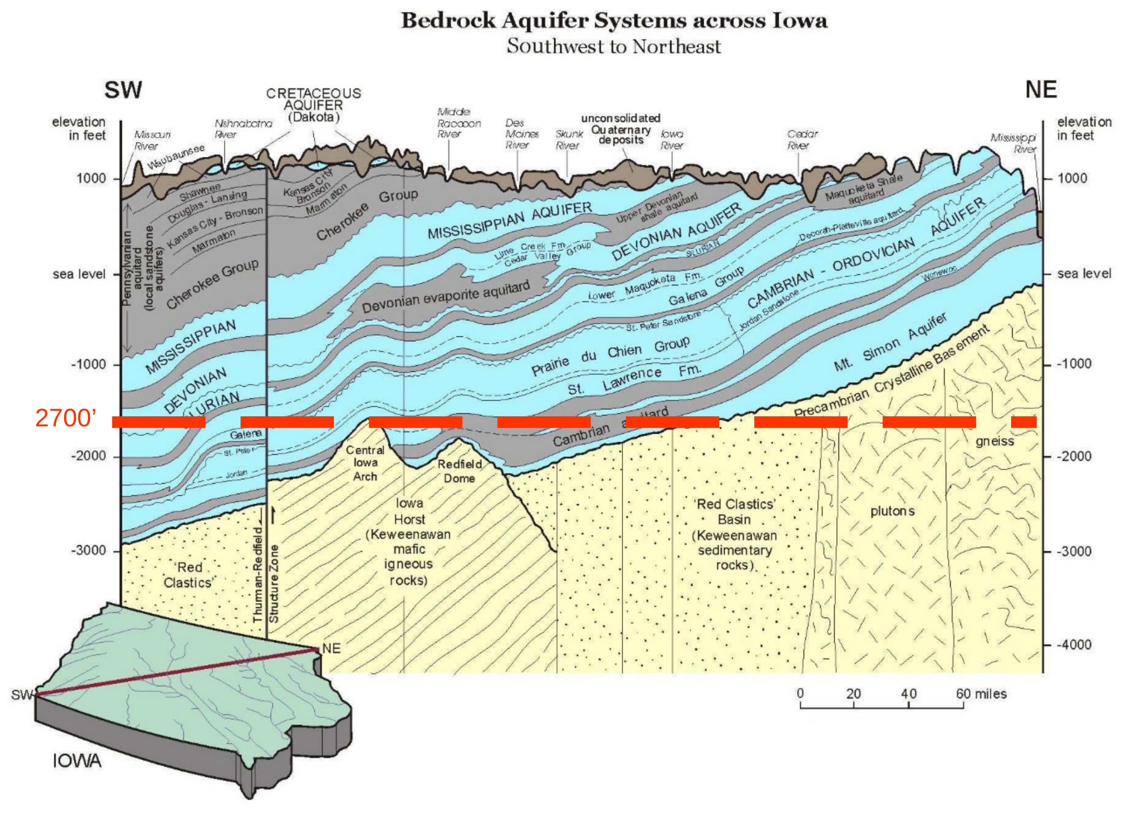

Potential for Geologic Sequestration of CO_2 in Iowa

Technical Information Series No. 58

The University of Iowa
IOWA GEOLOGICAL SURVEY
IIHR Hydroscience & Engineering

Cover Illustration: A northeast - southwest cross-section across Iowa identifies major bedrock aquifers (blue) separated by major aquitards (gray), underlain by Precambrian sedimentary and crystalline rocks (yellow) and overlain by glacial drift (brown). The dashed red line identifies the 2,700 foot depth below which hydrostatic pressure is sufficient to keep injected CO_2 in a liquid state.

Potential for Geologic Sequestration of CO_2 in Iowa

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Supported in part by grants from the U.S. Department of Energy and the Plains Regional CO_2 Sequestration Partnership

Iowa Geological Survey
Technical Information Series No. 58

IOWA GEOLOGICAL SURVEY

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INTRODUCTION

Atmospheric Carbon and Climate Change

Society's use of fossil fuels since industrialization has led to an increase of about 35% in the level of atmospheric carbon dioxide (CO_2), and this increase has raised significant concerns regarding the potential impacts on Earth's climate (ICPP, 2007). The basis for this concern is the ability of atmospheric CO_2 to adsorb incoming solar radiation, and transfer this as heat to the atmosphere, land surface, and oceans. This property of CO_2 (and of other "greenhouse gases") was first recognized over a century ago (Arrhenius, 1896).

Decreasing carbon emissions sufficiently to halt or reverse the increase in atmospheric CO_2 is a significant challenge, and will likely require a variety of approaches. For example, Pacala and Socolow (2004) described a variety of emission decreasing options, termed "stabilization wedges," which taken together would flatten the rate of atmospheric CO_2 concentration increase. These options consist of various approaches to conservation, energy efficiency improvements, alternative energy sources, and carbon capture and sequestration. This report deals with the sequestration part of the carbon capture and sequestration approaches and specifically with potential for geologic sequestration in Iowa.

Carbon Capture and Geologic Sequestration

Figure 1 schematically depicts carbon capture and sequestration (CCS). Carbon dioxide produced by electrical generation, ethanol production, cement and steel factories, and other major stationary (i.e., non-vehicular) sources must be separated from the total gaseous waste stream, compressed, and transported to a suitable location for injection into an appropriate geologic reservoir (Metz et al., 2005). Appropriate reservoirs are those considered to have the capacity to hold virtually all the injected CO_2 for periods beyond 1,000 years.

The most commonly considered geologic targets for sequestration include depleted crude oil and natural gas fields, deep, confined saline aquifers, and deep coal layers, particularly those producing methane. The targets must consist of permeable strata that will accept the injected carbon, and the permeable injection target must be overlain by a low-permeability layer, which acts as a seal or trap to keep the CO_2 well below the near-surface environment. Favorable targets are also located below a depth of about 2,700 ft (800 m), where pressures are sufficient to keep the compressed CO_2 in a supercritical or liquid phase (Herzog and Golomb, 2004).

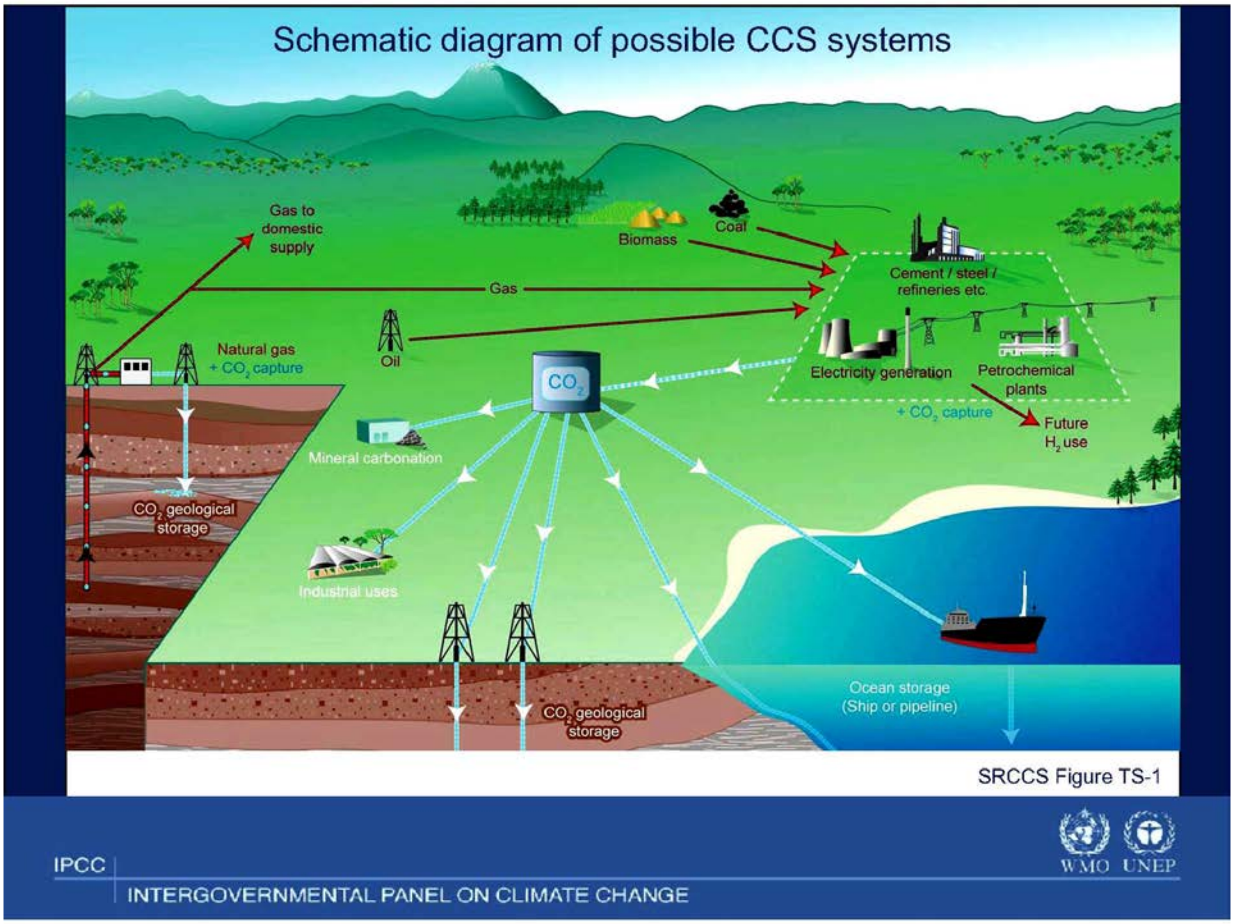


Figure 1. Schematic diagram of carbon capture and storage (CCS) (Metz et al., 2005).

Depleted oil and gas fields make attractive targets and have been a focus of many initial sequestration activities. They are proven permeable reservoirs; hydrocarbons have been withdrawn and therefore other liquids can be injected. They have sufficiently low-permeability seals to have trapped and held hydrocarbons for millions of years. In addition, injected CO_2 acts as a secondary recovery agent, removing the residual oil and providing an economic incentive for injection. Methane-producing coal seams are also considered as sequestration targets. Coals adsorb CO_2 preferentially to methane, resulting in trapping of CO_2 and release of methane (Schroeder et al., 2002), again providing an economic incentive for sequestration.

While oil and gas fields and deep coal strata provide economic incentives for sequestration, large-scale sequestration of CO_2, such as outlined by Pacala and Socolow (2004), would require injection into deep, confined saline aquifers (Schrag, 2007). These aquifers underlie a much larger part of the earth's surface, particularly in deep sedimentary basins.

Geologic Sequestration Targets in Iowa

In 2003, the U.S. Department of Energy began an initiative called the "Regional Carbon Sequestration Partnerships", to help develop the technology, infrastructure, geologic framework, and regulatory considerations to implement large-scale CO_2 sequestration in different regions and geologic formations across the Nation. Seven regional partnerships were formed. In 2005, Iowa was attached to the region included in the "Plains Regional CO_2 Partnership" (PCOR), led by the Energy and Environmental Research Center at the University of North Dakota, and planning to characterize Iowa's potential for geologic sequestration began.

Discussions between the Iowa Geological Survey (IGS) and PCOR identified approaches and several candidate geologic terrains for a "phase one" characterization, based on existing information and staff expertise. These include:

- Paleozoic sandstone and carbonate strata, which are unused, mineralized aquifers in the southwestern part of the state.
- Precambrian-age clastic rocks associated with the Mid-Continent Rift.
- Pennsylvanian strata and associated coals located in the southern part of the state.

