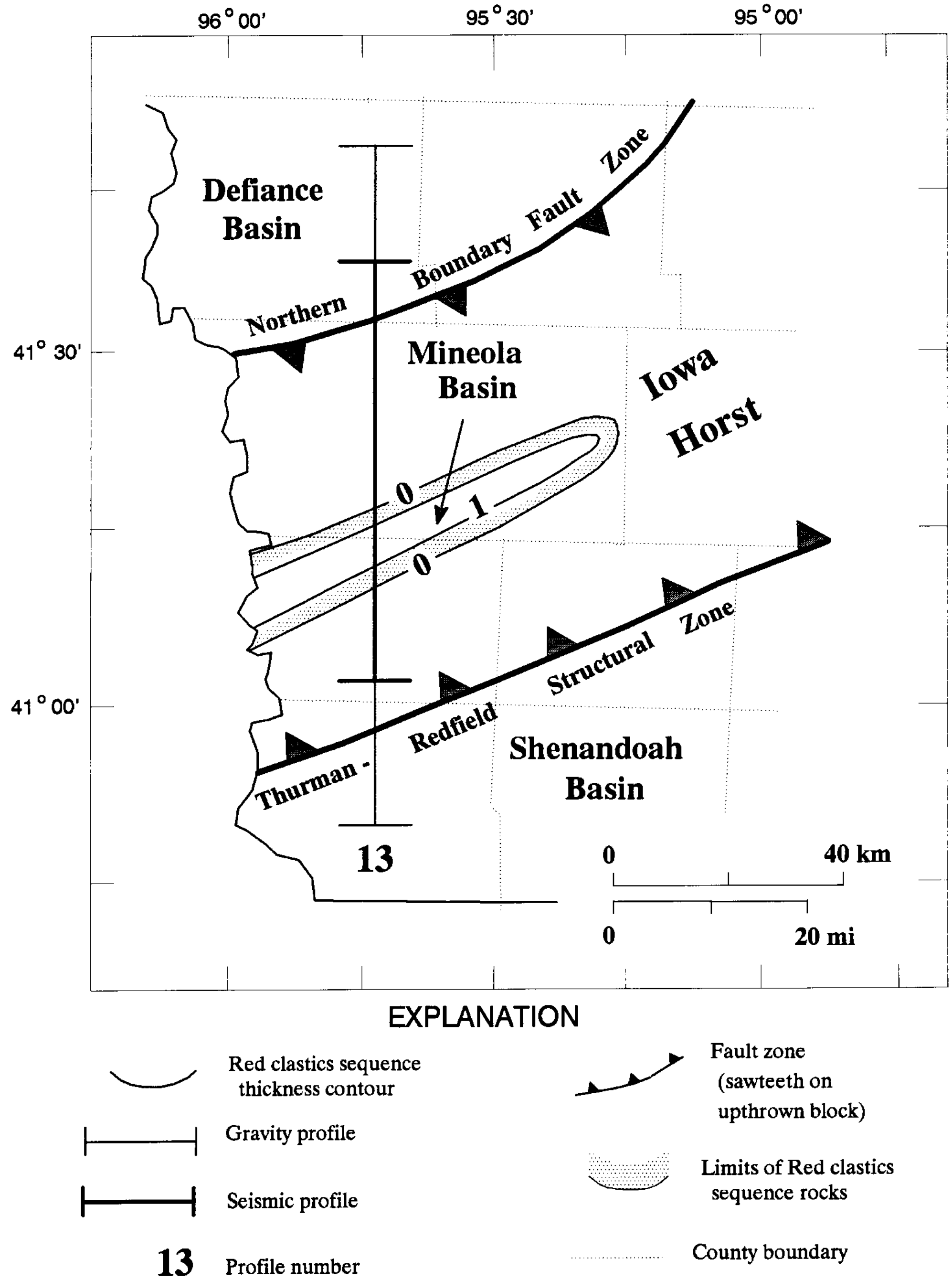


Figure I12. Thickness of upper Red clastics sequence in Mineola Basin, Midcontinent Rift System (MRS) of Iowa (from Anderson, 1992; and Anderson, 1997, fig. 15, modified with permission of the publisher, the Geological Society of America, Boulder, Colo., U.S.A., copyright © 1997 Geological Society of America). Contour interval 1 km (0.62 mi).

Anderson (1992). It is bounded on the west by the Perry-Hampton Fault Zone and on the east by the Thurman-Redfield Structural Zone. The Ames Block is apparently floored by a thick sequence of Keweenawan volcanic rocks, indicating that it is a part of the Iowa Horst (Anderson, 1992). Above the volcanic rocks, both lower and upper Red clastics sequence rocks have been structurally preserved (fig. I13). Both sequences have thicknesses nearly identical to those modeled in the flanking Wellsburg and Ankeny Basins. The Ames Block has been uplifted with respect to the flanking basins. This uplift has maximum values of about 2 mi at its northern (profile 12) and south-central (profile 11) regions, to only about 1 mi between them (profile 9) (see fig. I6).

The Ames Block is down-dropped with respect to the main body of the Iowa Horst, which is west of the

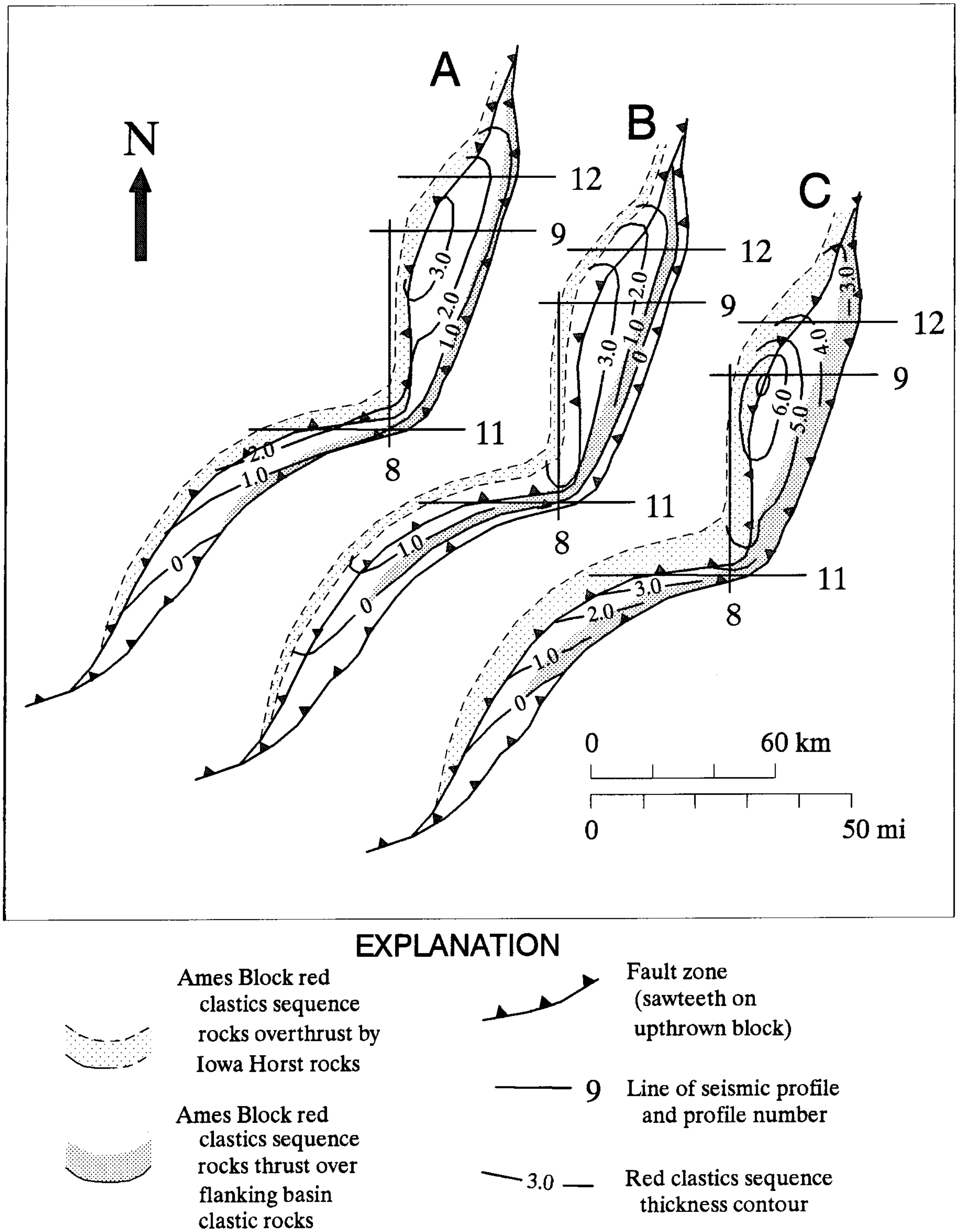


Figure I13. Thickness of (*A*) upper Red clastics sequence, (*B*) lower Red clastics sequence, and (*C*) total Red clastics on Ames Block, Midcontinent Rift System (MRS) of Iowa (from Anderson, 1992; and Anderson, 1997, fig. 13, modified with permission of the publisher, the Geological Society of America, Boulder, Colo., U.S.A., copyright ©1997 Geological Society of America). Contour interval 1 km (0.62 mi).

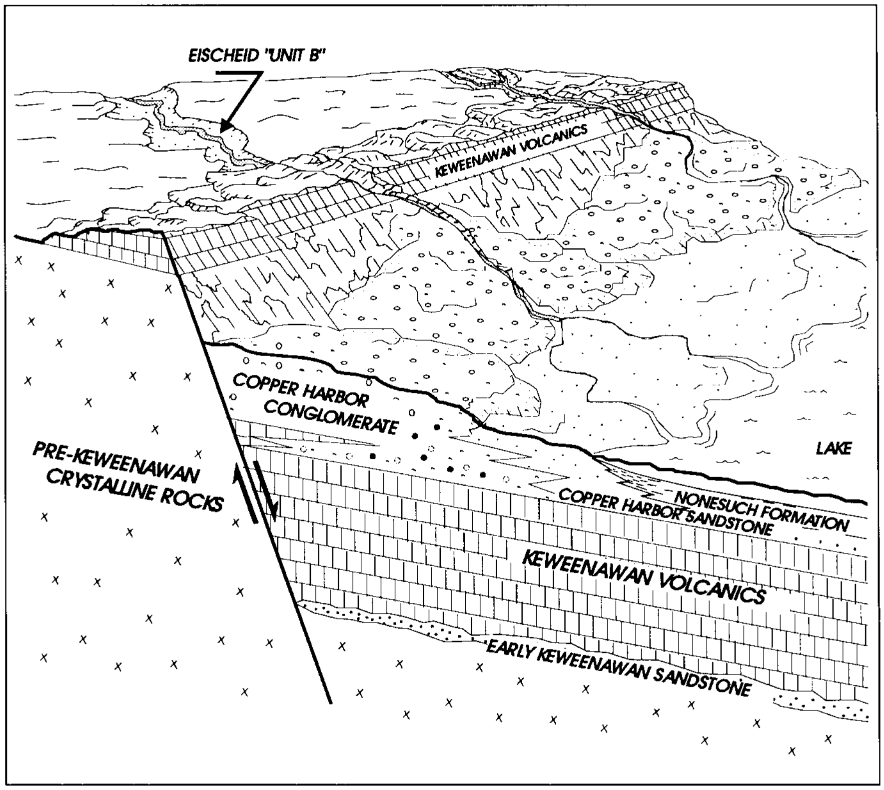


Figure I14. Depositional environment of unit B and lower Oronto Group equivalent rocks (from Anderson, 1992; and Anderson, 1997, fig. 6, modified with permission of the publisher, the Geological Society of America, Boulder, Colo., U.S.A., copyright © 1997 Geological Society of America).

Perry-Hampton Fault Zone. Anderson (1992) modeled apparent displacements, controlled by seismic interpretations, ranging from a minimum value of 1.9 mi along the southern end of profile 11, to 4.2 mi along profile 9, and 3.7 mi near the northern end of the block along profile 12.

The upper surface of the volcanic rocks on the Ames Block displays an apparent synclinal structure. There is no apparent vertical displacement along the Perry-Hampton Fault Zone on the southern end of the structure. Downward displacement of the block increases to the north, to a maximum near profile 9 (fig. I6), then decreases to its northern intersection with the Thurman-Redfield Structural Zone.

Both the upper and lower Red clastic sequence rocks are preserved on the Ames Block. Both sequences are apparently erosionally beveled along the southern end of the Ames Block, where drill data confirm the presence of volcanic rocks at the Precambrian surface. A total volume of about 3,400 mi^3 of Red clastics are preserved on the Ames Block.

Available information suggests that the uplift of the Iowa Horst included reactivation and reversal of the normal faults that bounded the central graben of the MRS in Iowa—the Northern Boundary Fault Zone on the west and the Thurman-Redfield Structural Zone on the east. However, along the central area of the eastern margin of the graben, a new structure formed, the Perry-Hampton Fault Zone. The thick Upper red clastics group rocks on the Ames block suggest that deposition of the unit on the block occurred at the same time as in the adjoining flanking basins. Then, at some late stage, the Ames Block was uplifted, probably along with the remainder of the Iowa Horst. Additional complexity is added by the absence of clastic rocks at the southern end of the block, as confirmed by well data. This southern end probably remained attached to the main part of the Iowa Horst, as it moved upwards (Anderson, 1992).