A particular challenge in characterizing Iowa's sequestration potential, particularly with quantitative estimates, is the relative lack of deep wells, core tests, geophysical logs, surface geophysics, and other data commonly generated in areas with oil, gas, or coal-bed methane production, particularly those which supply data on unit porosity and permeability. While a limited amount of oil and gas exploration has occurred, the data density and detail is far less than is available in areas of significant hydrocarbon production. Existing geologic data, modeling, and extrapolation of other data allow for characterization of the target units geometry and preliminary estimates. These geometries, coupled with any future data on porosity and permeability, will allow for improvements on the initial estimates provided.

General Geographic and Geologic Setting of Southwestern Iowa

The study area spans 24 counties in southwestern Iowa. This area was chosen primarily because it includes the most deeply buried Paleozoic bedrock strata in the state (saline aquifers) as well as other potential targets for carbon sequestration (coal, Midcontinent Rift System). The modern geography of this area incorporates several landform regions each characterized by distinctive topographic and geologic features. The western counties include the relatively flat Missouri River Alluvial Plain (see topography on Fig. 2), which is bordered to the east (10 to 20 mi wide) by the steep and deeply dissected Loess Hills. The Loess Hills are characterized by up to 200 ft (60 m) of wind-blown silt (loess). Loess generally decreases in thickness eastward, where it mantles older eroded Pleistocene deposits across much of the study area (except in modern alluvial systems). Most of the study area occurs within the Southern Iowa Drift Plain, a region underlain by a variety of glacial (pre-Illinoian) and alluvial sediments. This landform area is deeply dissected and includes the highest elevations in the study area (Fig. 2). The northeastern part of the study area, the Des Moines Lobe, includes the youngest glacial deposits in Iowa, and lacks a well-integrated drainage system across much of its extent. Most of the Des Moines Lobe is of relatively low relief, but it is deeply dissected by major river valleys. Loess is absent across the Des Moines Lobe as well as on the Missouri Alluvial Plain.

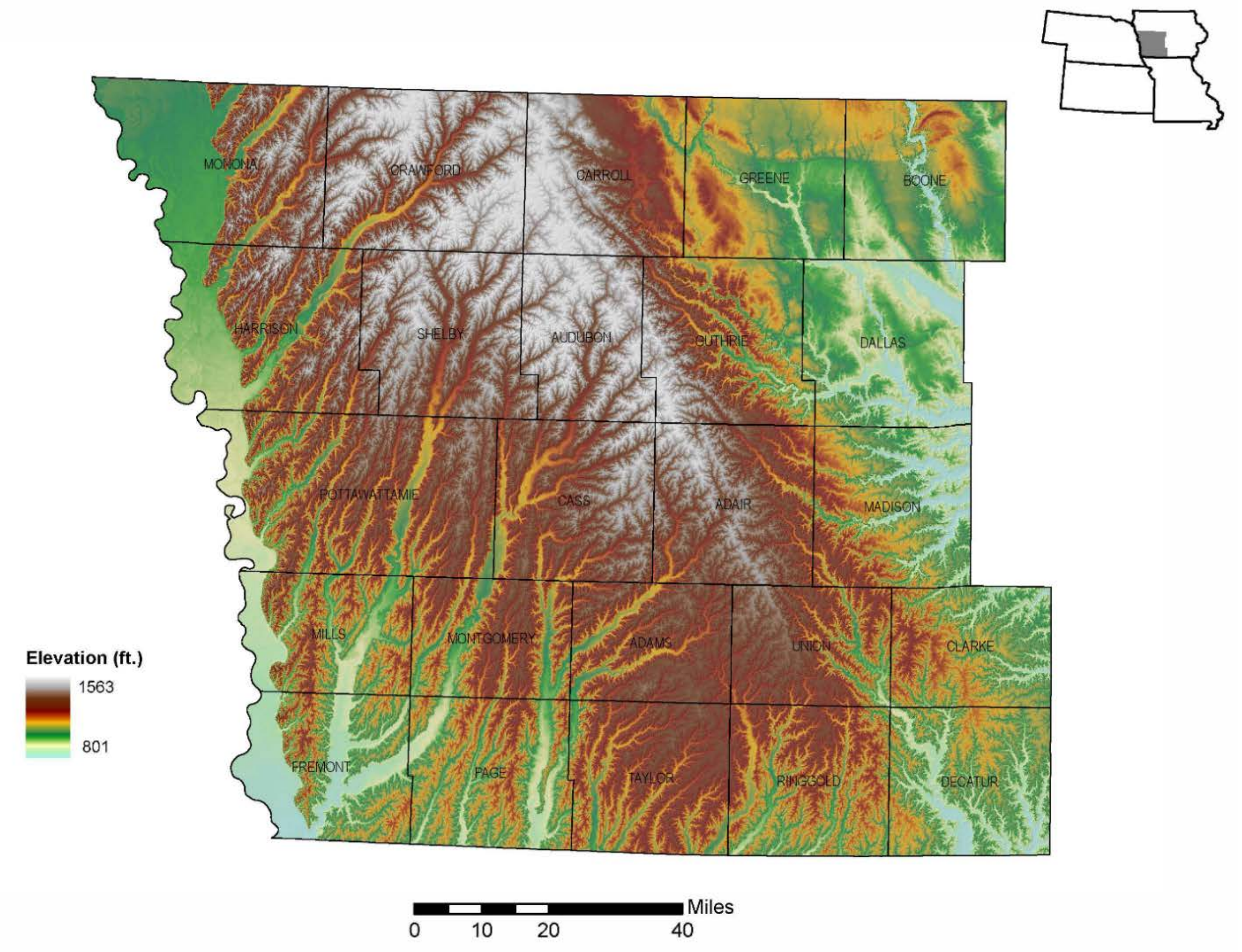


Figure 2. Topographic map (modern land surface) of the southwestern Iowa study area.

Unconsolidated late Cenozoic (primarily Pleistocene) sediments bury the bedrock surface across the southwestern Iowa study area, and bedrock exposures are rare to absent across most of the region. These unconsolidated sediments include glacial till (diamicton), alluvial materials (especially sand and gravel), and loess, with varying development of pedogenically-modified (soil) surfaces internally. The bedrock surface in southwestern Iowa (Fig. 3) is a complex surface created by the superposition of multiple episodes of late Cenozoic alluvial entrenchment and landscape erosion, most of it related to repetitive Early Pleistocene glacial and interglacial events. The most prominent feature on the bedrock surface (Fig. 3) is the north-south trending Fremont Channel which parallels the modern Missouri River and marks the position of a proto-Missouri River Valley. Unconsolidated Quaternary sediments deeply bury the bedrock surface across most of southwestern Iowa, averaging between 200 and 300 ft (60-90 m) thick in most areas but locally reaching thickness of 500 to 600 ft (50-180 m) in buried bedrock valleys (e.g., Fremont Channel). Quaternary sand and gravel resources are economically important across the region, and many domestic and farm wells utilize local Pleistocene and alluvial aquifers for primary water supplies across much of the study area. The Missouri valley alluvium forms a highly productive aquifer.

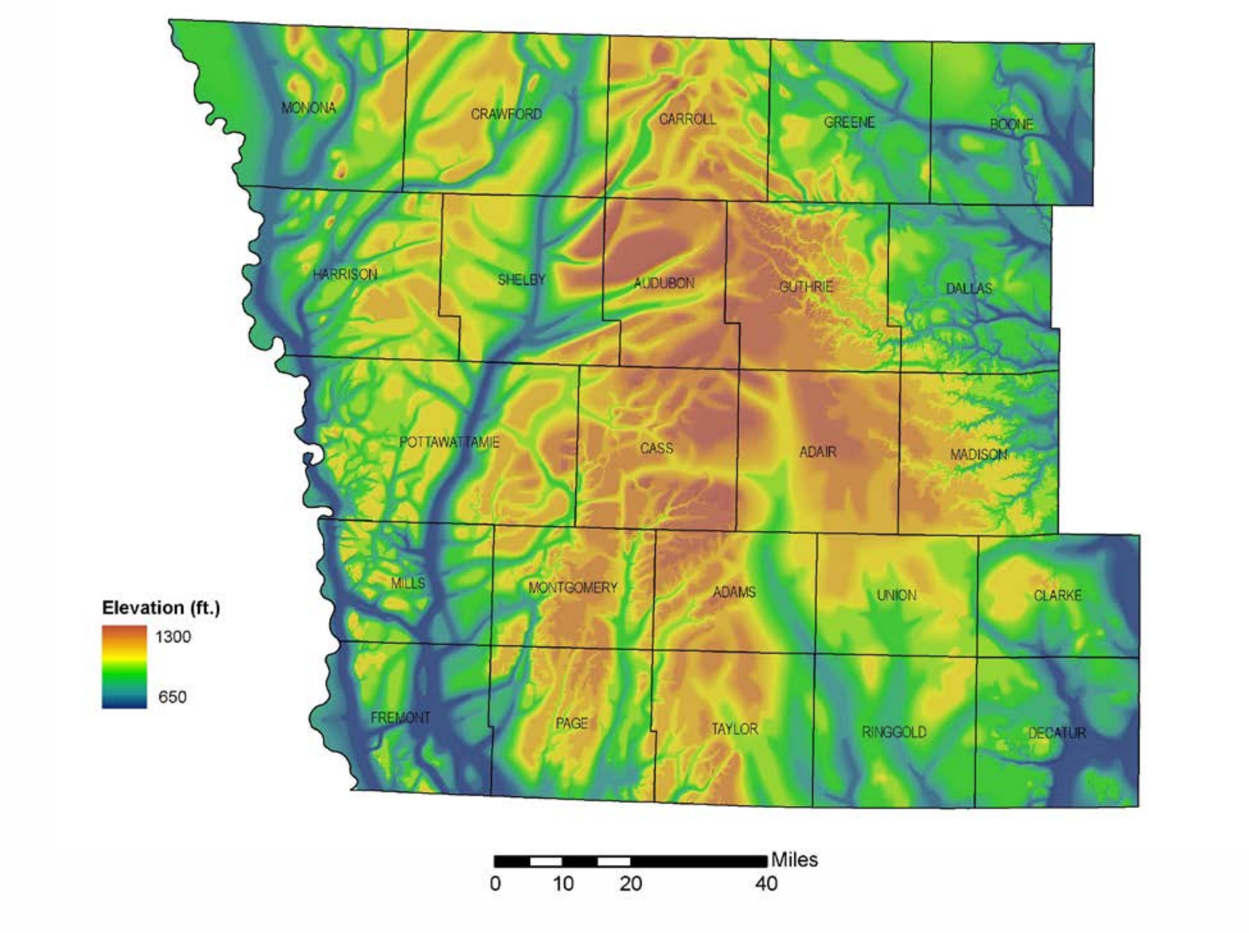


Figure 3. Bedrock topographic map of southwestern Iowa.

Although southwestern Iowa is marked by a thick cover of Quaternary sediments across most of its extent, natural and man-made bedrock exposures of Cretaceous and Pennsylvanian sandstone, shale/mudstone, and limestone strata are identified in the area. Bedrock exposures are most common in the northeastern portion of the study area (especially Guthrie and Madison counties). Pennsylvanian limestone units serve as an important source of high-quality aggregate in about half the counties of the study area (Hershey et al., 1960). In addition, Pennsylvanian coal beds in the area were locally mined during the late 19th and early 20th centuries, and most of the counties in the study area have had historic coal mining activity of varying extent (Landis and Van Eck, 1965). Coal-bearing Pennsylvanian strata of southwestern Iowa are discussed later in this report. The bedrock surface in southwestern Iowa is dominated by Pennsylvanian and Cretaceous strata, with small windows of Mississippian carbonate strata present in a few bedrock valleys in the northern-most counties (Fig. 4). Cretaceous strata of the Dakota Formation, primarily sandstone with lesser mudstone, overlie an eroded Pennsylvanian surface. The Dakota sandstone aquifer is locally utilized as a groundwater source, especially in the northern counties. Pennsylvanian strata are dominated by shale and mudstone, but limestone comprises a major part of some units (especially the Shawnee, Lansing, Kansas City, and Bronson groups; Fig. 4).

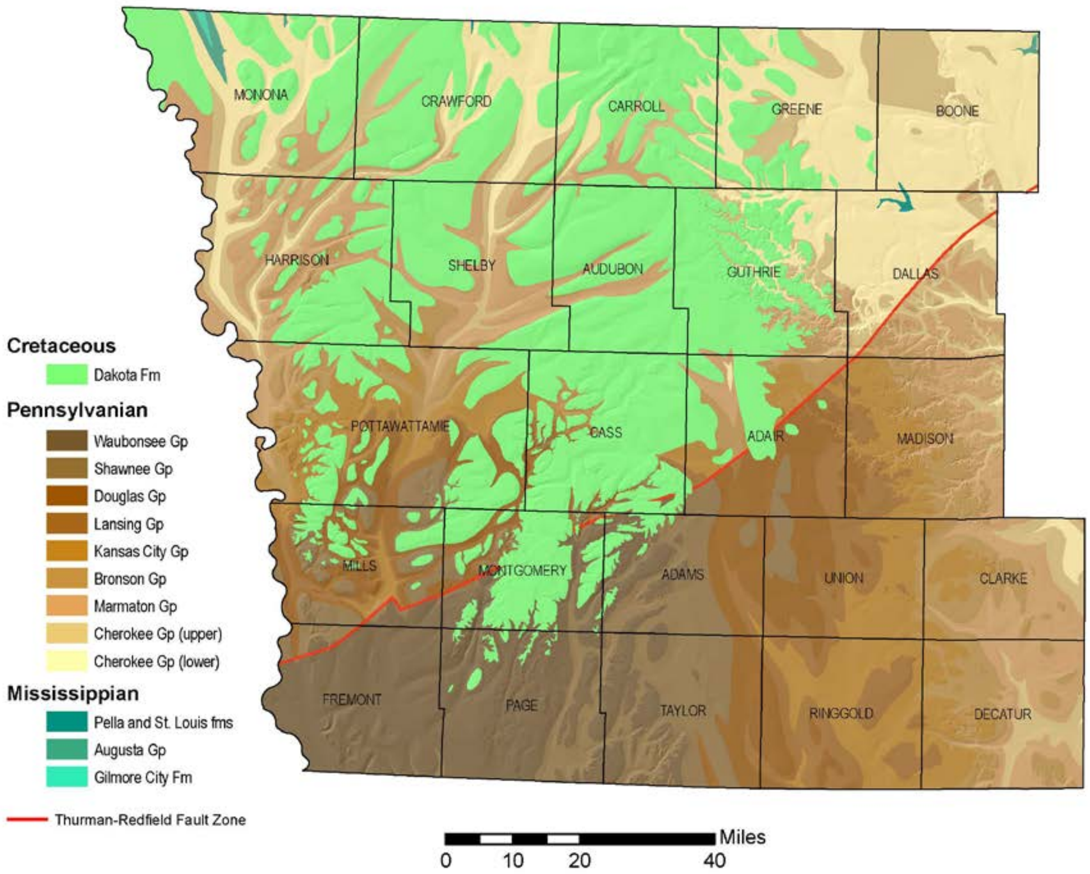


Figure 4. Bedrock geologic map of southwestern Iowa (modified from Pope et al., 2002; Witzke et al., 2003).

EVALUATION OF SALINE PALEOZOIC BEDROCK AQUIFERS FOR CARBON SEQUESTRATION

Introduction

The sub-Pennsylvanian Paleozoic stratigraphic succession in the 24-county area of southwestern Iowa is evaluated in a hydrostratigraphic context for this report, delimiting major aquifer units and their confining strata. Each major hydrostratigraphic unit is defined, as far as existing data permit, and thickness (isopach) maps of various units and the structural configuration (structure contour maps) of major delimiting surfaces within the stratigraphic succession are portrayed. In addition, information about water quality and aquifer parameters (porosity and permeability) are summarized where possible, although such data are extremely limited across the study area. The best sources of such information are derived from several gas storage structures in the region, where extensive sampling to constrain gas storage units and their caprocks has produced important data for certain stratigraphic intervals. However, these storage structures are limited to only a few small areas in the northeastern part of the study area (Redfield Dome and Dallas Center Structure in Dallas County; nearby Vincent Dome and Bagley-Herndon Structure immediately outside the study area in Webster County). Nevertheless, the data from these storage structures, when supplemented with other available deep well information across the study area (IGS GeoSam database), are used to constrain and characterize the hydrostratigraphic units in a more regional context.

The general structural configuration of Paleozoic strata across the study area is dominated by the Forest City Basin, an asymmetrical basin centered in northwestern Missouri and bounded to the east by the Humboldt Fault and Nemaha Uplift in adjacent southeastern Nebraska and northeastern Kansas. The Forest City Basin and its bounding uplifts are primarily if not entirely of Pennsylvanian age, and these structures are superimposed on earlier large-scale Paleozoic structures (basins and arches) that display different configurations and loci of subsidence and uplift (see summary in Bunker et al., 1988). Except along smaller subsidiary structural features (faults, domes), Paleozoic strata dip generally southwestward across the study area toward the center of the Forest City Basin. Paleozoic strata are disrupted by a major northeast-southwest trending high-angle fault zone, the now inactive Thurman-Redfield Fault Zone (TRFZ; location shown on Fig. 5), a feature that is largely coincident with the southern boundary fault of the central horst of the deeply buried Precambrian (Keweenawan) Midcontinent Rift System (see subsequent discussion of the MRS, page 35). This structure is apparent on all accompanying Paleozoic and Precambrian structure contour maps presented in this report. Maximum displacements of the TRFZ (downthrown side to the south) are seen along the western end of this fault (to 300 ft or more; 90 m) with generally decreasing displacements to the northeast (Witzke et al., 2003). There is evidence that fault displacements increase with depth, suggesting recurring episodes of fault movement during the Paleozoic. The TRFZ is primarily a faulted flexure (monocline) with most deformation accommodated in a relatively narrow fault zone (ibid.). However, there appears to be considerable structural complexity and variation associated with the TRFZ, and a series of subsidiary and parallel structures (especially domes) and faults are associated with the main structure, most of which remain poorly constrained (the majority lie within 25 mi [40 km] of the TRFZ, especially to the north). Such structures have been developed locally for storage of natural gas in the study area (Dallas Co.). The relatively large displacements along the TRFZ would be expected to add complexity to groundwater movement across the major aquifers that are not yet constrained.

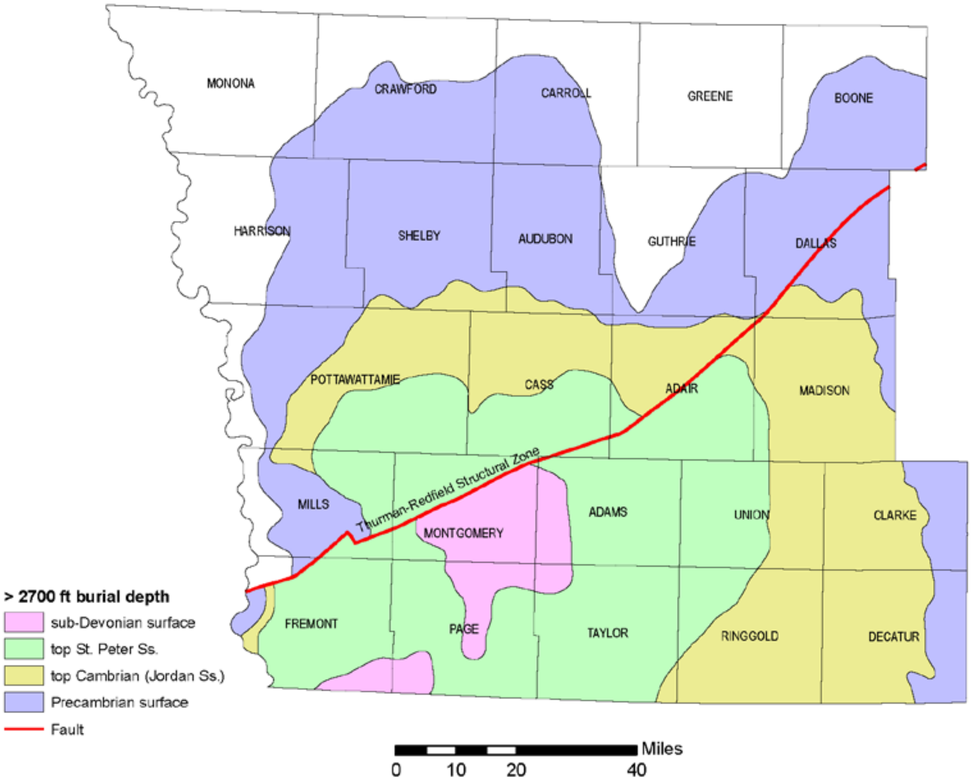


Figure 5. Areas where selected stratigraphic surfaces occur below burial depths of 2,700 ft (820 m) in the 24-county study area of southwestern Iowa. The top of the St. Peter Sandstone defines the top of the Cambro-Ordovician Aquifer and its lower part includes the Jordan Sandstone. The Mt. Simon Aquifer immediately overlies the Precambrian surface. The extent of the Thurman-Redfield Fault Zone is shown in red.

Since aquifer depths are critical for evaluating potentials for carbon sequestration, the structural configuration and elevation of the various aquifers are of critical importance. The pressure threshold for effective carbon dioxide sequestration is reached at burial depths of around 2,700 ft (820 m). As such, many of the shallow saline aquifers in the study area would be unsuitable reservoirs for carbon sequestration. The Mississippian, Upper Devonian Lime Creek, and most of the Devonian Cedar Valley aquifers occur entirely above the 2,700-foot burial threshold and can probably be excluded from consideration for sequestration. Only the basal part of the Devonian Cedar Valley aquifer occurs at depths in excess of 2,700 ft in the southwestern part of the study area (outlined by the sub-Devonian surface on Fig. 5). The underlying Silurian and Ordovician Galena-Maquoketa aquifers would occur at depths greater than 2,700 ft over a slightly larger area, delimited by the area shown on Figure 5 between the sub-Devonian surface and the top of the St. Peter Sandstone. The Cambro-Ordovician aquifer, whose top is delimited by the St. Peter Sandstone, occurs at depths greater than 2,700 ft over a slightly larger area that includes the southwestern one-third of the study area (Fig. 5). Underlying Cambrian units, especially the Mt. Simon aquifer, occur at depths greater than 2,700 ft over a much larger area. The basal Cambrian Mt. Simon Sandstone directly overlies the Precambrian surface, and this surface occurs below 2,700-foot threshold depths over the major part of the study area (excluding the northernmost and westernmost portions, Fig. 5). Therefore, the Mt. Simon aquifer has the broadest regional potential for carbon sequestration of all the Paleozoic aquifers in the study area.