Summary of Red Clastics in Iowa

MRS Red clastic rocks cover about 16,100 mi^2 of the Iowa basement (table I2). The two sequences, informally named “upper and lower Red clastics sequences” by Witzke (1990), are probably equivalents of the Oronto and Bayfield

Groups (and related rocks) of the Lake Superior area. Anderson (1992) estimated that a total volume of 39,800 mi^3 of these rocks are preserved in five basins flanking the Iowa Horst and three basins and a structural block on the central horst in Iowa. The Red clastics in Iowa are restricted to the subsurface and have been sampled by only 14 drill penetrations.

Depositional History of MRS Clastic Rocks in Iowa

MRS Lower Red Clastics Sequence

Much of the early stages of formation of the MRS was characterized by the emplacement of thick sequences of mafic-dominated volcanic rocks. Periods of magmatism were separated by periods of quiescence marked by erosion and the deposition of interflow clastic rocks. None of these interflow clastic rocks is known to be present in Iowa, but it is probable that they exist and they are similar to those described in the Lake Superior region (see Jirsa, 1984). Studies in the Lake Superior region by several geologists, including Daniels (1982), indicate that as rift volcanism waned, clastic sedimentation became the predominant depositional process along the axis of the rift. Although rift volcanism ceased, probably due to a relaxation of the tensile stresses, subsidence of the rift zone continued, driven in part by isostatic adjustments to the thick, dense pile of rift-filling volcanic rocks. In the Lake Superior area, the Oronto Group and related units are known primarily from exposures of deposits in the central graben. In the Eischeid well in Iowa the lower Red clastics sequence was deposited outside of the central graben. The basal unit of the Oronto Group, the Copper Harbor Conglomerate, is dominated by mafic volcanic rock fragments, apparently derived from volcanic rocks in the footwall of the graben-bounding normal faults (fig. I14). This suggests that deposition of Copper Harbor Conglomerate sediments was primarily limited to the area of the central horst. This unit and all other Oronto Group units are known only from this area, but related rocks may be buried beneath thick Bayfield Group sedimentary rocks as modeled by Mooney and others (1970) and Chandler and others (1989). Unit B in the M.G. Eischeid #1 well, the basal unit of the Red clastics in the horst-flanking basins in Iowa, was interpreted by Anderson (1992) as the distal equivalent of the Copper Harbor Conglomerate. These fluvial sediments were deposited by rivers that eventually flowed into the central graben. Two wells, the Ogden City #2 and Boone City #1, on the Iowa Horst in Boone County, encountered clastic rocks, probably Copper Harbor Conglomerate equivalent units.

Standing bodies of water, probably lakes but possibly an arm of the sea, that developed in the MRS grabens hosted the deposition of a sequence of siltstones and shales, the Nonesuch Formation and equivalent units. Although Hieshima and Pratt (1991) used sulfur/carbon isotope ratios to infer a marine environment for Nonesuch sedimentation, Anderson (1992) concluded that regional structures argued against a connection to the open ocean.

The water bodies in the MRS were apparently rich in algae and fungae (Moore and others, 1969), which created an organic-rich sediment. The Nonesuch Formation in the Lake Superior area, having a maximum known thickness of about 700 ft (Daniels, 1982), was apparently limited in deposition to the area of the central graben. In Iowa, however, an equivalent rock sequence (unit C) in the Eischeid well demonstrates that in this area the lacustrine environment extended beyond the limits of the central graben (Anderson, 1990c). The 1,470-ft thickness of unit C was deposited about 15 mi outside the graben and about 55 mi from the axis of the graben. Additionally, dark-gray shales of unit C were encountered in a number of research cores drilled on the central peak of the Manson Impact Structure, about 11 mi west of the Iowa Horst. These shales, as large breccia clasts in an impact melt-rock matrix, are apparently juxtaposed against underlying brecciated crystalline rocks, suggesting that unit C may over-step unit B near the margins of the flanking basins.

If interpreted graben margins in Iowa are correct, the lakes that filled the subsiding MRS were probably very large, possibly more than 60 mi wide and may have extended along most of the length of the Iowa segment of the MRS, and possibly the entire length of the rift. The thickness of the unit near the axis of the graben was probably several times the thickness of unit C (Anderson, 1992).

The rift-axial lakes were eventually filled by transgressing alluvial fans that deposited the fluvioclastic rocks of the Freda Formation in the Lake Superior area and equivalent units, including Eischeid well unit D. Deposition of the rift-related clastic rocks of the Oronto Group probably ceased only a few million to a few tens of millions of years at the most after the cessation of volcanism (about 1,086 Ma; Van Schmus and Hinze, 1995). The end of rift sedimentation was probably indicative of the end of rift subsidence and possibly the initiation of compressive tectonics. This marked the beginning of a period that was apparently dominated by erosion of the recently deposited clastics.

MRS Upper Red Clastics Sequence

Following a period of regional erosion, the area of the MRS was affected by increasing regional shortening that led to a reversal of movement along the fault system bordering the central grabens. The central grabens were forced upwards, ultimately forming axial horsts. Oronto Group sediments were eroded from the rising horsts and deposited in basins that formed along the horst flanks. The remobilized Oronto Group sediments, winnowed during fluvial transport, were also apparently enriched in quartz by mixing with clastics derived from the granitic terranes in which the MRS was emplaced (Ojakangas and Morey, 1982a). The sandstone-dominated sequences that were deposited by these processes, the Bayfield and equivalent units, reach a maximum of about 7,000 ft (Ojakangas and Morey, 1982a). In the Lake Superior area, the Bayfield Group is composed of three units (fig. I3). Two are feldspathic, fluvial sandstones (the basal Orienta Sandstone and upper Chequamegon Sandstone), and the intervening unit is a quartz arenite (the Devils Island Sandstone), interpreted as lacustrine in origin (Ojakangas and Morey, 1982b).

In Iowa, upper Red clastic sequence units E, F, and G in the Eischeid well were interpreted as equivalent to the Bayfield Group (fig. I7) by Witzke (1990). Additionally, Eischeid well unit H is also considered a part of the upper Red clastics sequence (McKay, 1990) and also equivalent to the Bayfield and related rocks (Anderson, 1990c). All upper Red clastic units in the Eischeid well are feldspathic sandstones. Unit G, however, is dominated by very fine grained to fine-grained sandstones and has a large component of siltstone, possibly indicative of deposition in a standing body of water. This is similar to the interpreted environment of the Devils Island Sandstone in the Lake Superior area. Units E through G show a progressive increase in the mafic volcanic content of the lithic fragment component of the sandstones and may record the progressive unroofing of the volcanic rocks of the central horst (Anderson, 1990c; 1992).

Seismic data were interpreted by Cannon and others (1989) to indicate the presence of Bayfield Group sedimentary rocks overlying the Oronto Group beneath central Lake Superior. On land, however, no Bayfield Group rocks have been identified on the central horsts. The exception may be found in Iowa, where the Mineola Basin, centered on the Iowa Horst in southwestern Iowa and modeled on profile 13, is filled with sediments interpreted as low-density upper Red clastic sequence rocks.

In Iowa, rocks of the Bayfield Group equivalent, the upper Red clastics sequence in the Eischeid well, totals 7,708 ft in thickness. Along several of the seismically controlled profiles, the upper sequence reaches a thickness of about 13,000 ft in the Wellsburg Basin and on the Ames Block.

Problems Associated with Differentiation of Clastics

Historically, geologists working in Iowa have had difficulty differentiating the Red clastics from the basal Paleozoic sandstones (traditionally called Mount Simon Sandstone). This problem arises from the similarity of the lithologies (sandstones, siltstones, and shales), color, and the scarcity of diagnostic fossils. Additionally, since the basal clastic units apparently contain no mineral resources or petroleum and are only rarely utilized as an aquifer, samples are rare and the units are not well understood. Previous examinations of samples and logs from the two deepest early penetrations of these clastic sequences (#1 Wilson and #1 Huntly oil tests) identified Cambrian fossils deep into the clastic sequence, leading to the interpretation of thick Mount Simon Sandstone basins above the Red clastic basins on the flanks of the MRS Iowa Horst (Bunker, 1982; Bunker and others, 1988). Such “reactivated” basins are not observed in similar positions along the MRS in Minnesota or Kansas (Sims, 1990). This interpretation of deep Mount Simon basins was investigated by additional studies of the petrology and other characteristics of strata in thick Mount Simon sequences. This information, combined with data from the study of the Red clastics in the M.G. Eischeid #1 well (see Anderson, 1990a) led to the development of criteria for distinguishing the two units.

Investigation of the UPH–2 Core

The first step in this stratigraphic investigation was to determine the characteristics of thick Mount Simon Sandstone strata. Such a thick Mount Simon sequence is present in northern Illinois, but no cores of this material had been described in detail. To provide this information the thick Mount Simon interval of the Consolidated Edison UPH–2 core drilled in Stephenson County, in northern Illinois near the town of Lena, was logged. The core, one of three, was recovered from the northwest flank of the Mount Simon Basin, mapped by Buschbach (1975) and known to exceed 2,460 ft in depth.

The Mount Simon Sandstone in the UPH–2 core is present at a depth between 1,310 and 2,178.5 ft and overlies Proterozoic granite porphyry. It can be characterized as a very fine to very coarse grained sandstone containing granules and pebbles. The unit contains less than 5 percent shale and includes many upward-fining sequences characterized by a poorly stratified base grading upward to better stratified upper units. The coarse-grained and pebbly beds generally increase in frequency with depth. The texture, grain size, and sorting are highly variable from bed to bed. The color of the sandstones of the Mount Simon is also highly variable from white (clear to frosted) to yellow and red, and the shales are predominantly red with some green and mottled colors.

Body fossils were not observed in the Mount Simon Sandstone in the UPH–2 core, but some trace fossils were observed, including *Skolithos*, *Arenicolites*, and *Cruziana* or *Rusophycus*, generally above 1,584.5 ft. Bioturbation is most common in the upper 220 ft of the Mount Simon and is totally absent below 1,600 ft.

The sandstones in the Mount Simon are well stratified, individual strata generally being less than 1 ft thick. Structures observed include parallel, horizontal, small- and large-scale cross-stratification. Clay drapes were observed over small-scale, cross-stratified intervals, mudstone rip-up clasts, minor flaser structures, and minor lenticular sandstone bodies.

A qualitative mineralogical assessment during logging determined that the sandstones were quartz-rich. Shales were silty, sandy, and micaceous. Nine thin sections, representing samples collected at about 100-ft intervals, were point-counted (appendix I2). These thin sections are quartz arenites, the quartz ranging from 91 to 100 percent of QFL grains. Feldspar grains compose as much as 8 percent (all potassium feldspar) of the rocks; lithic fragments were not observed. The mean composition for the framework grains in the nine sections was $Q_{99}F_1L_0$ (see appendix I2). The cement in the rock is predominantly quartz, with minor clay/oxides and rare carbonate minerals.

The UPH–2 core is reposited at the Iowa Geological Survey Sample Repository near Iowa City. A detailed log is on file at the Iowa Geological Survey Bureau.

Reinterpretation of the #1 Wilson Well

Only chip samples were collected during drilling of the #1 Wilson well. Sandstones interpreted as Reagan Sandstone were encountered at 3,555 ft, beneath an undifferentiated Arbuckle Group or Upper Cambrian (Carlson and others, 1990) dolomite sequence (fig. I15). Beneath the Reagan Sandstone, the top of the MRS Red clastic sequence is placed at a depth of 3,700 ft. The sandstone is dominated by coarse sand (with subordinate very coarse to very fine sand, minor green shale fragments and free dolomite rhombohedrons) to a depth of 3,935 ft. An 18-ft thick sequence of red silty, sandy shale was encountered at that depth. At 3,953 ft the well passed back into the sandstone, which continued to a depth of about 4,130 ft, where an alternating series of red shales and sandstones was encountered to 4,670 ft. Below a 30-ft sample gap, the nature of the samples changed to thick, dark-brown silty shale sequences interbedded with fine-grained to very fine grained sandstone to about 4,805 ft, light-brown siltstone interbedded with dark shale and sandstone to about 4,985 ft, interbedded red and dark-brown sandy, silty shales to 5,180 ft, and coarse-grained to very fine grained sandstone to 5,270 ft. Samples were not recovered from the interval 5,270–5,305 ft. The most recent previous interpretation of the clastic rocks in the Wilson well (Bunker, 1982; Bunker and others, 1988) inferred that the Mount Simon–Red clastics contact was within the sample gap from 4,670 to 4,700 ft, on the basis of the major change in lithology from a sandstone-dominated sequence containing subordinate red shales to a dark-brown and red-shale-dominated sequence containing subordinate brown siltstone. Figure I16 shows previous interpretations of the strata at the base of the Wilson well. Bunker's interpretation was strengthened by the presence of dolomitic green shale between the depths of 3,565 and 4,670 ft and by fossil fragments associated with minor green shales between 4,205 and 4,235 ft and at 4,380 ft. Most of the fossil fragments and dark-green grains of probable biogenic origin were not identifiable; however, a brachiopod and a trilobite fragment were noted. This interpretation of the basal contact of the Mount Simon Sandstone infers a unit thickness of 1,090 ft and was one of the key pieces of evidence that led to the interpretation of the deep Mount Simon basins flanking the Iowa Horst.

To evaluate this interpretation, samples from selected intervals of the #1 Wilson well were petrographically examined to identify the constituent framework grains and cements. Fossil fragments and associated matrix were collected and analyzed to identify the fossils and determine that the material was in place. Historic well files were reviewed to determine if any aspect of the drilling and construction history of the #1 Wilson well might have influenced sample integrity. Finally, the well chips were re-examined to determine a new position for the Mount Simon–Red clastics contact if the previous interpretation was found to be in error.

Petrographic Analysis

Samples were selected for petrographic analysis from 18 intervals in the clastic rock sequence at the base of the Wilson well, and thin sections were prepared and point-counted; both framework grains and cements were inventoried. The point-count data (appendix I2), when analyzed to display framework grain data in the QFL mode, showed a clustering into three groups that decreased in mineralogical maturity with depth. The uppermost three samples (3,655 ft) are the most mature (fig. I17), displaying a framework mode of $Q_{99.5}F_{0.5}L_{0.0}$. The second grouping included 10 samples from depths of 3,703–4,501 ft; these samples display a mean QFL mode of $Q_{91.6}F_{8.3}L_{0.1}$. The third group of three samples recovered from 4,814–5,206 ft are the least mature, having a mean QFL composition of $Q_{72.6}F_{27.0}L_{0.4}$. The sample gap that previously was interpreted as the contact between the Mount Simon and the Red clastics falls within the interval between the second and third maturity group.

Examination of Fossils

Samples from the intervals in the Wilson well that had been found to contain fossil fragments (between depths of 4,213–4,221 ft and 4,385 ft were examined under a binocular microscope. Representative fossil fragments, and fragments that displayed the best potential for identification, were collected from depths of 4,213 and 4,221 ft. The fossils included medium- to dark-green pellets, tubes, and fragments of gastropods and bryozoans, all having a phosphatic appearance and less than 2 mm in length. Also, fragmental molds of brachiopods in gray siltstone were recovered. Additionally, samples from selected overlying intervals of Paleozoic strata, which had lithologies similar to lithologies associated with the deep fossil fragments, were also examined. Fossil fragments similar in appearance to the deep fossil fragments were recovered from a sample of the base

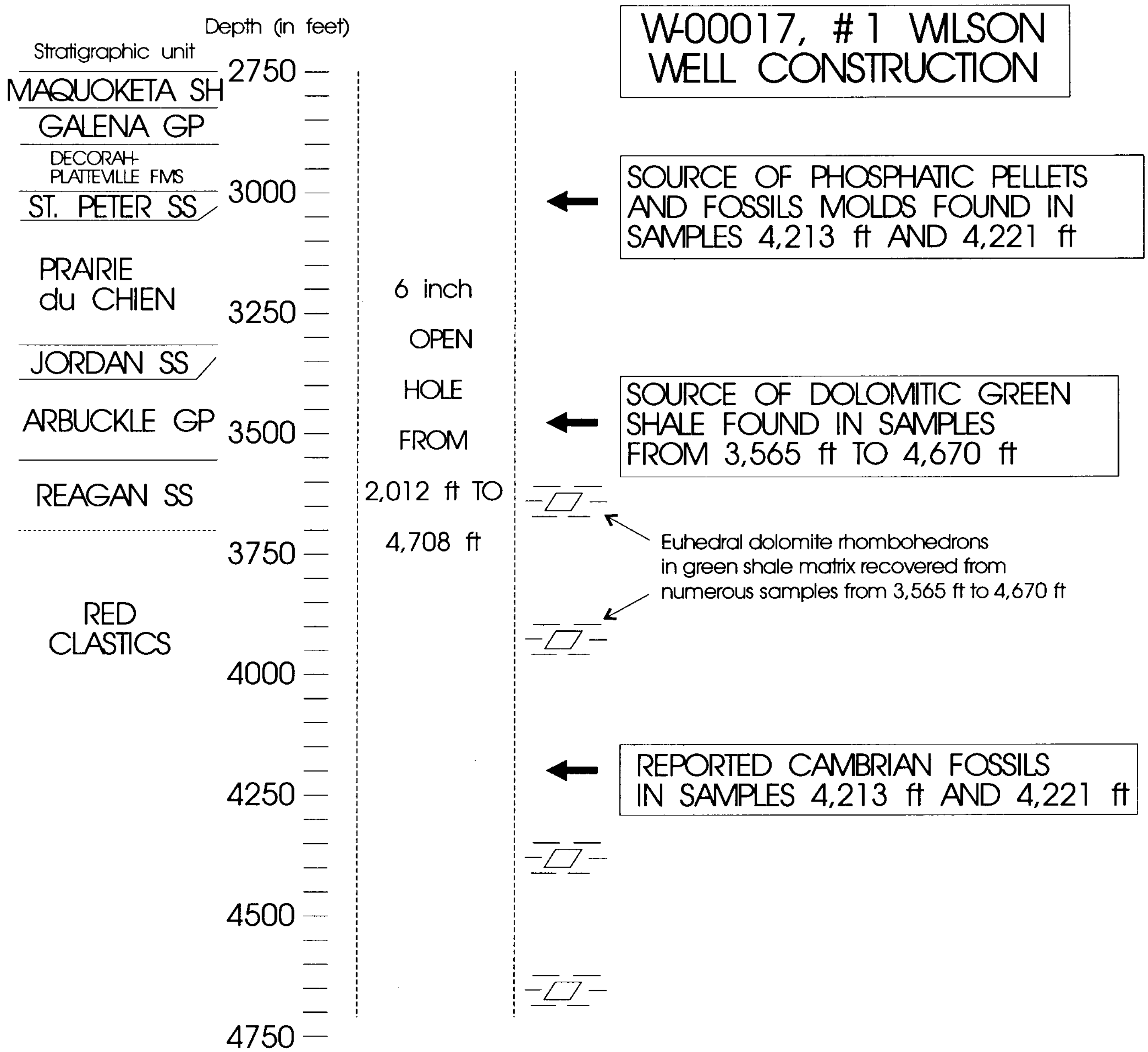


Figure I15. Stratigraphy and construction history of #1 Wilson oil exploration well, Page County, Iowa. FMS, Formations; GP, Group; SH, Shale; SS, Sandstone.

of the Ordovician St. Peter Sandstone (3,021–3,026 ft).

Fossil fragments were photographed through the binocular microscope (fig. I18), then 13 fossils, selected from each of the 3 intervals, were mounted in epoxy and a polished thin section produced. Upon petrographic analysis many fragments displayed an organized internal wall and chambered structure typical of microfossils. External walls and chambers were also observed, and the fossils displayed petrographic characteristics typical of finely crystalline apatite (phosphate). The 13 fossil fragments mounted on the polished thin section, 2 free individual fossil fragments, and 2 siltstone rock chips that contained phosphatic grains were prepared for analysis on a scanning electron microscope. Individual fossil fragments were examined, with secondary and backscattered electrons collected (fig. I19). Semi-quantitative microanalysis was conducted.

Electron dispersion (EDS) analysis showed the composition of most fossils to be predominantly calcium phosphate (apatite), and some secondary pyrite and dolomite. The bryozoans and gastropods showed moldic preservation and calcium phosphate composition, and brachiopods displayed moldic composition and possibly replaced original shell material. Other grains included indeterminate oval to irregularly shaped calcium phosphate pellets. Bryozoans were the predominant fossil fragment recovered. Some bryozoans appear to be Cryptostomes, and one was tentatively

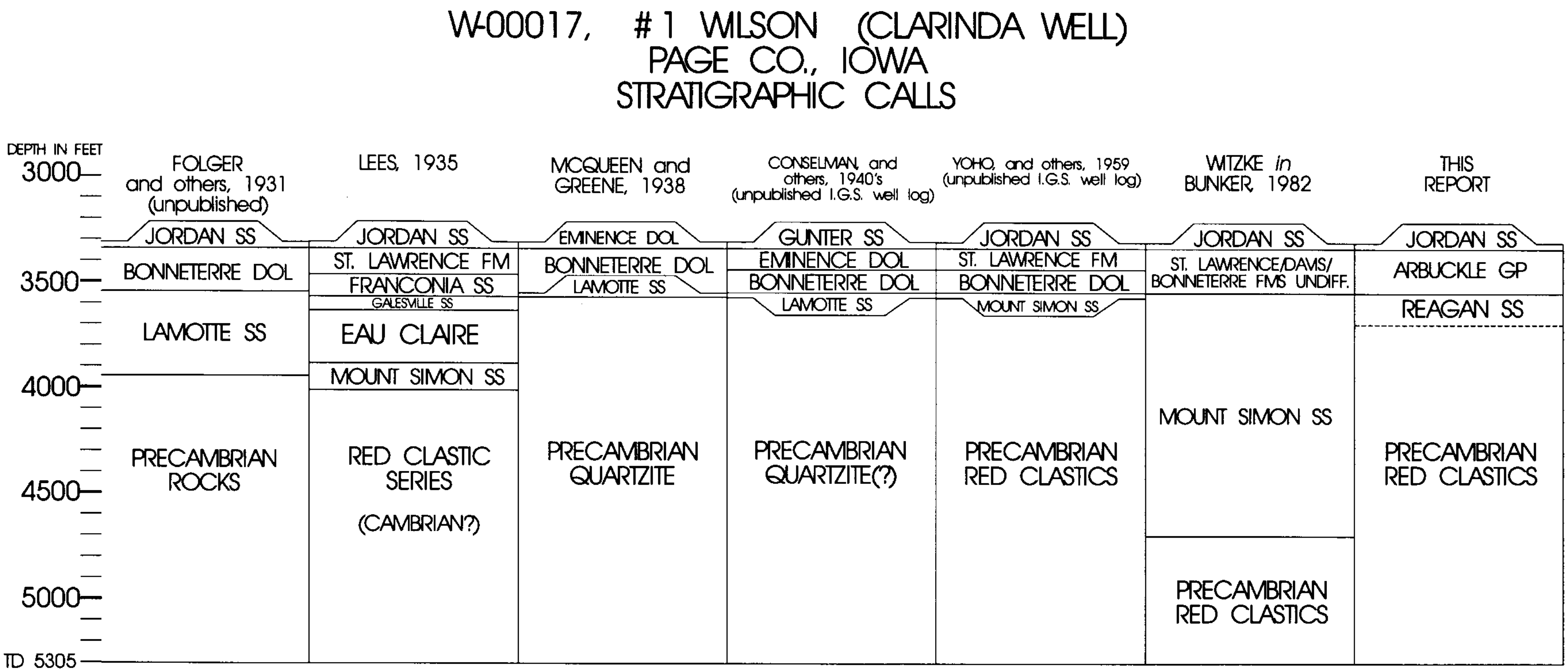


Figure I16. Historical interpretations of stratigraphy near base of #1 Wilson oil exploration well, Page County, Iowa. DOL, Dolomite; FMS, Formations; GP, Group; SH, Shale; SS, Sandstone.

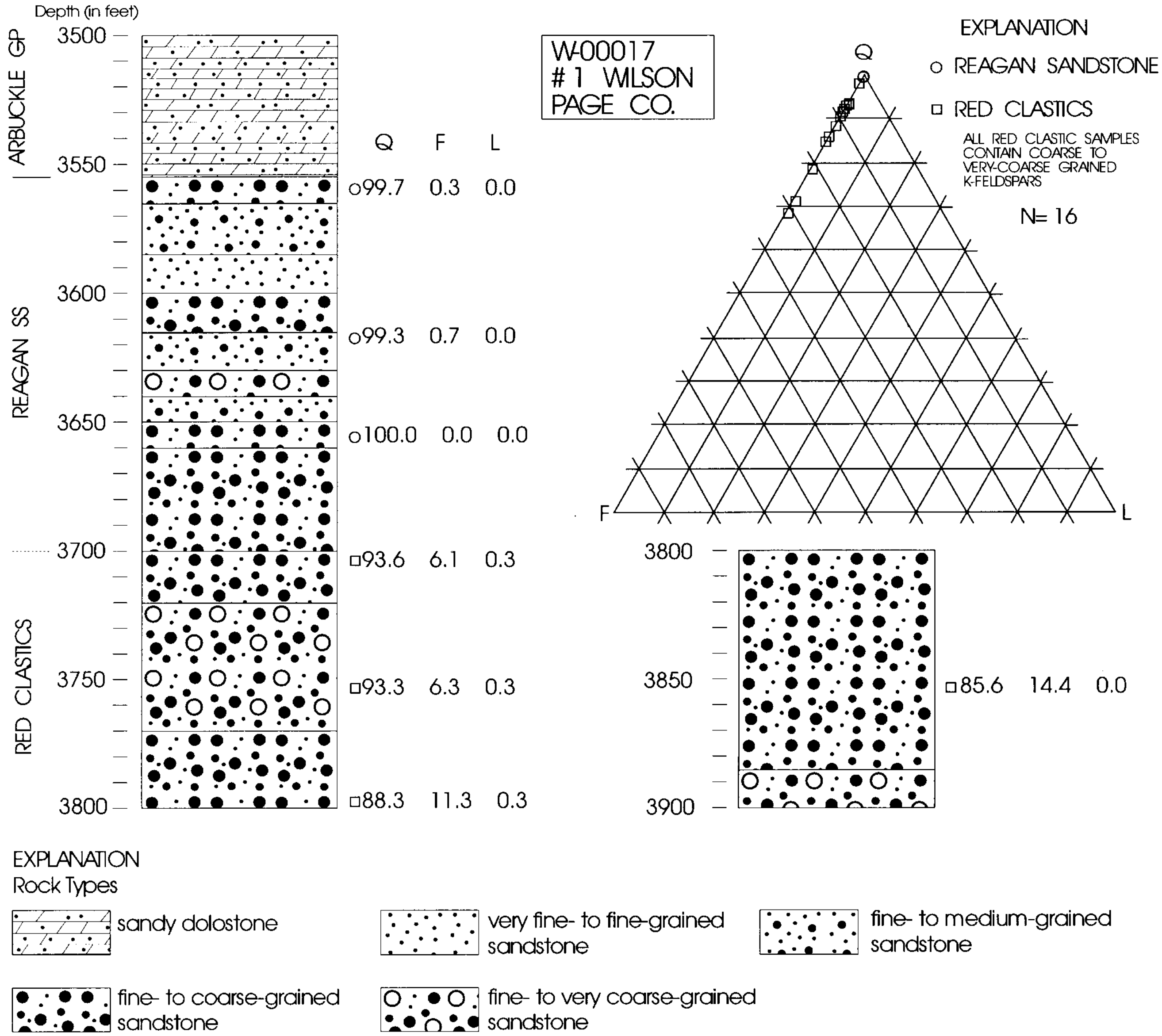


Figure I17. Lithic log and quartz–feldspar–lithic grain (QFL) diagram for part of #1 Wilson oil exploration well, Page County, Iowa. GP, Group; SS, Sandstone.

identified as a *Ptilodictya* sp (fig. I18*G*), but others were not identified. *Ptilodictya* sp was reported to be present in the St. Peter Sandstone in the Minneapolis area by Sardeson (1892, 1896) and Sloan and others (1987). Neither the brachiopods nor the gastropods could be identified.