Information on water quality for the various Paleozoic aquifers is very limited in the study area, but for the most part total dissolved solids (TDS) exceed 1,000 mg/L in the Paleozoic aquifers. Only the Mississippian aquifer in parts of the northeastern sector of the study area is known to have water with <1,000 mg/L TDS. Based on limited information and regional trends, TDS values are expected to exceed 2,000 to 3,000 mg/L (with high sulfate content) in all aquifers over the southwestern one-third to one-half of the study area. TDS values are locally known to exceed 5,000 mg/L in all of the aquifers, especially in the southern study area and locally within certain geologic structures (including the gas storage structures of Dallas and Webster counties, where TDS to 14,800 mg/L have been recorded). Most of the water contained within the Paleozoic aquifers of southwestern Iowa varies between slightly saline (1,000-3,000 mg/L) and moderately saline (3,000-10,000 mg/L). Excluding a small area of the Mississippian aquifer where water may be marginally potable and has been locally developed, Paleozoic aquifers in the study area are considered to be non-potable and are not utilized for water supply.

Hydraulic head measurements for the Paleozoic aquifers of southwestern Iowa are sparse, but regional relationships show a general southward or southwestward decrease in the potentiometric surface across the study area for each aquifer. The general southward decrease in water quality for each aquifer is consistent with this observation, indicating that groundwater flow is into, not out of, the Forest City Basin. The progressive increase of TDS suggests relatively sluggish or stagnant groundwater flow systems which tend to concentrate dissolved solids basin-ward.

The Paleozoic aquifers are hosted within stratigraphic intervals that are dominated by either sandstone or carbonate rock (dolomite or limestone). All confining units (aquitards) are dominated by shale, shaley carbonate, or evaporite (gypsum-anhydrite). Matrix permeability measurements of individual core samples from the gas storage structures of Dallas County (and supplemented with data from structures just outside the study area in Webster County) are available for most stratigraphic units. In the case of relatively homogeneous sandstone aquifers, these matrix measurements probably closely reflect permeabilities for the unit as a whole. However, such core measurements are not expected to accurately reflect larger-scale unit permeabilities of the carbonate aquifers. Permeabilities within carbonate aquifers are largely controlled by the distribution of fracture systems and bedding surfaces (which may be solutionally enlarged), and the densities of these features are not directly measured by matrix permeability analyses. Unfortunately, no large-scale unit permeability or hydraulic conductivity analyses or evaluation of fracture densities are available for any aquifer within the study area. Fracturing would be expected to show significant local and regional variation, resulting in more heterogeneous and less predictable regional aquifer systems. In general, permeabilities within carbonate aquifers are expected to show a wider range of values, with considerable local variation, than for the more predictable and homogeneous sandstone aquifers. Any use of carbonate aquifers for carbon sequestration would necessitate more detailed evaluation of aquifer properties, especially site-specific studies, than is currently available for the study area.

Mississippian Aquifers

A general description and summary of the Mississippian succession of carbonate strata in southwestern Iowa is presented in Figure 6. Although groundwater systems within Mississippian carbonate strata of Iowa have commonly been regarded to form a single aquifer (the "Mississippian Aquifer"), it is probably more realistic to consider the Mississippian interval to comprise two separate aquifers separated by an aquitard interval of shale and shaley carbonate strata (Warsaw-Keokuk aquitard; Fig. 6) over most the study area. The possibility of two separate carbonate aquifers within the Mississippian of Iowa was first suggested by Horick and Steinhilber (1973) in their statewide summary. However, the Warsaw-Keokuk interval loses its shaley character to the southwest in the study area, and it is likely that the upper and lower Mississippian aquifers conjoin into a single carbonate groundwater system in that area. The upper Mississippian aquifer is confined above by Pennsylvanian shale and mudstone strata, but as noted earlier basal Pennsylvanian sandstone units may locally be in hydrologic connection with the upper Mississippian aquifer. This upper aquifer overlies the Warsaw-Keokuk aquitard over most of the study area, but sub-"St. Louis" erosional truncation (with up to 100 ft; 30 m of relief) locally brings the upper aquifer in direct hydrologic connection with the lower aquifer. In addition, deep sub-Pennsylvanian erosional incision (up to 300 ft; 90 m of regional relief) locally cuts through the upper aquifer and Pennsylvanian confining beds and directly overlies the lower aquifer. These various stratigraphic relationships would create complex and, as yet, poorly defined groundwater systems within the Mississippian carbonate succession of the study area. No porosity or permeability analyses for Mississippian strata are currently available anywhere in the study area.

As noted previously, the relatively shallow depths of Mississippian strata in the study area would likely preclude its use for carbon sequestration (Fig. 7). Mississippian strata reach thicknesses in excess of 400 ft (120 m) in the study area (Fig. 8), but the thicknesses of the constituent formations are highly variable due to regional stratigraphic variations coupled with sub-Pennsylvanian and sub-"St. Louis" erosional truncation. Limited water quality information is available from Mississippian groundwater systems in the area (see especially Horick and Steinhilber, 1973), and a partial contour map of TDS is presented (Fig. 9). Most water quality data are for the lower Mississippian aquifer, but some data from the upper aquifer are also included. Some municipal and private water supplies have been developed in the Mississippian aquifers in the northeastern part of the study area, where the groundwater is marginally potable (<1,500 mg/L TDS). However, non-potable moderately saline waters (1,500 to 5,000 mg/L TDS) characterize much of the study area (Fig. 9). The potentiometric surface of the Mississippian aquifers generally decreases southward (Fig. 10). Relatively low specific capacities have been calculated for two municipal wells in the northern study area by Horick and Steinhilber (1973; 1.0-1.2 gpm/ft drawdown).

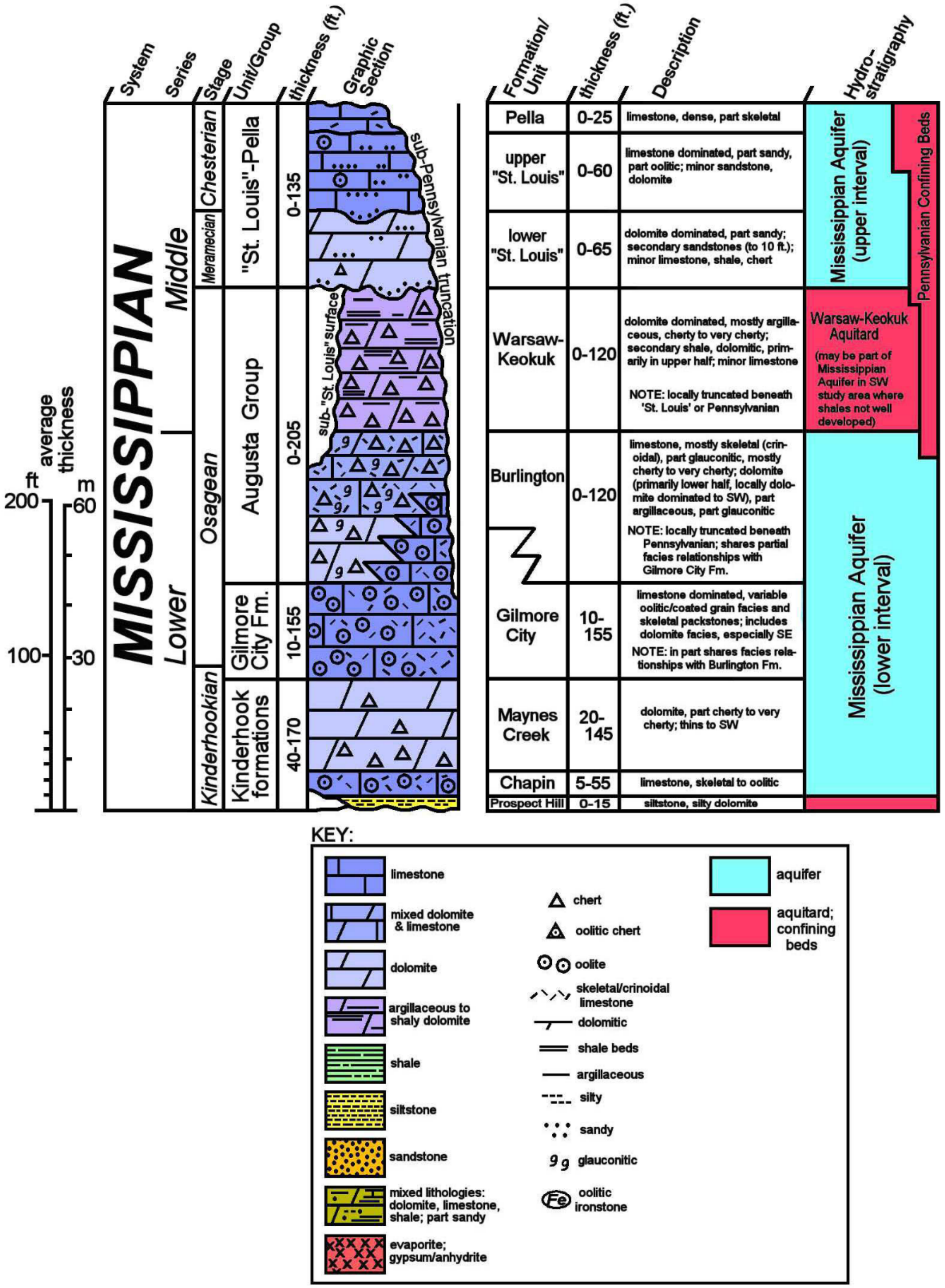


Figure 6. General summary of Mississippian stratigraphy and hydrostratigraphy for southwestern Iowa.

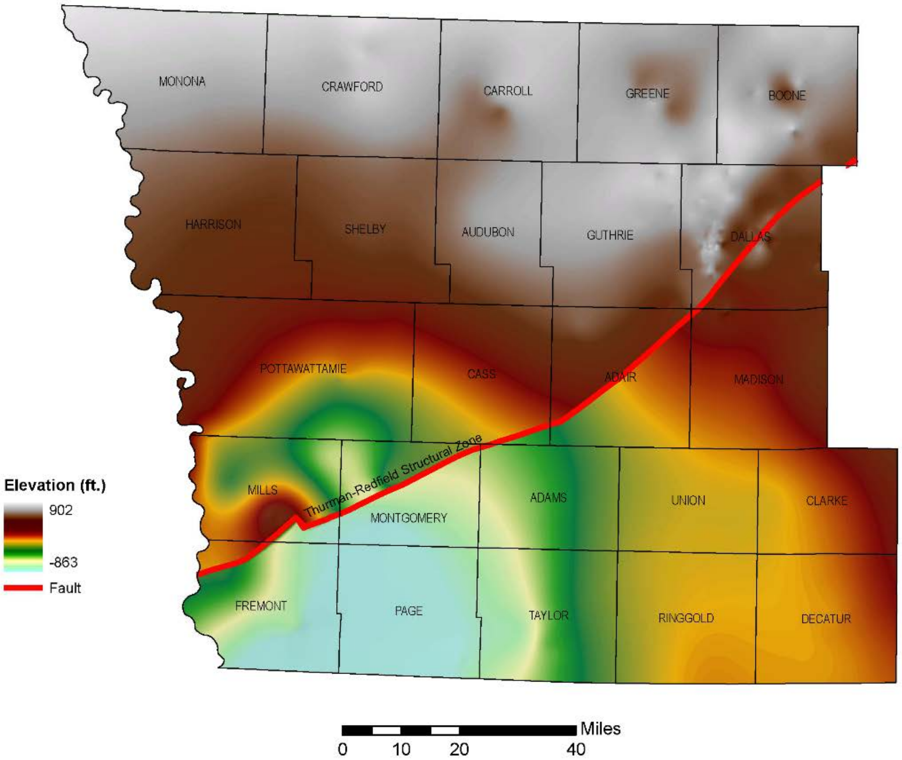


Figure 7. Elevation at the top of Mississippian strata in southwestern Iowa. This is primarily the sub-Pennsylvanian surface except for a few small areas in Monona and Crawford counties where Mississippian strata form the bedrock surface.