Bryozoans do not appear in the geologic record below the base of the Ordovician, brachiopods appear at the base of the Cambrian, and gastropods appear in the Cambrian (McKerrow, 1978). The presence of bryozoans in the samples recovered from depths of 4,213 and 4,221 ft in the Wilson well, deep within a thick sandstone sequence that is unlike any lithology within the Ordovician strata of the region, and below documented Cambrian strata, indicates that the fossils are not indigenous to the sample intervals from which they were recovered. They appear to be similar in every way to the fossil fragments recovered and analyzed from the base of the Ordovician St. Peter Sandstone (3,021–3,026 ft). The fossils reported in the #1 Wilson samples from depths of 4,205–4,235 ft and 4,385 ft are interpreted as contamination that fell down the borehole from the base of the St. Peter Sandstone at a depth of 3,021–3,026 ft.

Examination of Chip Samples

A re-examination of samples from depths of 3,000–5,305 ft in the #1 Wilson well revealed that the sandstones between 3,555 and 4,700 ft are contaminated due to caving with green dolomitic shales and phosphatic

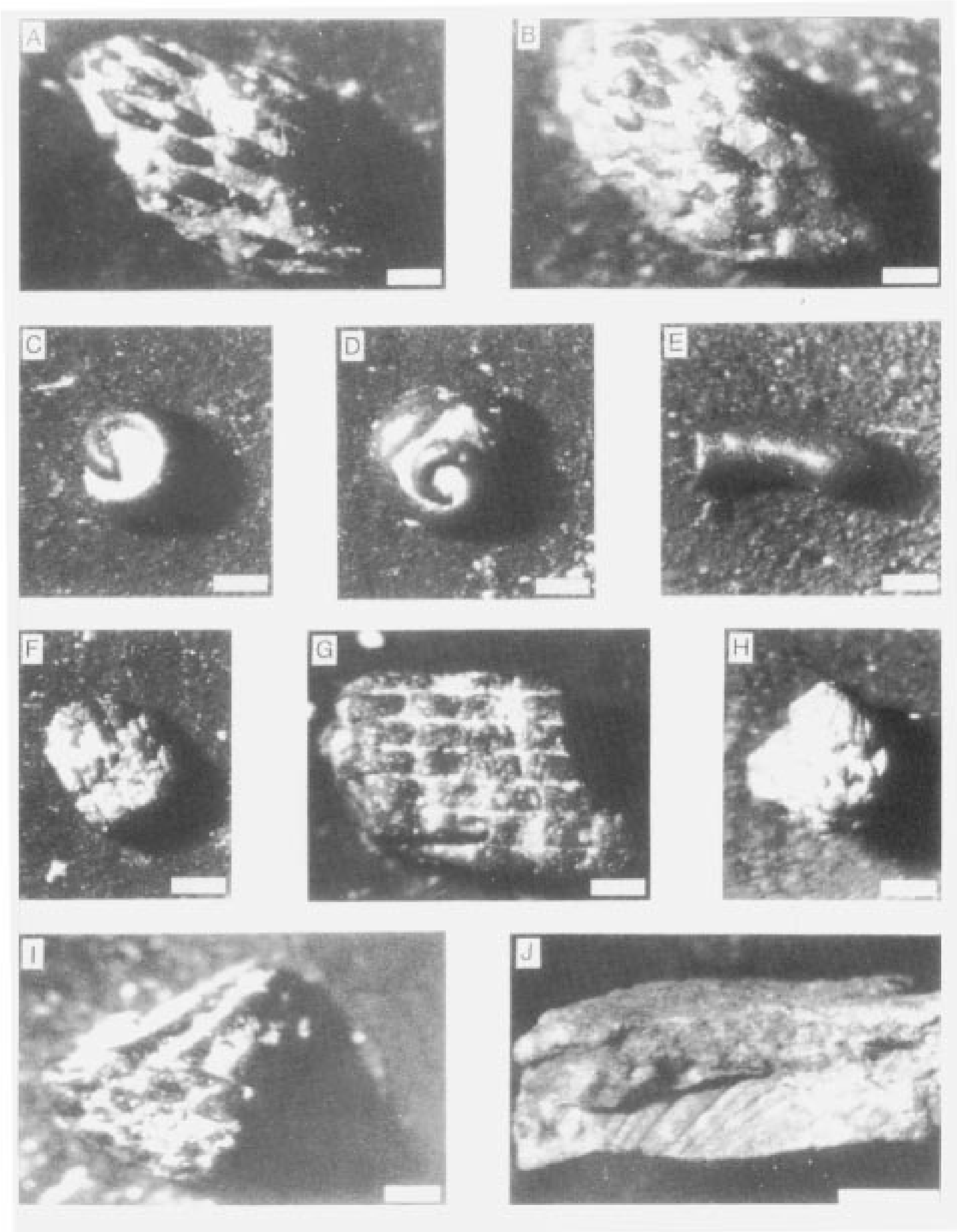

A
B
C
D
E
F
G
H
I
J

Figure I18 (previous page). Photographs of selected microfossils recovered from chip samples from #1 Wilson oil exploration well (W–00017), Page County, Iowa. Specimens from the interval 3,021–3,026 ft were collected from basal St. Peter Sandstone (Ordovician). Specimens from 4,213–4,221 ft are from two intervals interpreted as Red clastics in this report. All specimens are preserved as calcium phosphate molds. Bar scale A–I=0.25 mm; J=1.0 mm. *A*, Cryptostome bryozoan: 3,021–3,026 ft. *B*, Cryptostome bryozoan: 4,213 ft. *C*, Gastropod: 4,213 ft. *D*, Gastropod: 3,021–3,026 ft. *E*, Curved tube (gastropod fragment?): 4,221 ft. *F*, Cryptostome bryozoan (?*Ptilodictya* sp.): 4,213 ft. *G*, Cryptostome bryozoan (?*Ptilodictya* sp.): 3,021–3,026 ft. *H*, Cryptostome bryozoan: 4,213 ft. *I*, Cryptostome bryozoan: 4,213 ft. *J*, Brachiopod impression in siltstone: 4,221 ft.

microfossils. Identical dolomitic green shales first occur in the Wilson samples at 3,465 ft, and this interval in the middle Arbuckle Group is confidently identified as the source of the dolomitic shale in the deeper sample sets. The fossils originate from the overlying St. Peter Sandstone. There are no reported occurrences of dolomitic shales in the Mount Simon of the northern midcontinent and very few occurrences of dolomitic cements. Finally, rounded to well-rounded, frosted quartz grains found throughout the contaminated interval may, in part, be derived from the Jordan, St. Peter, or other mature Cambrian or Ordovician sandstones.

Investigation of the drilling records for the #1 Wilson disclosed that the well was drilled over a 2-yr period (1929–31) with a cable tool drill rig. The hole was cased to the top of the Ordovician Maquoketa Shale (depth of about 2,012 ft) and then left open until the well reached 4,708 ft, the next casing point. The drilling of this 2,700-ft interval was estimated from well file records to have taken about 1 yr, and over that period of time the caving intermittently contaminated the newly drilled samples. At a depth of 4,700 ft the well was cased, and the lithologies observed in the samples below this depth change dramatically. This change was apparently due to the casing sealing upper intervals of the borehole, preventing contamination of the samples below the casing. The contamination of the interval above 4,700 ft indicates that the samples collected are not representative of the lithologies in the borehole and point-count data from these intervals are compromised. The samples collected below 4,700 ft are probably representative of the lithologies in the borehole.

Conclusions

On the basis of the results of this research, the contact between the base of the Reagan Sandstone and the top of the Red clastics is placed at a depth of about 3,700 ft. QFL analysis of framework grains from point-count data show a substantial increase in coarse feldspar grains over this interval (from 0.52 percent to 18.75 percent). This coarse-grained feldspar content is much higher than observed in any interval of the Mount Simon in the UPH–2 core. However, the presence of two metamorphic rock fragments in the 3,655-ft interval leads to some uncertainty with this interpretation. Metamorphic and volcanic rock fragments are extremely rare in the Mount Simon Sandstone, except in the very lowest strata where clasts of the underlying lithology are sometimes incorporated into basal sands. Additional petrographic studies will be undertaken in the near future in an attempt to define the contact more accurately.

Re-examination of the #1 Huntley Well

The #1 Huntley well in Butler County, Iowa, was drilled in 1963–65 and penetrated almost 1,900 ft of clastic rocks in the basal half of the well. The clastic rocks penetrated included Cambrian Lone Rock, Wonewoc, Eau

Figure I19. Back-scattered electron photomicrograph of Cryptostome bryozoan from #1 Wilson oil exploration well (W–00017), Page County, Iowa. Image collected from a carbon-coated polished thin section. Photograph shows well-defined wall and chamber structure. Both walls and chambers are composed principally of calcium phosphate. Bright, high-relief spots are pyrite; dull, low-relief spots are dolomite. Slightly darker material along left margin is aluminum oxide polishing compound. Sample No. W–00017–2–D3–BS; sample depth, 4,221 ft; accelerating voltage, 20 kV; magnification, 250×; bar scale, 120 µm.

Claire, and Mount Simon Formations overlying a thick sequence (about 1,280 ft) originally interpreted as Red clastics. A number of brachiopod fragments were reported to be present at depths of 3,505–3,525 ft near the bottom of the well and were originally interpreted as contamination due to caving (IGSB unpublished log by D.L. Koch, 1965).

Re-examination of the chips in the late 1970's led to a revised interpretation of the stratigraphy (Bunker, 1981; 1982; and Bunker and others, 1988). The new interpretation placed the basal 1,465 ft of the clastics in the Mount Simon Sandstone. This was based on the lack of a distinct contact with the Red clastics, the coarse to very coarse sand grains present throughout the unit, dolomitic cement, and the fossils near the base of the well that were thought to be imbedded in a matrix that was unlike any lithology observed in overlying units. The fossils were, therefore, interpreted to be in place.

For this study, the history of the drilling of the well was investigated (fig. I20); samples were collected from 18 intervals of chips, and grain-mount thin sections were produced and point-counted. The data collected (appendix I2) was analyzed to determine QFL framework mineralogy (fig. I21). The QFL analysis of the data produced two populations. The upper interval (2,150–2,305 ft) was mineralogically mature, having a composition of $Q_{98.4}F_{1.6}L_{0.0}$; no lithic grains were encountered. This composition is typical of the Mount Simon Sandstone. Point counts of 13 thin sections showed the underlying intervals to have a mean QFL composition of $Q_{78.3}F_{16.2}L_{5.5.}$ This is similar to the composition of unit H of the Eischeid well. On the basis of the maturity and lithic grain composition of the framework grains, examination of the natural gamma-ray log, and feldspar lithic grain size, the contact between the Mount Simon and the Red clastics is judged to be at 2,305 ft in the #1 Huntley well. This interpretation results in the Mount Simon being 175 ft thick, much thinner than the previous interpretation, which suggested a unit thickness of 1,400 ft.

Fossil fragments and their matrix from chip samples of the depth interval between 3,505 and 3,575 ft were examined. Fragments of inarticulate brachiopods were identified in a greenish, argillaceous, glauconitic, very fine grained to fine-grained sandstone matrix. Using existing lithologic logs of the well as a guide, chips from selected intervals of Cambrian shales in the well were re-examined, and several samples were identified that may have been the source of the brachiopods and their matrix. Identical brachiopods and matrix were observed in the basal Eau Claire and uppermost Mount Simon Sandstones in the depth interval from 2,020 to 2,040 ft. This higher level, brachiopod-rich interval remained uncased, and the open hole caved during the drilling to its final depth of 3,595 ft (see fig. I20). Examination of the well file records indicates that the well was affected by severe caving through this interval, and since this caving-prone, brachiopod-bearing interval was never cased off, it is concluded, therefore, that the inarticulate brachiopods identified between 3,505 and 3,530 ft in the Huntley well results from contamination from the basal Cambrian Eau Claire Sandstone. On the basis of this restudy, the top of the Proterozoic Red clastics is placed at a depth of 2,305 ft.