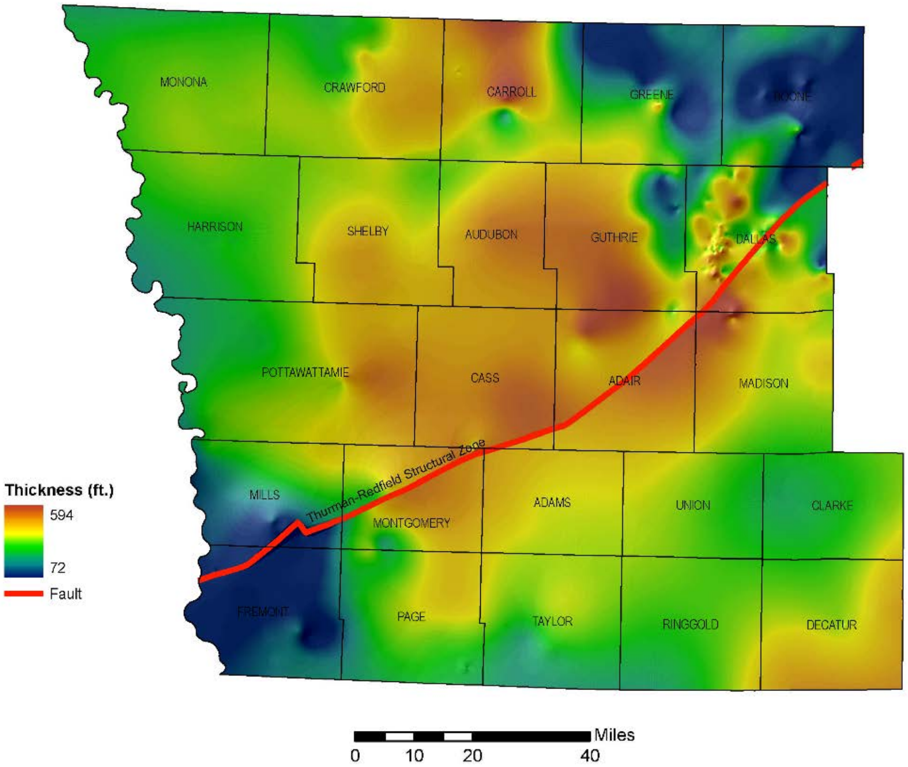


Figure 8. Thickness of Mississippian strata in southwestern Iowa.

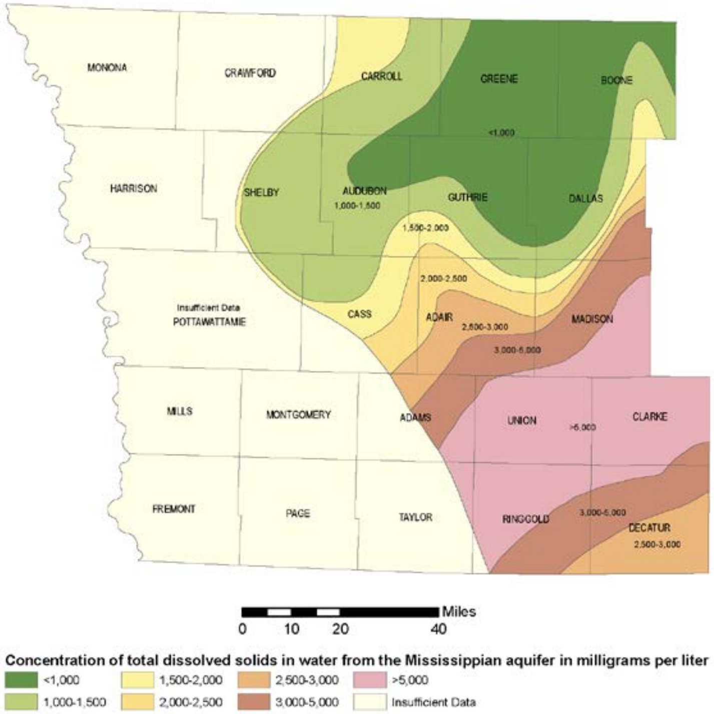


Figure 9. Mapped distribution of TDS (mg/L) in waters from the Mississippian Aquifer in southwestern Iowa. Data are insufficient in the western map area.

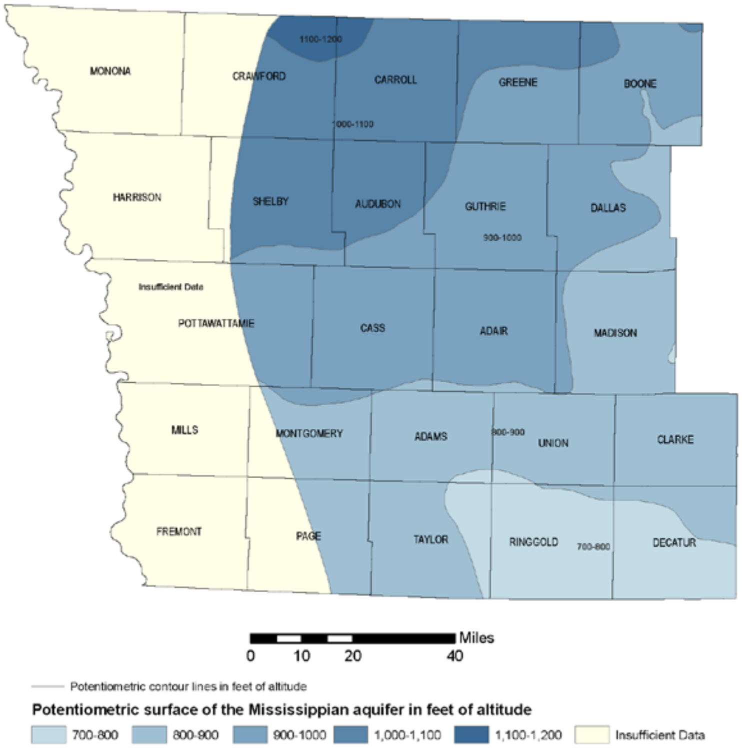


Figure 10. Potentiometric surface (ft of altitude) of the Mississippian Aquifer in southwestern Iowa. Data are insufficient in the western map area.

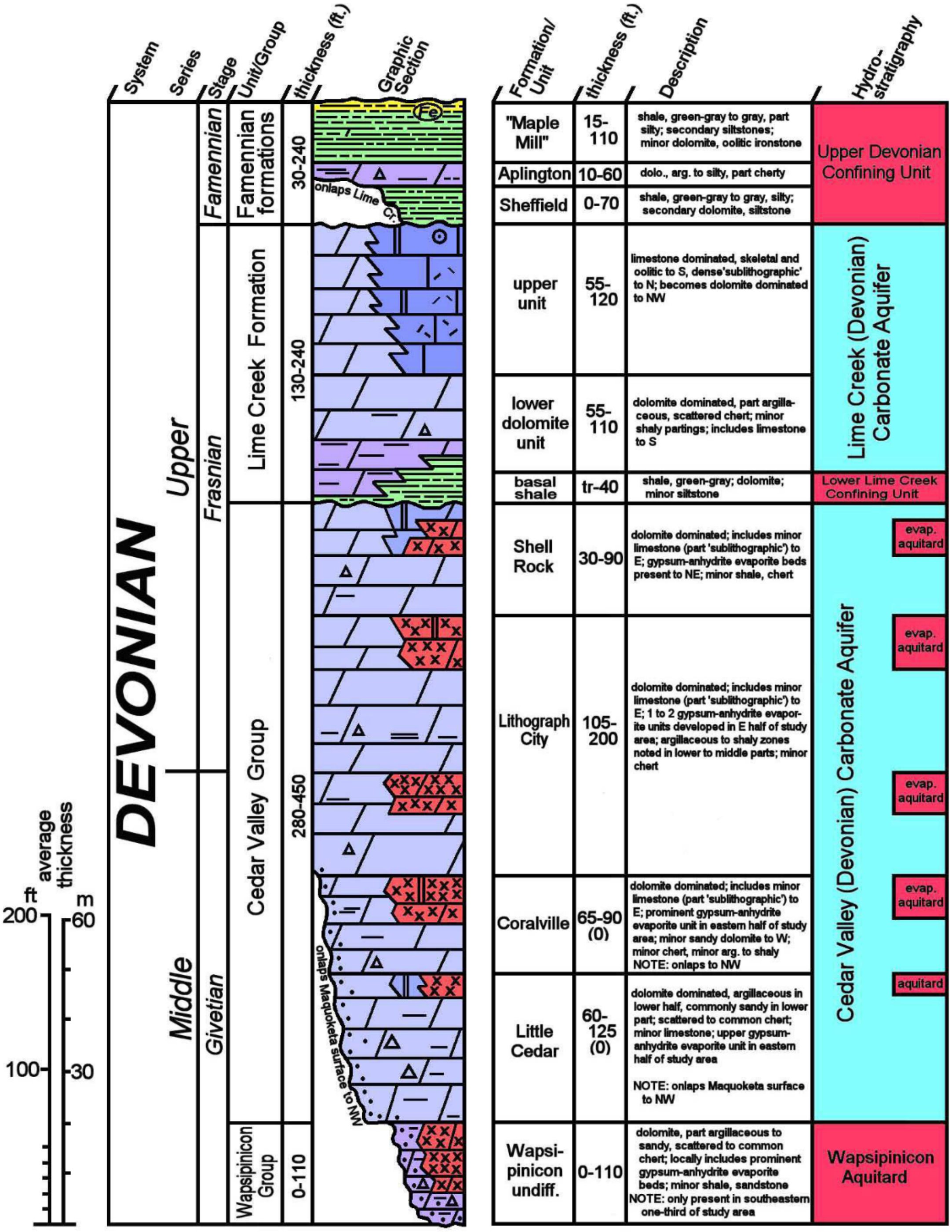
Devonian Aquifers

The full Silurian and Devonian stratigraphic interval, which is a thick succession of carbonate, shale, and evaporite strata in the study area, has commonly been considered to form a single aquifer system (the "Silurian-Devonian Aquifer"; see Horick, 1984). Accordingly, previous studies failed to differentiate what is more likely a complex groundwater system that includes several individual aquifers, each bounded by confining beds. This is unfortunate as most regional data summaries have lumped together water quality measurements and aquifer parameters from multiple aquifers into a single system (Horick, 1984). Studies of Devonian groundwater systems in northern Iowa demonstrated that the lower part of Devonian stratigraphic succession in that area hosts a complex multi-aquifer system (Libra et al., 1984). A similar multi-aquifer system is interpreted for the Devonian succession in southwestern Iowa, which includes two or more carbonate aquifers (Fig. 11). Devonian strata reach thicknesses in excess of 900 ft (275 m) in the study area (Fig. 12). The elevation at the top of the Devonian shows a general southwestward deepening into the Forest City Basin (Fig. 13).