Evaluation of Criteria for Picking the Mount Simon–Red Clastics Contact

This study of the Mount Simon–pre-Mount Simon contact in Iowa has led to the identification of several lithostratigraphic correlation characteristics that appear useful. Traditionally, several criteria have defined the base of the Mount Simon and the top of the Red clastics. Primary among these criteria is the change in color from the buff sandstones and gray-green shales of the Mount Simon to the pink, orange, or red sandstone and red siltstone and shale of the Red clastics. Other criteria include the lack of fossils in the Red clastics, the first appearance of red shales and siltstones, and an increase in consolidation with depth of the Red clastics over the Mount Simon. This study, conducted by Robert McKay, suggests that these criteria may not be valid. Examination of the UPH–2 core indicates that the Mount Simon sandstone can be either red or orange and can include interbedded red shales. Additionally, the UPH–2 core shows that the Mount Simon can be well lithified. While it is true that no fossils are known to be present in MRS sandstones, caving within a drillhole can bring fossils from Paleozoic units down the hole to mix with Red clastics samples. The study by McKay identified several criteria that appear to be useful in delineating the contact:

Feldspar size and shape.—Whereas the Mount Simon Sandstone is predominantly a quartz arenite, some intervals may contain 30 percent or more feldspar (fig. I22). The Mount Simon feldspar is limited to potassium feldspar; many grains display well-defined potassium feldspar overgrowths on detrital potassium feldspar grains that form subhedral to euhedral, pore-filling crystals. Detrital feldspar grains in the Mount Simon are always smaller (very fine grained to medium grained) than associated quartz grains and are rounded to subrounded. Feldspar is a common constituent of the Red clastics; potassium feldspar is most common, but minor plagioclase can also be found. Authigenic feldspar is also present in the Red clastics but much less common than detrital feldspar. Most diagnostic is the observation that detrital feldspar grains in Red clastics are as large or larger than the quartz grains with which they are associated. Additionally, detrital feldspar grains are commonly angular to subangular and generally display pronounced cleavage faces.

Cement mineralogy.—The mineralogy of the cements observed in the Mount Simon and the Red clastics can also be helpful in differentiating the units. The Mount Simon is

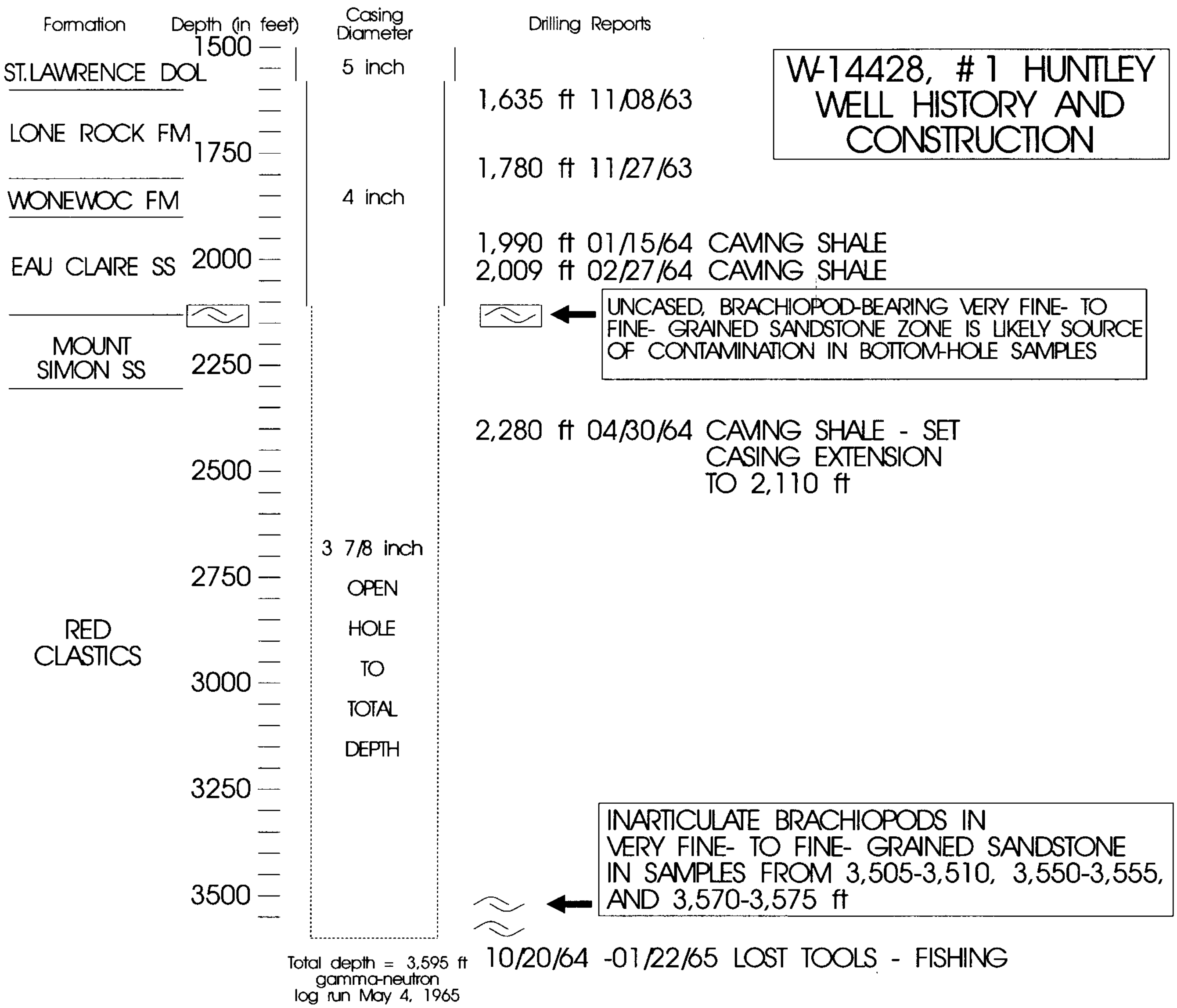


Figure I20. Stratigraphy and construction history of #1 Huntley oil exploration well, Butler County, Iowa. DOL, Dolomite; FM, Formation; SS, Sandstone.

dominated by quartz and potassium feldspar cement and contains minor carbonate, hematite and clay (kaolinite and illite) cement. Red clastics sandstones are predominantly cemented by quartz, calcite, hematite, and clay, and minor authigenic feldspar.

Detrital rock fragments.—Detrital rock fragments are very rare in the Mount Simon Sandstone. Detrital rock fragments were not observed in point counts of nine thin-sections from the UPH–2 core; rock grains were identified in only one thin section of samples collected from seven intervals of Mount Simon Sandstone from other wells. Detrital rock fragments constitute an important constituent of the Red clastics rocks studied. Lithic fragments were observed to constitute as much as 19.8 percent (appendix I1) of some Red clastic intervals studied, with felsic volcanic and metamorphic rock fragments being the most common lithologies of the lithic fragments. The presence of common lithic rock fragments is indicative of Proterozoic Red clastics.

Sandstone-to-mudstone ratio.—Although not as useful in defining the contact, the sandstone-to-mudstone (shale and siltstone) ratio can be helpful in determining if a depositional sequence should be assigned to the Mount Simon or the Red clastics. More than 90 percent of observed Mount Simon rocks are sandstone, mudstone representing <5 percent of the section. The Red clastics display a much more variable sandstone-to-mudstone ratio, ranging from about 20 percent to greater than 80 percent mudstone. This discriminator may be rendered invalid if Proterozoic units equivalent to the Hinckley Sandstone of Minnesota are observed in the Iowa subsurface. The Hinckley, like the Mount Simon, is strongly dominated by sandstone.

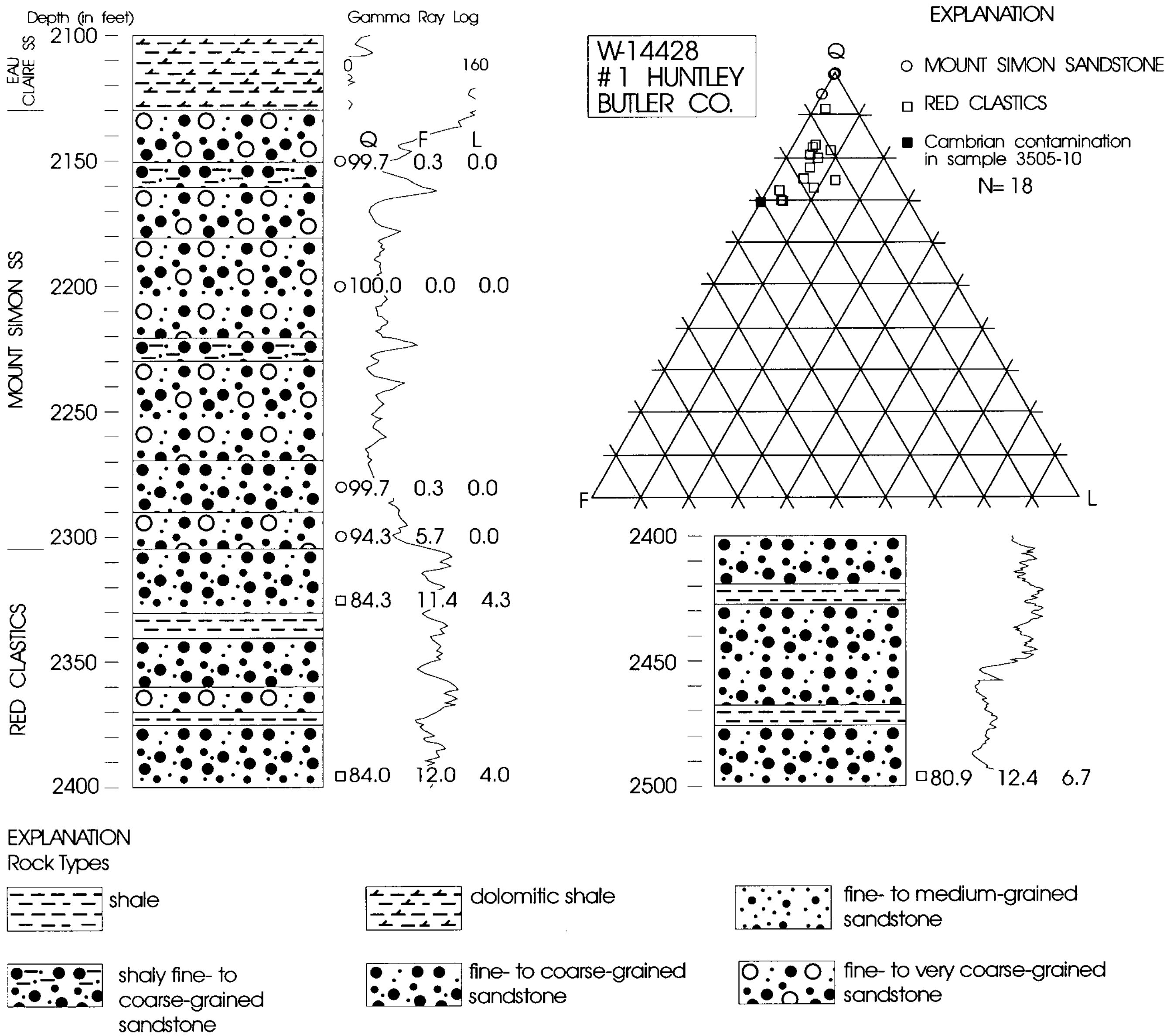


Figure I21. Lithic and gamma logs and quartz–feldspar–lithic grain (QFL) diagram for part of #1 Huntley oil exploration well, Butler County, Iowa. SS, Sandstone.

Presence of quartz arenites.—All quartz arenites (>90 percent quartz) that have been encountered near the Mount Simon–Red clastics contact in Iowa have been assigned to the Mount Simon. Petrographic examination of the Mount Simon has shown it to be strongly dominated by quartz arenites. Quartz arenites have not been observed in the Red clastics of Iowa.

The comparative study of the Mount Simon Sandstone and Red clastics also identified a number of criteria that are **not** useful in defining the contact between these units. They include:

Color.—Color has not been shown to be an effective tool for the differentiation of Mount Simon and Red clastic rocks. Sandstones in both units can range in color from buff to pink, orange, or red. While Mount Simon shales and siltstones are commonly gray to grayish-red in the subsurface, red shales are not uncommon. The shales observed in the Red clastics range in color from red to green mottled to brown, dark gray, or even black.

Grain size.—The Mount Simon Sandstone has been observed to range from very fine to very coarse grained, granules being frequently observed. The Red clastics display a similar variability in grain size.

Induration.—Both the Mount Simon and the upper Red clastics sequence are generally poorly indurated, but both may be well indurated in selected intervals. While it appears that the Red clastics may, as a unit, be slightly better

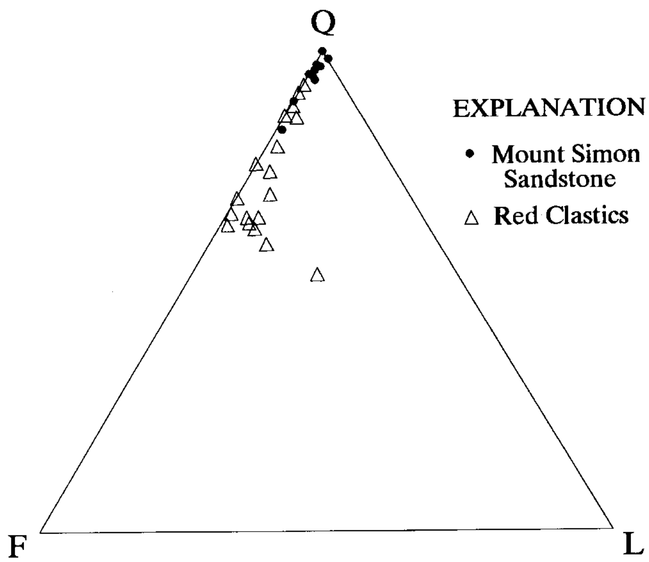


Figure I22. Quartz–feldspar–lithic grain (QFL) diagram of analyses of Mount Simon Sandstone and Red clastics from selected Iowa wells.

indurated, both units show sufficient variability to invalidate the usefulness of this criterion.

METALLIC MINERAL POTENTIAL OF MRS CLASTIC ROCKS IN IOWA

Examination of the lithologic logs from 9 of the 14 wells that penetrate MRS clastic rocks (Red clastics) in Iowa, and examination of the 481 ft of Red clastics core from 6 wells (table I1), have not disclosed any metallic mineral occurrences. Only one log, the mud log for the M.G. Eischeid #1 well, identified metallic mineral occurrence. The log identified “copper or chalcopyrite” at a depth of 15,440 ft. We carefully examined samples from that interval under a binocular microscope, but we found no copper, chalcopyrite, or any other metallic mineral.

PETROLEUM RESOURCES

Potentially valuable petroleum resources may be present in MRS clastic rocks. The Nonesuch Formation is dominated by dark-gray to black, organic shale and siltstone that were apparently deposited in a lake or other oxygen-starved euxinic body of standing water. Oil seeps from the Nonesuch ceiling rock in older parts of the Copper Range (White Pine) Mine, in northern Michigan, have been known for many years. This oil was shown to be indigenous to the Nonesuch Formation by Barghoorn and others (1965), and Rb-Sr dating of calcite containing primary petroleum inclusions by Kelly and Nishioka (1985) yielded a minimum age of 1,047±35 Ma for the hydrocarbons. The petroleum is a paraffinic, low-sulfur oil of 32° API gravity (Dickas, 1987).

Petroleum Potential Studies of Eischeid Samples

Since the target of the Amoco drilling was to search for economic deposits of petroleum and to learn more about petroleum potential of the sedimentary rocks of the Keweenawan Supergroup, core and chip samples from the M.G. Eischeid #1 well were examined by several workers. 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 (1990) in units B, C, and D–1, unit C being dominated by black to dark-gray shale and siltstone, all organic-rich and potential petroleum source rocks. Finally, the large sandstone component of the upper and lower Red clastics sequences and interbedded finer grained units offer the potential for petroleum accumulation and stratigraphic or unconformity traps, as well as structural traps that may have formed as a result of the late compressional phase of the MRS.

Source-Rock Potential

Samples collected from 53 intervals of Proterozoic and Paleozoic units in the Eischeid well were analyzed for total organic carbon (TOC) by Palacas and others (1990) to determine their source-rock potential. Selected samples were also analyzed for the maximum pyrolysis temperatures (T_{max}), the hydrogen index (HI), the oxygen index (OX), the production index (PI), the free hydrocarbons (S_1), and the pyrolytic yield (S_3). All upper Red clastics sequence samples contained less than 0.1 percent TOC, and most values were in the range of 0.03–0.05 percent. The lower Red clastics sequence showed higher values of TOC, unit D values all being less than 0.1 percent. Unit C was the most organic-rich, reaching a maximum value of 1.4 percent and averaging 0.6 percent. The only analysis from unit B displayed a TOC of 0.4 percent. These TOC values are low, but many petroleum geologists consider a TOC of 0.5 percent a minimum for a source rock (J.G. Palacas, oral commun., 1990). By this definition the carbonaceous rocks of unit C can be considered a marginal potential source rock.

Although the TOC content of unit C in the Eischeid well might suggest that it is a marginal source rock, determinations of T_{max} (the temperature at which the yield of pyrolysis products is maximized) for samples collected from six intervals of unit C core by Palacas and others

(1990) indicate that the organic material in the unit is overmature 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 and others, 1990). This advanced stage of thermal maturity was corroborated by several other studies including homogenization measurements on two-phase fluid inclusions in calcite and quartz veins in unit C by Barker (1990). 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 (1990) measured homogenization temperatures of two-phase liquid-vapor fluid inclusions in calcite veins near the top of unit C ranging from 125 to 178.6 °C. Pollastro and Finn (1990) used clay geothermometry to calculate a minimum paleotemperature of 175–180 °C for samples from the top of unit C, and to estimate the minimum bottom hole (at 17,851 ft) paleotemperature of 192–197 33 °C. Reflectance measurements on vitrinite-like particles, measurements of thermal-alteration index, and indices for chloroform-extractable organic matter determined by Palacas and others (1990) indicated that the organic matter in unit C has advanced well into the gas-generation zone. Palacas and others (1990, p. 119) 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 (1990) and Ludvigson and others (1990). Schmoker and Palacas utilized a variety of down-hole geophysical logs to calculate the porosity of sandstones between depths of 11,450 and 17,340 ft (units B and C and the lower part of unit D). They determined porosity ranging from 1 to 6 percent (averaging 2.3 percent) in this interval, with "better" porosity (3.5 percent or more) in about 14 percent of the section distributed in their upper (in unit D) and lower (in unit B) zones. The Eischeid mud log noted the detection of methane and ethane gases in these two zones and reported intergranular black residue, possibly a bitumen or pyrobitumen-like material (Schmoker and Palacas, 1990), in the lower zone.

Ludvigson and others (1990) and Barnes (1990) noted, however, that optically resolvable porosity was not observed in samples below 8,000 ft. The disparity between the low porosity reported by Schmoker and Palacas and the virtual absence of porosity noted by Ludvigson and Barnes may be the presence of micropores (not observable by optical microscopic techniques) or pores as inclusions filled with gas and (or) liquid in calcite and quartz veins and in calcite cements. Also, chips from many intervals included abundant loose (not cemented) grains, indicating possible areas of incomplete cementation and higher porosity.

Conclusions

It appears that some intervals of the lower Red clastics sequence in the M.G. Eischeid #1 well, especially unit C, once contained high levels of organic carbon and probably produced significant volumes of petroleum. However, hydrocarbon production probably reached its peak relatively early in the rock's history, about 800 Ma (Palacas and others, 1990). Black intergranular residue reported on the Eischeid mud log may identify paths of petroleum migration through overlying 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 overmature 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 pore space may have been destroyed by compaction and the precipitation of intergranular cements.

Petroleum Potential of MRS Clastic Rocks

The absence of commercial petroleum and the low 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 MRS. The advanced state of maturity observed in unit C by Palacas and others (1990) is the result of high temperatures affecting the Proterozoic rocks in the Eischeid well, probably early in their history. The methane-filled fluid inclusions in tectonic veinlets described by Ludvigson and Spry (1990) indicate that late Keweenawan deformation was coeval with petroleum migration in the Defiance Basin. Pollastro and Finn (1990) 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, 1990). It seems unlikely that this thermal regime was the product of deeper burial alone. The heat source was probably elevated heat flow from the igneous activity along the trend of the Midcontinent Rift, and possibly by hydrothermal activity associated with later stages of this activity. The elevated heat flow and geothermal activity were most pronounced nearest the axis of the rift.

At more distal areas the maximum temperatures would probably have been lower. Interpretations of seismic data acquired over the Defiance Basin by Anderson (1992) suggest that reflectors assigned to unit C lithologies continue for at least 7 mi and possibly as far as 15 mi 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 affecting 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, trapped in stratigraphic and (or) structural traps. Citing fluid inclusion and isotopic evidence, Ludvigson and Spry (1990) suggested that during uplift of the axial horst, fluid transport in the Keweenawan sedimentary basins was away from the rift axis. The petroleum migrated up dip, generally away from the axis of the rift, suggesting that the best potential exploration targets may exist on the outer flanks of the MRS (Ludvigson and Spry, 1990).

It appears that some intervals of the lower Red clastics sequence in the M.G. Eischeid #1 well, especially unit C, once contained high levels of organic carbon and may have produced large volumes of petroleum. However, hydrocarbon generation probably reached its peak relatively early in the rock's history, about 800 Ma (Palacas and others, 1990). Black intergranular residue reported on the Eischeid mud log may identify paths of petroleum migration through surrounding 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 overmature, retaining no potential for producing commercial petroleum. Porosity is also very low in the Proterozoic clastic rocks in the Eischeid well. Much of the original pore space may have been destroyed by compaction and the precipitation of intergranular cements.

CONCLUSIONS

This study of the clastic rocks associated with the Midcontinent Rift System in Iowa has yielded significant information that is useful in understanding these rocks, their relationships to the units in their Lake Superior exposure area, and their mineral potential. Significantly, petrographic characteristics have been identified that can be used to descriminate Midcontinent Rift clastics rocks and lithologically similar basal Paleozoic strata. Some of the major conclusions of this investigation are as follows:

- Cutting samples and cores from the Amoco M.G. Eischeid #1 deep oil test were studied. The well penetrated 15,049 ft of MRS clastic rocks that were assigned to two sequences, the upper Red clastics sequence and the lower Red clastics sequence. The upper sequence was subdivided into four units; the lower sequence was divided into three units. The lower Red clastics sequence is similar in many ways to the Oronto Group of the Lake Superior area, but a direct correlation is not possible. The upper Red clastics sequence bears many similarities to the Bayfield Group of Wisconsin but also cannot be directly correlated.

  Unit C in the lower Red clastics sequence contained abundant dark-gray and black shale and siltstone beds and is tentatively correlated with the Nonesuch Formation of the Oronto Group of Wisconsin and Michigan. They are presently relatively low in TOC (averaging about 0.6 percent) and are overmature with respect to their source-rock potential. They presently do not constitute a potential source of economic quantities of petroleum, but probably produced large amounts of petroleum early in their geologic history. Presence of black intergranular residues in a number of samples strongly suggests the migration of liquid petroleum at some time in the geologic past.

  Reflectors interpreted as the result of strata similar to unit C have been identified in deep seismic data in southwestern Iowa. These reflectors indicate that the unit may extend for 15 mi or more away from the Iowa Horst. This interpretation was strengthened by the discovery of unit C rocks on the central peak of the Manson Impact Structure. In the more distal areas, the effects of the elevated heat flow and possible hydrothermal effects associated with the axial regions of the rift may be less pronounced and the organics in the unit may not have reached thermal maturity as early in their histories. Consequently, the possibility of encountering economic concentrations of petroleum, derived from MRS clastics rocks, may be greater in these distal areas.

- Red clastic rocks are preserved in a series of basins at the Precambrian surface of Iowa. Five large half-graben basins flank and deepen towards the Iowa Horst of the MRS. These basins—two west of the horst and three to the east—preserve an estimated volume of 35,400 mi^3 of upper and lower Red clastic strata. Red clastics are also preserved in several areas on the Iowa Horst. These include three basins and one down-dropped block that preserve an additional 4,400 mi^3 of Red clastics.

- A reinvestigation of core and chip samples of MRS Red clastic rocks in Iowa did not yield any evidence of economic mineralization. Copper or chalcopyrite reported from the Eischeid well was not confirmed by our investigation. The lack of mineral occurrences in these rocks does not preclude the possibility of its presence in Red clastics in other parts of Iowa, since the available sample set is extremely limited.

- Well samples previously interpretated as evidence of deep basal Cambrian basins overlying the Red clastics basins that flank the Iowa Horst were re-examined with petrographic and SEM techniques. Cambrian fossils previously thought to be in place deep in the basal clastic sequence in two wells were proven to be contamination by caving of stratigraphically higher units during the drilling. Chip samples of the clastics from these deeper intervals were shown to be petrographically similar to Red clastics, not basal Cambrian units. No evidence of the deep Cambrian basins was found.
- Following restudy of samples from a number of wells in Iowa and Illinois, a series of lithostratigraphic correlation characteristics were identified that will prove useful in determining the contact between the basal Cambrian sandstone and the underlying Red clastics in the region. These distinguishing characteristics were described earlier. One of the most useful characteristics is the very mature mineralogy of the framework grains in the Mount Simon Sandstone, which is composed of quartz arenites (>90 percent quartz) in almost all intervals, and the very limited number of lithic fragments encountered, especially volcanic and metamorphic grains. The Red clastics framework grains always display a higher feldspar content, and lithic rock fragments are a common component of the framework.

ACKNOWLEDGMENTS

The authors wish to acknowledge the persistant encouragement and logistical assistance provided by Warren Day and the extremely helpful reviews by P.K. Sims, both of the U.S. Geological Survey. Additionally, the authors would like to acknowledge the funding assistance provided by the U.S. Geological Survey Midcontinent Strategic and Critical Minerals Program.

REFERENCES CITED

Anderson, R.R., 1981, Bouguer gravity anomaly map of Iowa: Iowa Geological Survey Miscellaneous Map Series 7, scale 1:100,000.

———1988, Precambrian geology of Iowa and adjacent areas: Iowa Department of Natural Resources Geological Survey Bureau Open File Map 88–3, scale 1:100,000.

———1990a, The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa—Report of preliminary investigations: Iowa Department of Natural Resources, Geological Survey Bureau Special Report Series #2, 185 p.

———1990b, Review of the Precambrian geologic history of the central United States and the Midcontinent Rift System, *in* Anderson, R.R. ed., The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa—Report of preliminary investigations: Iowa Department of Natural Resources, Geological Survey Bureau Special Report Series #2, p. 1–26.

———1990c, Interpretation of geophysical data over the Midcontinent Rift System in the area of the M.G. Eischeid #1 oil test, Carroll County, Iowa, *in* Anderson, R.R. ed., The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa—Report of preliminary investigations: Iowa Department of Natural Resources, Geological Survey Bureau Special Report Series #2, p. 27–38.

———1992, The Midcontinent Rift System of Iowa: Iowa City, University of Iowa, Ph.D. dissertation, 324 p.

———1995, Keweenawan Supergroup clastic rocks of the Midcontinent Rift System in Iowa, *in* Ojakangas, R.W., Dickas, A.B., and Green, J.C., eds., Basement tectonics 10; Proceedings of the Tenth International Conference on Basement Tectonics, held in Duluth, Minnesota, U.S.A., August, 1992: Dordrecht, The Netherlands, Kluwer Academic Publishers, p. 55–59.