The Lime Creek Formation, which is dominated by carbonate strata (dolomite, limestone) across the study area, forms the upper aquifer in the study area. It is very similar lithologically to underlying strata of the Cedar Valley Group, and the two aquifers likely possess similar aquifer properties. The Lime Creek Aquifer is capped by a widespread shale-dominated succession of Famennian strata which forms the Upper Devonian confining unit (Fig. 11). These confining strata consistently separate the Lime Creek Aquifer from the lower Mississippian Aquifer; varying in thickness from less than 50 ft (15 m) to over 200 ft (60 m) in the southwest corner (Fig. 14). The Lime Creek Aquifer is separated from the underlying Cedar Valley Aquifer by shale and shaley dolomite strata in the lower Lime Creek Formation (lower Lime Creek confining unit; Fig. 11). The lower Lime Creek aquitard is present across most of the study area (reaching thicknesses to 40 ft; 12 m), but it is poorly developed to the southwest, where the Lime Creek and Cedar Valley aquifers may conjoin.

Strata of the Cedar Valley Group are dominated by carbonate lithologies (primarily dolomite) throughout southwest Iowa, but there are significant geographic variations in lithofacies, especially evaporite (gypsum-anhydrite) units across the area. Up to five evaporite intervals are identified in the eastern half of the study area, best developed in the northeastern area (Adair, Guthrie, Boone, Dallas, and Madison counties). The number of evaporite units decreases southwestward (1-3 units in Union, Ringgold, Decatur, Taylor, and Page counties). No evaporites are present in the western half of the study area, where the Cedar Valley Group forms an uninterrupted succession of carbonate strata, dominantly dolomite. Cedar Valley strata variably overlie the Devonian Wapsipinicon Group over portions of the eastern half of the study area (parts of Guthrie, Madison, Adair, Cass, Union, Clarke, and possibly Ringgold and Taylor counties). Strata of the Wapsipinicon Group (which includes gypsum-anhydrite evaporite and dolomite) are interpreted to form an aquitard that separates the Cedar Valley and Silurian aquifers. However, over much of the area Cedar Valley strata directly overlie an eroded surface on Silurian strata with no apparent hydrologic separation (including parts of parts of Dallas, Boone, Madison, Adams, Page, Fremont, Mills, Montgomery, and Pottawattamie counties). Further stratigraphic complexity is added by the progressive northwestward onlap of Cedar Valley formations across an eroded surface on the Maquoketa Formation

(Greene, Audubon, Shelby, Harrison, and Monona, Crawford, and Carroll counties). In addition, southwestward thinning of Cedar Valley strata is evident in Page and Fremont counties, possibly due to depositional thinning or downlapping.



Formation/ Unit	thickness (ft.)	Description	Hydro-stratigraphy
"Maple Mill"	15-110	shale, green-gray to gray, part silty; secondary siltstones; minor dolomite, oolitic ironstone	Upper Devonian Confining Unit
Aplington	10-60	dolo., arg. to silty, part cherty	
Sheffield	0-70	shale, green-gray to gray, silty; secondary dolomite, siltstone	
upper unit	55-120	limestone dominated, skeletal and oolitic to S, dense'sublithographic' to N; becomes dolomite dominated to NW	Lime Creek (Devonian) Carbonate Aquifer
lower dolomite unit	55-110	dolomite dominated, part argillaceous, scattered chert; minor shaly partings; includes limestone to S	
basal shale	tr-40	shale, green-gray; dolomite; minor siltstone	Lower Lime Creek Confining Unit
Shell Rock	30-90	dolomite dominated; includes minor limestone (part 'sublithographic') to E; gypsum-anhydrite evaporite beds present to NE; minor shale, chert	Cedar Valley (Devonian) Carbonate Aquifer evap. aquitard
Lithograph City	105-200	dolomite dominated; includes minor limestone (part 'sublithographic') to E; 1 to 2 gypsum-anhydrite evaporite units developed in E half of study area; argillaceous to shaly zones noted in lower to middle parts; minor chert	evap. aquitard evap. aquitard
Coralville	65-90 (0)	dolomite dominated; includes minor limestone (part 'sublithographic') to E; prominent gypsum-anhydrite evaporite unit in eastern half of study area; minor sandy dolomite to W; minor chert, minor arg. to shaly NOTE: onlaps to NW	evap. aquitard
Little Cedar	60-125 (0)	dolomite dominated, argillaceous in lower half, commonly sandy in lower part; scattered to common chert; minor limestone; upper gypsum-anhydrite evaporite unit in eastern half of study area NOTE: onlaps Maquoketa surface to NW	aquitard
Wapsipinicon undiff.	0-110	dolomite, part argillaceous to sandy, scattered to common chert; locally includes prominent gypsum-anhydrite evaporite beds; minor shale, sandstone NOTE: only present in southeastern one-third of study area	Wapsipinicon Aquitard

Figure 11. General summary of Devonian stratigraphy and hydrostratigraphy for southwestern Iowa. Symbols shown in Figure 6.

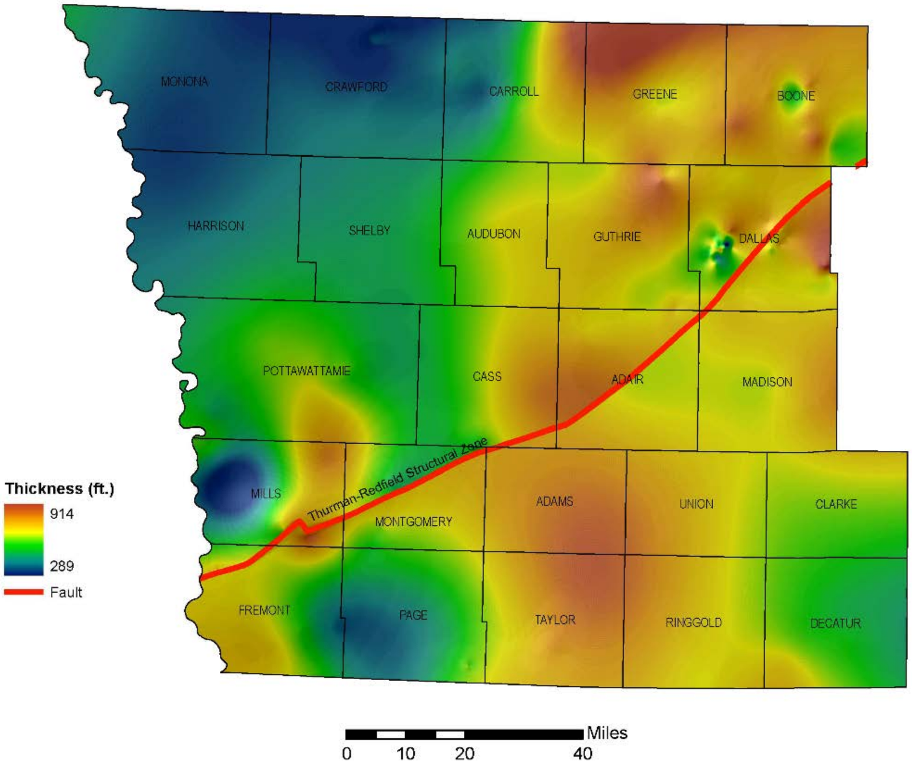


Figure 12. Thickness of Devonian strata in southwestern Iowa.

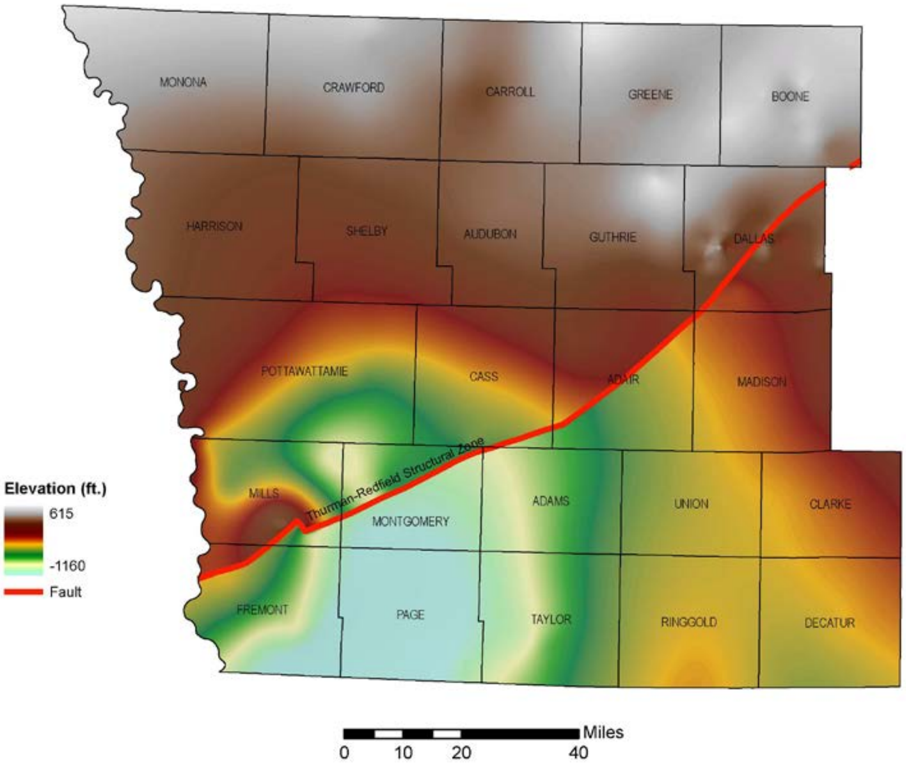


Figure 13. Elevation at the top of Devonian strata in southwestern Iowa. This surface is entirely covered by Mississippian strata across the map area.

These various and complex stratigraphic relationships suggest the following interpretations of groundwater systems within the Cedar Valley aquifer of the study area. However, to date there have been no hydrologic studies that confirm these speculations.

1) In the eastern half of the study area the Cedar Valley is subdivided into two to five aquifers, each separated by widespread evaporite aquitards (Fig. 11).
2) In the southwestern portion of the study area the Cedar Valley succession forms a single carbonate aquifer system that is hydraulically connected with the underlying Silurian aquifer.
3) In the northwestern area the Cedar Valley Group directly overlies an eroded surface on the Ordovician Maquoketa Formation, and Cedar Valley and Maquoketa aquifers are interpreted to be in hydrologic connection in that area.
4) Since the lower Lime Creek aquitard is poorly developed in the western half of the study area, the Cedar Valley and Lime Creek aquifers may be hydraulically connected in that area.

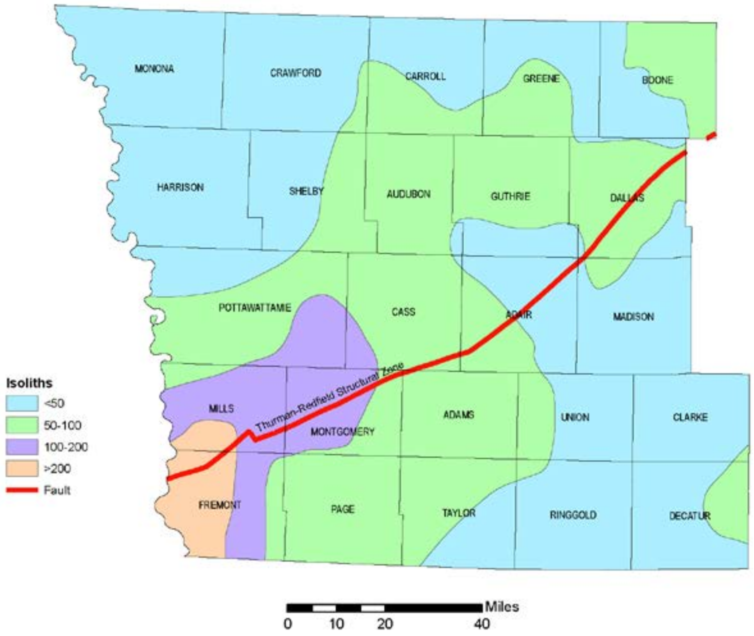


Figure 14. Thickness of Famennian (Upper Devonian) confining strata in southwestern Iowa. These strata are dominated by shale and shaley dolomite.

Water quality data for the Devonian aquifers is quite limited in the study area. A contour map of TDS for the combined and undifferentiated Silurian and Devonian aquifers (an over-simplified concept for these groundwater systems) is presented in Figure 15. As for the other Paleozoic aquifers, water quality generally decreases southward. The potentiometric surface for the combined Silurian-Devonian remains largely unconstrained for the area (Fig. 16). Water quality data for the Lime Creek Aquifer are available from a few wells (including some municipal wells) for Carroll, Boone, and Dallas counties, where values vary between 1,640 and 4,100 mg/L TDS with no apparent geographic pattern. Water quality data from the Cedar Valley aquifer are available for Dallas and Crawford counties, varying between 1,660 and 4,786 mg/L TDS with no apparent geographic or stratigraphic pattern. Water derived from wells open to both

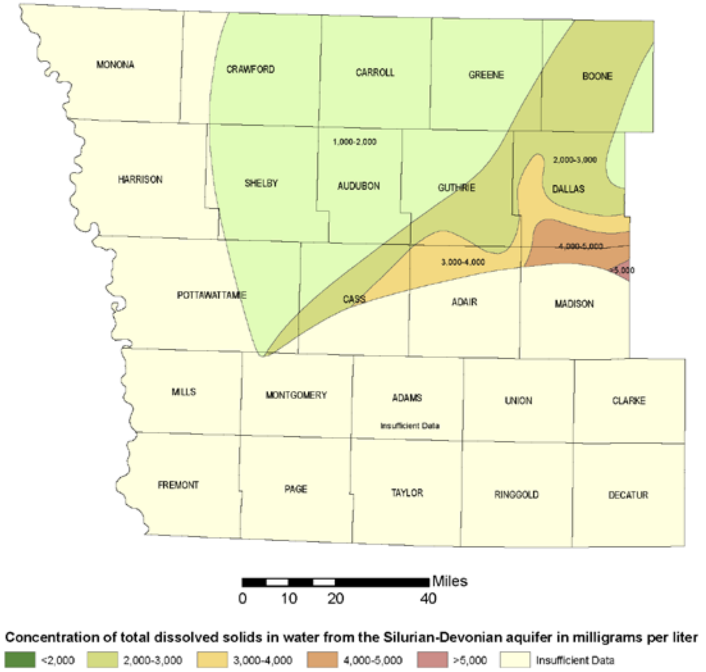


Figure 15. Mapped distribution of TDS (mg/L) in waters from the "Silurian-Devonian Aquifer" in southwestern Iowa (after Horick, 1984). Data are insufficient in the western and southern map areas.

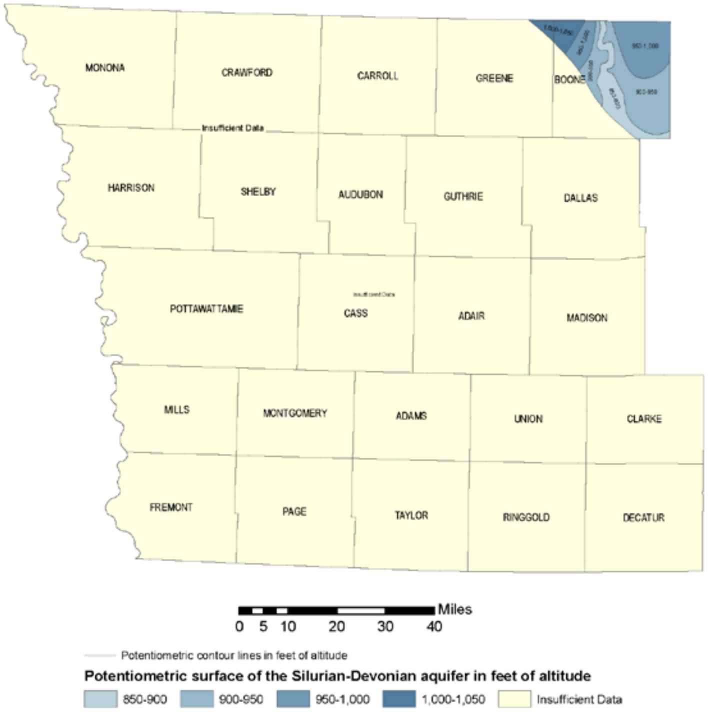


Figure 16. Potentiometric surface (ft of altitude) of the "Silurian-Devonian Aquifer" in southwestern Iowa (after Horick, 1984). Data are insufficient across most of the map area.

the Cedar Valley and Lime Creek aquifers in Pottawattamie, Adair, Greene, and Guthrie counties have yielded values of 1,360 to 4,082 mg/L TDS with no apparent geographic trend. Therefore, water quality in the Devonian aquifers is interpreted to be slightly to moderately saline throughout the study area. Matrix permeability measurements of lower Cedar Valley cores from gas storage structures in Webster County (immediately north of the study area) are highly variable (immeasurable up to 100 millidarcies (mD) indicating a highly heterogeneous carbonate aquifer. Unit permeabilities in the fractured carbonate systems would presumably be much higher. Limited pumping information from Adair, Pottawattamie, Guthrie, and Dallas counties show variable specific capacities (1.28, 2.27, 0.11, and 13.3 gpm/ft drawdown, respectively) lending further support to the heterogeneous character of the Devonian aquifers.

Silurian Aquifer

The Silurian Aquifer is widely used for water supply in eastern Iowa, but the aquifer in the southwestern Iowa study area is saline and has not been utilized. It occupies about half of the study area, but is absent to the northwest and southeast due to sub-Devonian erosion (sub-Devonian surface developed across eroded Silurian and Maquoketa strata, Fig. 17a). It reaches maximum burial depths in the southwestern portion of the study area (Silurian surface, Fig. 17b). Silurian strata are characterized by relatively pure carbonate rocks, primarily dolomite and cherty dolomite, but include minor limestone in some areas (Fig. 18). Silurian strata reach thickness in excess of 350 ft (110 m) in portions of Fremont County, but the Silurian is notably thinner across most of the area (Fig. 19).

The Silurian Aquifer is capped by the Wapsipinicon aquitard in some of the eastern counties in the study area, but it likely is in direct hydrologic connection with the Cedar Valley Aquifer over most of its extent where the Wapsipinicon aquitard is absent. The Silurian Aquifer is bounded below by shales of the Upper Maquoketa aquitard (Ordovician). Maquoketa shales are best developed in the eastern half of the study area, but are significantly thinner in the western half where in some counties north of the TRFZ they are less than 10 ft (3 m) thick and are locally absent (Fig. 20). In those areas the Silurian Aquifer may be in direct hydrologic connection with the Maquoketa carbonate aquifer.

Matrix porosity and permeability measurements are available for Silurian dolomite strata in Dallas County (gas storage structure). It is relatively porous (11-18%), macroscopically characterized by an abundance of small voids (fossil molds) with scattered larger vugs. Permeabilities are variable, ranging between 24 and 476 mD and averaging about 86 mD. Unit permeabilities undoubtedly are much higher in the fractured carbonate system than these measurements suggest. Water quality information is only available for Mills and Dallas counties (2,510 mg/L and 3,906-4,295 mg/L TDS, respectively). As with the overlying, and in part hydrologically connected Devonian aquifers, the Silurian Aquifer is expected to be characterized by non-potable saline waters throughout the study area.

Upper Ordovician Aquifers

Upper Ordovician strata in the southwestern Iowa study area include a relatively thick but complex carbonate aquifer system here termed the Galena-Maquoketa Aquifer (Fig. 18). This carbonate aquifer is used for water supply in northeast Iowa, but it is non-potable and has not been utilized in the study area. However, porous and permeable carbonate strata in the middle Maquoketa Formation are used as a secondary reservoir for gas storage and recovery in Dallas County. The Maquoketa Formation reaches thickness in excess of 300 ft (90 m) in the southwestern part of the study area where capped by Silurian strata, but it is only 100-200 ft (30-60 m) thick where it is erosionally beveled beneath the Devonian to the northwest. The formation is dominated by dolomite and cherty dolomite, but it is variably argillaceous and includes several shaley intervals, most prominently the Brainard-Neda shale unit at the top which forms the regional Upper Maquoketa Aquitard (Fig. 18). The elevation of this surface is shown in Figure 21. Additional shaley intervals are developed in the eastern part of the study area that include shales of the Clermont Member (note edge in Fig. 20) and shaley units in the basal Elgin-uppermost Galena Group which are interpreted to form aquitards in those areas (Fig. 18). The Clermont aquitard forms an effective caprock for a gas reservoir in the Elgin Member of Dallas County. However, the Maquoketa succession over most of the area lacks these shaley units (replaced by non-shaley dolomite) where the combined Maquoketa-Galena interval is interpreted to be part of a single aquifer system. Porous dolomite strata are best developed in the upper part of the Elgin Member and the upper part of the Fort Atkinson-Clermont interval (Fig. 18). Where Maquoketa strata are directly overlain by the Cedar Valley Group, the Galena-Maquoketa and Cedar Valley aquifers are likely in direct hydrologic connection.

The underlying Galena Group is dominated by dolomite and cherty dolomite in its upper part (Wise Lake-Dunleith formations) and by a lower interval of shaley to sandy dolomite and limestone interstratified with shale (the Decorah Formation; Fig. 18). The upper Galena interval is a porous carbonate interval that forms the lower part of the Galena-Maquoketa Aquifer. However, the lower part (Decorah) along with underlying units of the Platteville and Glenwood formations comprises the Decorah-Platteville Aquitard (averages 50 ft, 15 m thick). This aquitard regionally separates the overlying aquifer from the Cambro-Ordovician Aquifer below. The Galena Group thins southwestward in the area with an overall increase in Decorah shale thickness to the northwest.