———1997, Keweenawan Supergroup clastic rocks in the Midcontinent Rift of Iowa, *in* Ojakangas, R.W., Dickas, A.B., and Green, J.C., eds., Middle Proterozoic to Cambrian Rifting, central North America: Geological Society of America Special Paper 312, p. 211–230.

Barghorn, E.S., Meinschein, W.G., and Schopf, J.W.,1965, Paleobiology of Precambrian shale: Science, v. 148, p. 461–472.

Barker, C.E., 1990, Reconnaissance fluid inclusion study, Amoco Eischeid #1 well, Defiance Basin, Midcontinent Rift System, Iowa, *in* Anderson, R.R., ed., The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa—Report of preliminary investigations: Iowa Department of Natural Resources, Geological Survey Bureau Special Report Series #2, p. 169–174.

Barnes, D.A., 1990, Sandstone petrology from conventional core in the M.G. Eischeid #1 well, Carroll County, Iowa, *in* Anderson, R.R., ed., The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa—Report of preliminary investigations: Iowa Department of Natural Resources, Geological Survey Bureau Special Report Series #2, p. 113–118.

Bunker, B.B., Witzke, B.J., Watney, W.L., and Ludvigson, G.A., 1988, Phanerozoic history of the central midcontinent, United States, *in* Sloss, L.L., ed., Geology of North America: Geological Society of America, v. DD–2, p. 243–260.

Bunker, B.J., 1981, Phanerozoic structural development in the area of the Forest City Basin, southwestern Iowa (a brief overview): Iowa Geological Survey Miscellaneous Publication MP–27, 20 p.

———1982, Phanerozoic structural development in the area of the Forest City Basin, southwestern Iowa (a brief overview), *in* Van Eck, O.J, ed. Regional tectonics and seismicity of southwestern Iowa: Annual report, August 1980–July 1981, NUREG/CR–2548, Nuclear Regulatory Commission, Appendix IV, p. 42 –58.

Burnie, S.W., Schwarcz, H.P., and Crocket, J.H., 1972, A sulphur isotope study of the White Pine Mine, Michigan [abs.]: Geological Society of America Abstracts with Program, v. 4, no. 7, p. 462.

Buschbach, T.C., 1964, Cambrian and Ordovician strata of northeastern Illinois: Illinois State Geological Survey Report of Investigations 218, 90 p.

———1975, Cambrian System, *in* Willman, H.B., Atherton, E., Bushbach, T.C., Collinson, C., Frey, J.C., Hopkins, M.E., Lineback, J.A., and Simon, J.A., Handbook of Illinois stratigraphy: Illinois State Geological Survey Bulletin 95, p. 34–46.

Cannon, W.F., Green, A.G., Hutchinson, D.R., Lee, M., Behrendt, J.C., Halls, H.C., Green, J.C., Dickas, A.B., Morey, G.B., Sutcliffe, R., and Spencer, C., 1989, The North American Midcontinent Rift beneath Lake Superior from GLIMPCE seismic reflection profiling: Tectonics, v. 8, no. 2, p. 305–332.

Carlson, M.P., McKay, R.M., and Palmer A.R., 1990, Faunal zones and transgression within the Sauk Sequence (Upper Cambrian–Lower Ordovician), Nebraska-Iowa region [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 7, p. A320.

Carmichael, R.S., and Black, R.A., 1986, Analysis and use of MAGSAT satellite magnetic data for interpretation of crustal structure and character in the U.S. Midcontinent: Physics of the Earth and Planetary Interiors, v. 44, no. 4, p. 333–347.

Chandler, V.W., McSwiggen, P.L., Morey, G.B., Hinze, W. J., and Anderson, R.R., 1989, Interpretation of seismic reflection, gravity, and magnetic data across the Middle Proterozoic Mid-Continent Rift System, northwestern Wisconsin, eastern Minnesota and central Iowa: American Association of Petroleum Geologists Bulletin, v. 73, p. 261–275.

Conselman, M., Gardner, D., Carmody, R.A., 1940's, Well log of the #1 Wilson (Clarinda Well): Iowa Geological Survey unpublished well log.

Dickas, A.B., 1987, The potential for oil and/or gas within the Midcontinent Rift System, *in* 19th Geology Field Conference Guidebook: River Falls (Wisconsin) Geological Society, p. 31–37.

Elmore, R.D., 1981, The Copper Harbor Conglomerate and Nonesuch Shale: Sedimentation in a Precambrian intercratonic rift, upper Michigan: Ann Arbor, University of Michigan, Ph.D. dissertation, 200 p.

Folger, A., McQueen, H.S., Edson, F., and Price, G., 1931, Correlation of the Clarinda, Iowa well: Iowa Geological Survey unpublished well file records, 1 p.

Green, J.C., 1982, Geology of Keweenawan extrusive rocks, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior Basin: Geological Society of America Memoir 156, p. 47–56.

Hall, C.W., Meinzer, O.E., and Fuller, M.L., 1911, Geology and underground waters of southern Minnesota: U.S. Geological Survey Water Supply Paper 256, 376 p.

Henderson, J.R., and Vargo, J.L., 1965, Aeromagnetic map of central Iowa: U.S. Geological Survey Geophysical Investigations Map GP–476.

Hershey, H.G., Brown, C.N., van Eck, O.J, and Northup, R.C., 1960, Highway construction materials from the consolidated rocks of southwestern Iowa: Iowa Highway Research Board Bulletin 15, 151 p.

Hieshima, G.B., and Pratt, L.M., 1991, Sulfur/carbon ratios and extractable organic matter of the Middle Proterozoic Nonesuch Formation, North American Midcontinent rift: Precambrian Geology, v. 54, p. 65–79.

Heishima, G.B., Zoback, D.A., and Pratt, L.M., 1989, Petroleum potential of Precambrian Nonesuch Formation, Mid-Continent Rift System in western Lake Superior: American Association of Petroleum Geologists Bulletin, v. 73, no. 3, p. 363.

Jirsa, M.A., 1984, Interflow sedimentary rocks in the Keweenawan North Shore Volcanic Group, northeastern Minnesota: Minnesota Geological Survey Report of Investigations 30, 20 p.

Kelly, W.C., and Nishioka, G.K., 1985, Precambrian oil inclusions in late veins and rht role of hydrocarbons in copper mineralization at White Pine, Michigan: Geology, v. 13, p. 334–337.

King, P.B., 1978, Precambrian geology of the United States—An explanatory text to accompany the geologic map of the United States: U.S. Geological Survey Professional Paper 902, 85 p.

King, P.B., and Zietz, Isidore, 1971, Aeromagnetic study of the Midcontinent Gravity High of central United States: Geological Society of America Bulletin, v. 82, p. 2187–2208.

Kurtz, V.E., Thacker, J.L., Anderson, K.H., and Gerdemann, P.E., 1975, Traverse in Late Cambrian strata from the Ste. Francois Mountains, Missouri to Delaware County, Oklahoma: Missouri Department of Natural Resources, Geological Survey Report of Investigations, no. 55, 118 p.

Lees, J.H., 1935, Additional deep wells: Iowa Geological Survey Annual Report, v. 36, p. 365–420.

Ludvigson, G.A., McKay, R.M., and Anderson, R.R., 1990, Petrology of Keweenawan sedimentary rocks in the M.G. Eischeid #1 Drillhole, *in* Anderson, R.R., ed., The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa—Report of preliminary investigations: Iowa Department of Natural Resources, Geological Survey Bureau, Special Report Series #2, p. 77–112.

Ludvigson, G.A., and Spry, P.G., 1990, Tectonic and hydrologic significance of carbonate veinlets in the Keweenawan sedimentary rocks of the Amoco M.G. Eischeid #1 drillhole, *in* Anderson, R.R., ed., The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa—Report of preliminary investigations: Iowa Department of Natural Resources, Geological Survey Bureau Special Report Series #2, p. 153–168.

McKay, R.M., 1990, Regional aspects of the Mount Simon Formation and the placement of the Mount Simon–pre-Mount Simon sedimentary contact in the Amoco M.G. Eischeid #1 drillhole, *in* Anderson, R.R., ed., The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa—Report of preliminary investigations: Iowa Department of Natural Resources, Geological Survey Bureau Special Report Series #2, p. 59–66.

McKerrow, W.S., 1978, Classification of organisms, *in* McKerrow, W.S., ed., The ecology of fossils: Cambridge, Massachusetts Institute of Technology Press, p. 30–48.

McQueen, H.S., and Greene, F.C., 1938, The geology of northwest Missouri: Missouri Division of Geological Survey and Water Resources Report, Second Series, v. 25, 110 p.

Milavec, G.J., 1986, The Nonesuch Formation—Precambrian sedimentation in an intracratonic rift: Norman, University of Oklahoma, M.S. thesis, 142 p.

Mooney, H.M., Craddock, C., Farnham, P.R., Johnson, S.H., and Volz, G., 1970, Refraction seismic investigations of the northern midcontinent gravity high: Journal of Geophysical Research, v. 75, p. 5056–5086.

Moore, L.R., Moore, J.R., and Spinner, E., 1969, A geo-microbiological study of the Precambrian Nonesuch Shale: Proceedings of Yorkshire Geological Society, v. 37, p. 1174–1185.

Morey, G.B., and Ojakangas, R.W., 1982, Keweenawan sedimentary rocks of eastern Minnesota and northwestern Wisconsin, *in* Wold, R.J., and Hinze, W.J., ed., Geology and tectonics of the Lake Superior Basin: Geological Society of America Memoir 156, p. 135–146.

Norton, W.H., 1928, Deep wells of Iowa (a supplementary report): Iowa Geological Survey Annual Report XXXIII, p. 9–447.

Norton, W.H., and others, 1912, Underground water resources of Iowa: Iowa Geological Survey Annual Report XXI, p. 29–1181.

Ojakangas, R.W., 1986, Reservoir characteristics of the Keweenawan Supergroup, Lake Superior region, *in* Mudrey, M.G., Jr., ed., Precambrian petroleum potential, Wisconsin and Michigan: Geoscience Wisconsin, v. 11, p. 25–31.

Ojakangas, R.W., and Morey, G.B., 1982a, Proterozoic sedimentary rocks, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior Basin: Geological Society of America Memoir 156, p. 83.

———1982b, Keweenawan pre-volcanic quartz sandstones and related rocks of the Lake Superior region, *in* Wold, R.J., and Hinze, W.J., eds., Geology and tectonics of the Lake Superior Basin: Geological Society of America Memoir 156, p. 85–96.

Osweiler, D.J., 1982, A geological interpretation of the Stratford Geophysical Anomaly on the Midcontinent paleorift zone, central Iowa: Iowa City, University of Iowa, M.S. thesis, 166 p.

Palacas, J.G., Schmoker, J.W., Davis, T. A., Pawlewicz, M.J., and Anderson, R.R. 1990, Petroleum source-rock assessment of Middle Proterozoic (Keweenawan) sedimentary rocks, Eischeid #1 well, Carroll County, Iowa, *in* Anderson, R.R., ed., The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa—Report of preliminary investigations: Iowa Department of Natural Resources, Geological Survey Bureau Special Report Series #2, p. 119–134.

Pollastro, R.M., and Finn, T.M., 1990, Clay mineralogy and bulk rock composition of selected chip samples from the Amoco Eischeid #1 well, Carroll County, Iowa—A reconnaissance study from X-ray powder diffraction analysis, *in* Anderson, R.R., ed., The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa—Report of preliminary investigations: Iowa Department of Natural Resources, Geological Survey Bureau Special Report Series #2, p. 143–152.

Sardeson, F.W., 1892, Fossils in the St. Peter sandstone: Minnesota Academy of Natural Science Bulletin, v. 3, p. 319–326.

———1896, The St. Peter sandstone: Minnesota Academy of Natural Science Bulletin, v. 4, no. 1, pt. 1, p. 64–87, p. 326–343.

Schmoker, J.W., and Palacas, J.G., 1990, Porosity of Precambrian sandstones in lower portion of the Eischied #1 well, Carroll County, Iowa, *in* Anderson, R.R., ed., The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa—Report of preliminary investigations: Iowa Department of Natural Resources, Geological Survey Bureau Special Report Series #2, p. 135–142.

Sims, P.K., 1990, Precambrian basement map of the northern midcontinent, U.S.A.: U.S. Geological Survey Miscellaneous Investigations Series Map I–1853–A, scale 1:1,000,000 and accompanying text, 10 p.

Sloan, R.E., Rice, W.F., Hedblom, E., and Mazzullo, J.M., 1987, The Middle Ordovician of the Twin Cities area, *in* Balaban, N.H., ed., Field trip guidebook for the Upper Mississippi Valley, Minnesota, Iowa, and Wisconsin: Minnesota Geological Survey Guidebook Series Number 15, p. 53–69.

Taft, J.A., 1902, Atoka Foleo, Indian Territory: U.S. Geological Survey, Geological Atlas of the United States, Folio 79, 14 p.

Thiel, G.A., 1944, The geology and underground waters of southern Minnesota: Minnesota Geological Survey Bulletin 31, 506 p.

Van Schmus, W.R., and Hinze, W.J., 1985, The Midcontinent Rift System: Annual Review of Earth and Planetary Sciences, v. 13, p. 345–383.

Van Schmus, W.R., Wallin, E.T., and Shearer, C.T., 1990, Age relationships for gabbro from the Amoco M.G. Eischeid #1 well, *in* Anderson, R.R., ed., The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa—Report of preliminary investigations: Iowa Department of Natural Resources, Geological Survey Bureau Special Report Series #2, p. 67–76.

Walcott, C.D., 1914, Cambrian geology and paleontology: Smithsonian Miscellaneous Collection, v. 57, p. 345–412.

Witzke, B.J., 1990, General stratigraphy of the Phanerozoic and Keweenawan sequences, M.G. Eischeid #1 drillhole, Carroll County, Iowa, *in* Anderson, R.R., ed., The Amoco M.G. Eischeid #1 deep petroleum test, Carroll County, Iowa—Report of preliminary investigations: Iowa Department of Natural Resources, Geological Survey Bureau Special Report Series #2, p. 39–58.

Yoho, W.H., Hamilton, T., Conselman, M., 1959, Well log of the #1 Wilson (Clarinda Well): Iowa Geological Survey unpublished well log.

Zietz, Isidore, Gilbert, F.P., and Keys, J.R., 1976, Aeromagnetic map of Iowa—Color coded intensities: U.S. Geological Survey Geophysical Investigations Map GP–911.

APPENDIXES

Appendix I1. Results of petrographic analyses of thin-sectioned samples collected from the basal Mount Simon Sandstone and Red clastics interval of the M.G. Eischeid #1 well in Carroll County, Iowa.

[Q, quartz; F, feldspar; L, lithic grains; Qm, monocrystalline quartz; Qp, polycrystaline quartz; P, plagioclase; K, potassium feldspar; Ls, sedimentary lithic grains; Lm, metamorphic lithic grains; Lv, volcanic lithic grains; M, mica; H, heavy minerals; Qtz cem, quartz cement; Carb cem, carbonate cement; MS, samples of Mount Simon Sandstone; units H, G, F, and E are from upper Red clastics sequence; units D, C, and B are from lower Red clastics sequence]

Strat. Unit	Sample Interval	Qm	Qp	P	K	Ls	Lm	Lv	M	H	Qtz Cem	Carb Cem	Clay/oxide Cement	Total Frameworks	Q Mode	F Mode	L Mode
Unit H	2800-2830	263	2	0	59	1	0	2	13	7	20	19	14	327	81	18	1
Unit H	3500-3510	136	1	0	39	1	0	0	5	0	5	3	10	177	77	22	1
Unit G	3790-3800	286	3	3	41	17	2	7	4	2	3	16	16	359	81	12	7
Unit G	4000-4010	286	1	1	60	6	2	14	0	4	12	4	8	370	78	16	6
Unit G	4500-4510	271	3	2	58	5	7	19	0	8	13	1	10	365	75	16	8
Unit F	5000-5010	223	3	22	45	9	16	3	0	18	7	26	28	321	70	21	9
Unit F	5500-5510	221	0	15	71	16	14	12	1	21	12	0	17	349	63	25	12
Unit F	5930-5940	251	2	9	65	10	12	18	1	11	14	0	7	367	69	20	11
Unit F	6000-6010	268	2	12	66	1	7	15	0	14	8	0	7	371	73	21	6
Unit F	6500-6510	263	0	17	61	15	10	3	0	7	4	5	14	369	71	21	8
Unit F	7000-7010	228	1	27	61	5	15	13	2	11	5	16	16	350	65	25	9
Unit E	7100-7110	224	0	22	64	21	8	25	0	19	1	3	13	364	62	24	15
Unit E	7340-7350	320	9	49	116	13	11	14	0	14	7	0	47	532	62	31	7
Unit E	7490-7504	323	10	20	93	20	20	14	3	8	17	8	64	500	67	23	11
Unit E	8000-8010	333	9	60	75	17	13	34	0	15	10	6	26	541	63	25	12
Unit E	8500-8510	359	10	55	74	26	18	17	1	16	5	6	13	559	66	23	11
Unit E	9000-9010	349	18	55	60	18	20	15	3	21	6	14	21	535	69	21	10
Unit E	9420-9430	334	7	37	78	23	24	24	0	35	3	2	33	527	65	22	13
Unit E	9500-9510	127	9	1	12	10	12	1	0	5	1	4	18	172	79	8	13
Unit E	10,000-10,010	107	2	7	13	18	11	3	0	9	2	0	28	161	68	12	20
Unit E	10,080-10,090	110	2	6	25	7	12	2	1	6	4	3	22	164	68	19	13
Unit E	10,500-10,510	104	2	12	14	14	11	1	2	13	2	4	21	158	67	16	16
Unit D	11,000-11,010	117	3	14	13	5	8	5	0	12	0	1	22	165	73	16	11
Unit D	12,500-12,510	113	1	10	20	2	5	0	3	8	2	15	21	151	75	20	5
Unit D	13,000-13,010	118	0	6	34	11	0	0	1	5	1	0	24	169	70	24	7
Unit D	13,420-13,430	123	0	12	31	2	1	1	0	5	1	10	14	170	72	25	2
Unit D	13,500-13,510	360	13	35	97	3	2	3	4	17	1	42	25	513	73	26	2
Unit D	14,000-14,010	456	3	8	82	5	3	3	4	11	2	7	16	560	82	16	2
Unit D	14,500-14,510	130	0	11	25	1	0	0	0	2	3	5	15	167	78	22	1
Unit D	14,740-14,750	293	2	6	62	2	1	0	9	4	2	4	15	366	81	19	1
Unit D	15,000-15,010	235	0	37	23	9	0	0	30	8	2	31	25	304	77	20	3
Unit C	15,240-15,250	56	0	12	13	0	0	0	2	1	0	15	1	81	69	31	0
Unit C	15,680-15,690	244	4	3	51	3	2	14	3	8	0	50	17	321	77	17	6
Unit B	16,460-16,470	302	9	6	35	2	1	0	5	2	1	20	17	355	88	12	1
Unit B	16,500-16,510	281	9	4	45	0	1	1	7	7	3	23	19	341	85	14	1
Unit B	16,750-16,760	310	9	6	27	4	0	1	2	2	1	16	22	357	89	9	1
Unit B	16,960-16,970	175	2	3	14	0	0	1	0	0	0	5	0	195	91	9	1
Unit B	17,000-17,010	169	5	2	15	1	0	0	0	1	1	3	3	192	91	9	1
Unit B	17,100-17,110	183	1	0	14	0	0	1	0	0	0	0	1	199	92	7	1
Unit B	17,500-17,510	301	1	5	52	0	1	0	1	2	5	6	26	360	84	16	0
Unit B	17,740-17,744	137	3	14	26	0	2	0	5	0	4	3	6	182	77	22	1

Appendix I2. Results of petrographic analyses of thin-sectioned samples collected from Mount Simon Sandstone and Red clastics intervals of several wells in Iowa and Illinois.

[Petrographic data from study of samples from the M.G. Eischeid #1 well are reproduced in appendix I1. WNUMBER, Iowa well identification number; SPLTYPE, sample type (CUT, cuttings/chip samples; CORE, core samples); NUMCOUNTS, number of points counted; Q, percent quartz grains; F, percent feldspar grains; L, percent lithic grains;: #1 Wilson, W00017, Page Co., Iowa; #1 Huntley, W14428, Butler Co., Iowa; M.G. Eischeid #1, W27933, Carroll Co., Iowa; UPH–2, W27606, Stephenson Co., Ill.]

WELL NAME	WNUMBER	SPL TYPE	DEPTH TOP	NUM COUNTS	Q	F	L
EISCHEID #1	27933	CUT	2770.0	100	100.0	0.0	0.0
EISCHEID #1	27933	CUT	2800.0	300	81.8	11.8	6.4
EISCHEID #1	27933	CUT	2840.0	300	74.2	15.3	10.5
EISCHEID #1	27933	CUT	2900.0	300	74.5	17.4	8.1
EISCHEID #1	27933	CUT	2950.0	300	79.5	13.5	7.1
EISCHEID #1	27933	CUT	3000.0	300	75.8	16.8	7.4
EISCHEID #1	27933	CUT	3040.0	300	81.1	15.2	3.7
EISCHEID #1	27933	CUT	3090.0	300	79.3	17.1	3.7
EISCHEID #1	27933	CUT	3150.0	300	76.4	13.1	10.4
EISCHEID #1	27933	CUT	3200.0	300	79.8	11.4	8.8
EISCHEID #1	27933	CUT	3250.0	300	76.5	12.8	10.7
EISCHEID #1	27933	CUT	3290.0	300	85.2	7.7	7.1
UPH #2	27606	CORE	1300.4	200	100.0	0.0	0.0
UPH #2	27606	CORE	1403.5	200	99.4	0.6	0.0
UPH #2	27606	CORE	1499.5	200	91.7	8.3	0.0
UPH #2	27606	CORE	1584.0	200	100.0	0.0	0.0
UPH #2	27606	CORE	1747.0	200	100.0	0.0	0.0
UPH #2	27606	CORE	2006.6	200	100.0	0.0	0.0
UPH #2	27606	CORE	2060.8	200	100.0	0.0	0.0
UPH #2	27606	CORE	2109.3	200	100.0	0.0	0.0
UPH #2	27606	CORE	2174.0	200	100.0	0.0	0.0
#1 WILSON	00017	CUT	3560.0	300	99.7	0.3	0.0
#1 WILSON	00017	CUT	3616.0	300	99.3	0.7	0.0
#1 WILSON	00017	CUT	3655.0	300	100.0	0.0	0.0
#1 WILSON	00017	CUT	3703.0	300	93.6	6.1	0.3
#1 WILSON	00017	CUT	3752.0	300	93.3	6.3	0.3
#1 WILSON	00017	CUT	3800.0	300	88.3	11.3	0.3
#1 WILSON	00017	CUT	3852.0	300	85.6	14.4	0.0
#1 WILSON	00017	CUT	3903.0	300	90.4	9.6	0.0
#1 WILSON	00017	CUT	4054.0	300	92.7	7.3	0.0
#1 WILSON	00017	CUT	4221.0	300	93.7	6.3	0.0
#1 WILSON	00017	CUT	4322.0	300	98.0	2.0	0.0
#1 WILSON	00017	CUT	4368.0	300	93.7	6.3	0.0
#1 WILSON	00017	CUT	4501.0	300	86.6	13.4	0.0
#1 WILSON	00017	CUT	4814.0	206	67.0	32.0	1.0
#1 WILSON	00017	CUT	4975.0	200	72.1	27.4	0.5
#1 WILSON	00017	CUT	5206.0	200	78.7	21.3	0.0

Appendix I2. Results of petrographic analyses of thin-sectioned samples collected from Mount Simon Sandstone and Red clastics intervals of several wells in Iowa and Illinois—Continued

WELL NAME	WNUMBER	SPL TYPE	DEPTH TOP	NUM COUNTS	Q	F	L
#1 HUNTLEY	14428	CUT	2150.0	300	99.7	0.3	0.0
#1 HUNTLEY	14428	CUT	2200.0	300	100.0	0.0	0.0
#1 HUNTLEY	14428	CUT	2280.0	300	99.7	0.3	0.0
#1 HUNTLEY	14428	CUT	2300.0	300	94.3	5.7	0.0
#1 HUNTLEY	14428	CUT	2325.0	300	84.3	11.4	4.3
#1 HUNTLEY	14428	CUT	2395.0	300	84.0	12.0	4.0
#1 HUNTLEY	14428	CUT	2500.0	300	80.9	12.4	6.7
#1 HUNTLEY	14428	CUT	2600.0	300	82.4	10.2	7.5
#1 HUNTLEY	14428	CUT	2800.0	300	81.0	15.3	3.7
#1 HUNTLEY	14428	CUT	2900.0	300	72.7	24.9	2.4
#1 HUNTLEY	14428	CUT	3000.0	300	69.5	26.5	4.0
#1 HUNTLEY	14428	CUT	3105.0	300	74.7	18.9	6.4
#1 HUNTLEY	14428	CUT	3200.0	300	70.0	26.9	3.1
#1 HUNTLEY	14428	CUT	3350.0	300	75.3	12.5	12.2
#1 HUNTLEY	14428	CUT	3400.0	300	73.8	17.4	8.7
#1 HUNTLEY	14428	CUT	3500.0	300	78.3	16.0	5.7
#1 HUNTLEY	14428	CUT	*3505.0	300	69.3	30.7	0.0
#1 HUNTLEY	14428	CUT	3550.0	300	91.0	6.7	2.2

* Note that this cuttings-chip is considered to be a chip of Cambrian sandstone which contaminates this sample interval.

Online version prepared by Joan Nadeau

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that may be listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" may no longer be available.

Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices listed below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, DC 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Residents of Alaska may order maps from

U.S. Geological Survey, Earth Science Information Center
101 Twelfth Ave., Box 12
Fairbanks, AK 99701

OVER THE COUNTER

Books and Maps

Books and maps of the U.S. Geological Survey are available over the counter at the following U.S. Geological Survey offices, all of which are authorized agents of the Superintendent of Documents.

- **ANCHORAGE, Alaska**–Rm. 101, 4230 University Dr.
- **LAKEWOOD, Colorado**–Federal Center, Bldg. 810
- **MENLO PARK, California**–Bldg. 3, Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**–USGS National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**–Federal Bldg., Rm. 8105, 125 South State St.
- **SPOKANE, Washington**–U.S. Post Office Bldg., Rm. 135, West 904 Riverside Ave.
- **WASHINGTON, D.C.**–Main Interior Bldg., Rm. 2650, 18th and C Sts., NW.

Maps Only

Maps may be purchased over the counter at the following U.S. Geological Survey offices:

- **FAIRBANKS, Alask**a–New Federal Bldg, 101 Twelfth Ave.
- **ROLLA, Missouri**–1400 Independence Rd.
- **STENNIS SPACE CENTER, Mississippi**–Bldg. 3101

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations; as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales, they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. The series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; the principal scale is 1:24,000, and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from USGS Map Distribution, Box 25286, Building 810, Denver Federal Center, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879-1961" may be purchased by mail and over the counter in paperback book form and as a set microfiche.

"Publications of the Geological Survey, 1962-1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971-1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only.

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" is available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.–Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.