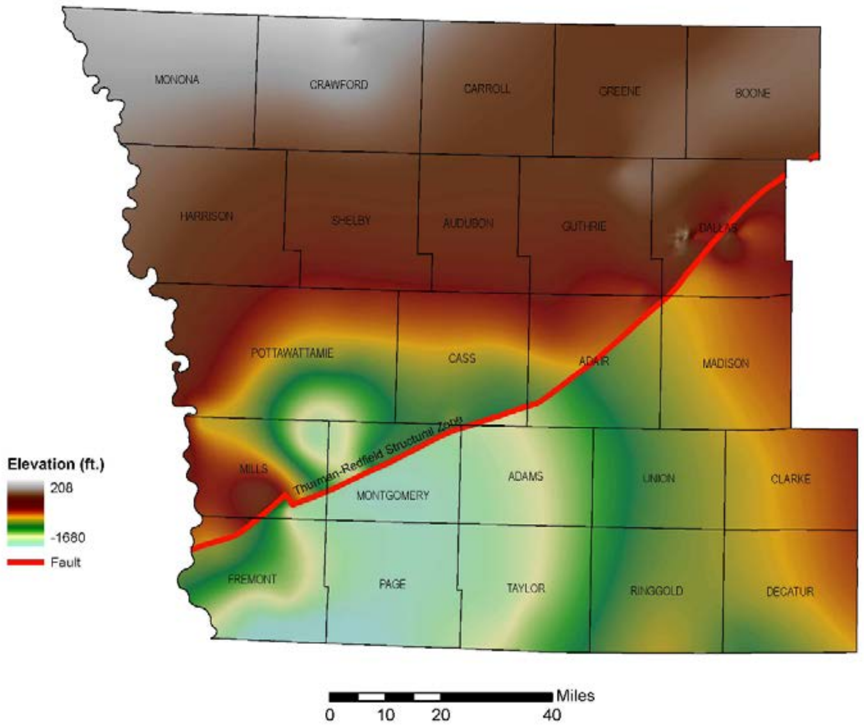


Figure 17a. Elevation of sub-Devonian surface in southwestern Iowa. This is an erosional surface developed on Silurian and Upper Ordovician (Maquoketa) strata.

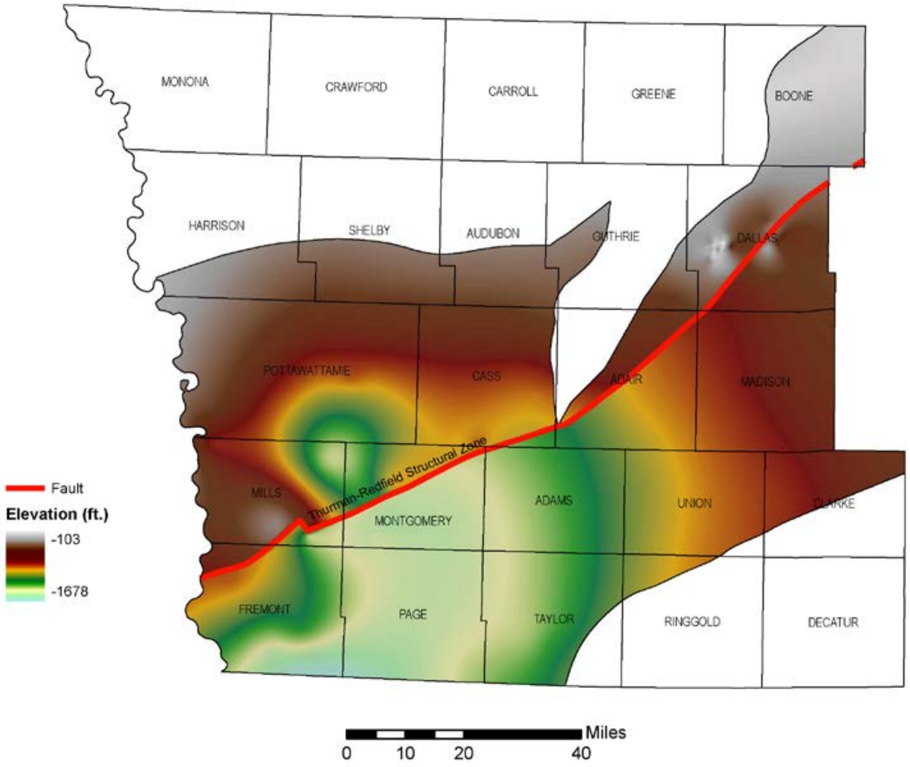
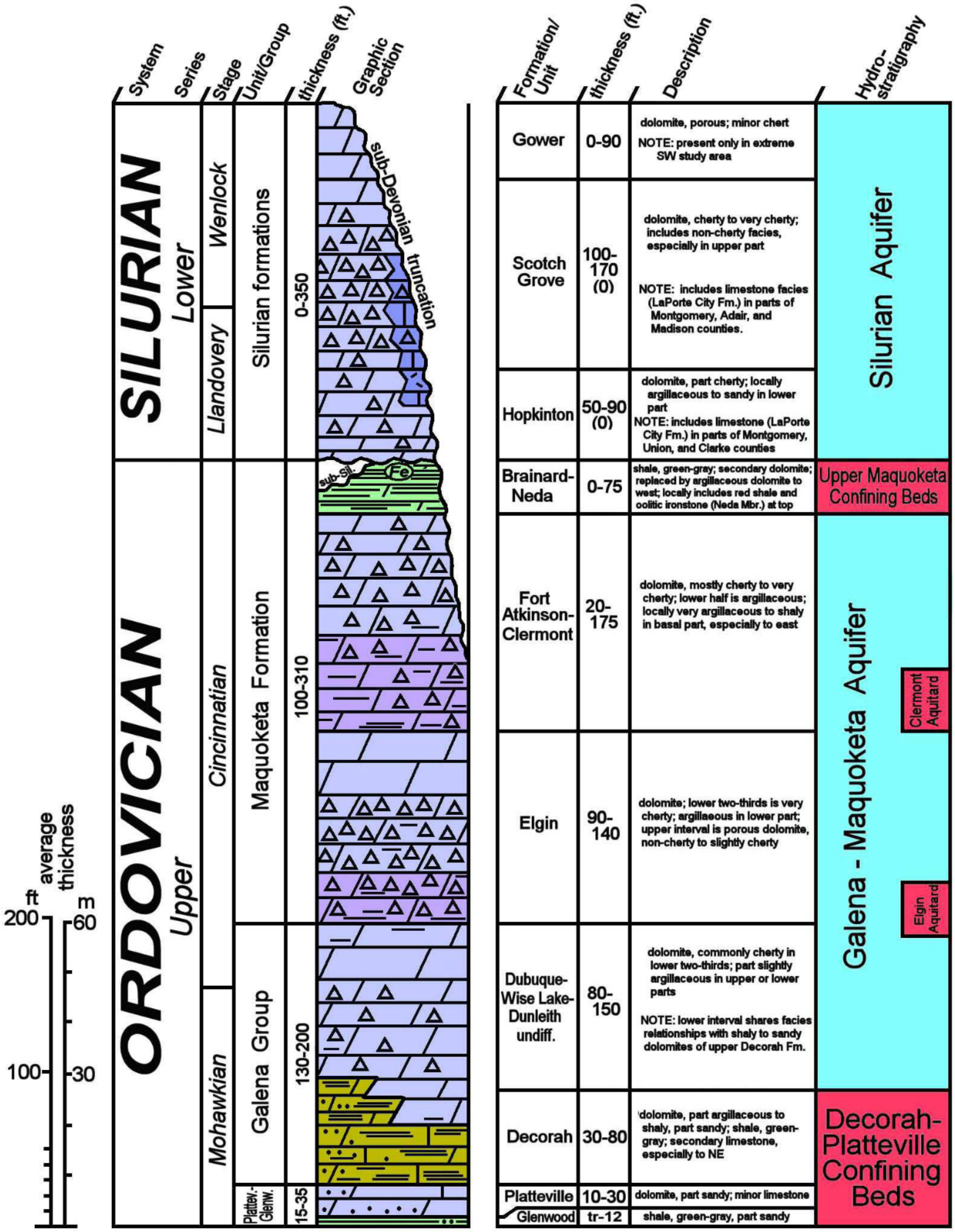


Figure 17b. Elevation at the top of Silurian strata in southwestern Iowa. This surface is entirely covered by Devonian strata.



Formation/ Unit	thickness (ft.)	Description	Hydro-stratigraphy
Gower	0-90	dolomite, porous; minor chert NOTE: present only in extreme SW study area	Silurian Aquifer
Scotch Grove	100-170 (0)	dolomite, cherty to very cherty; includes non-cherty facies, especially in upper part NOTE: includes limestone facies (LaPorte City Fm.) in parts of Montgomery, Adair, and Madison counties.	
Hopkinton	50-90 (0)	dolomite, part cherty; locally argillaceous to sandy in lower part NOTE: includes limestone (LaPorte City Fm.) in parts of Montgomery, Union, and Clarke counties	
Brainard-Neda	0-75	shale, green-gray; secondary dolomite; replaced by argillaceous dolomite to west; locally includes red shale and oolitic ironstone (Neda Mbr.) at top	Upper Maquoketa Confining Beds
Fort Atkinson-Clermont	20-175	dolomite, mostly cherty to very cherty; lower half is argillaceous; locally very argillaceous to shaly in basal part, especially to east	Galena - Maquoketa Aquifer Clermont Aquitard
Elgin	90-140	dolomite; lower two-thirds is very cherty; argillaeous in lower part; upper interval is porous dolomite, non-cherty to slightly cherty	Elgin Aquitard
Dubuque-Wise Lake-Dunleith undiff.	80-150	dolomite, commonly cherty in lower two-thirds; part slightly argillaceous in upper or lower parts NOTE: lower interval shares facies relationships with shaly to sandy dolomites of upper Decorah Fm.	
Decorah	30-80	dolomite, part argillaceous to shaly, part sandy; shale, green-gray; secondary limestone, especially to NE	Decorah-Platteville Confining Beds
Platteville	10-30	dolomite, part sandy; minor limestone	
Glenwood	tr-12	shale, green-gray, part sandy	

Figure 18. General summary of Silurian and Upper Ordovician stratigraphy for southwestern Iowa. Symbols shown in Figure 6.

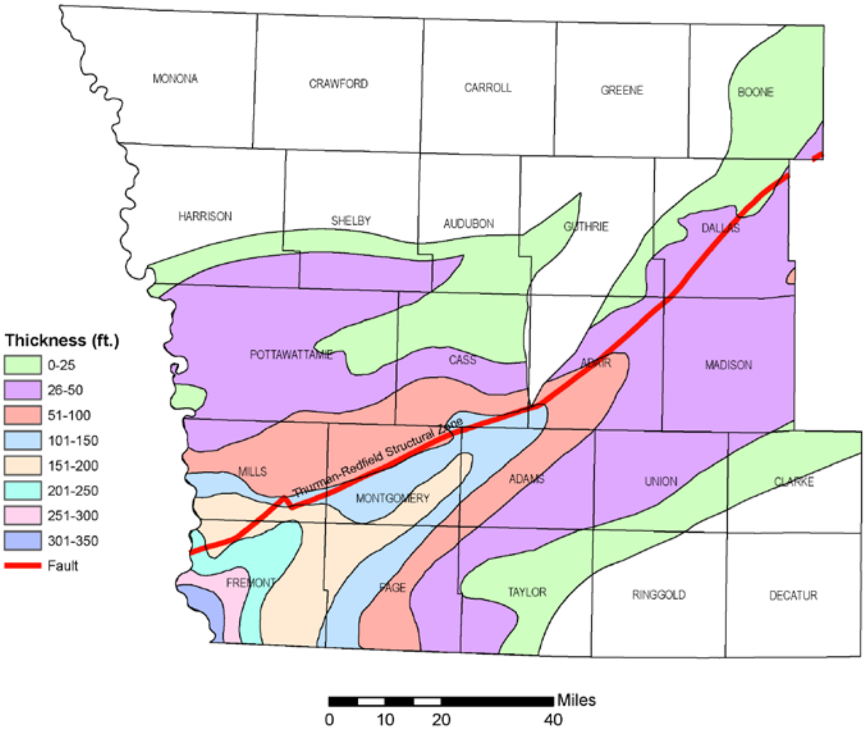


Figure 19. Thickness of Silurian strata in southwestern Iowa.

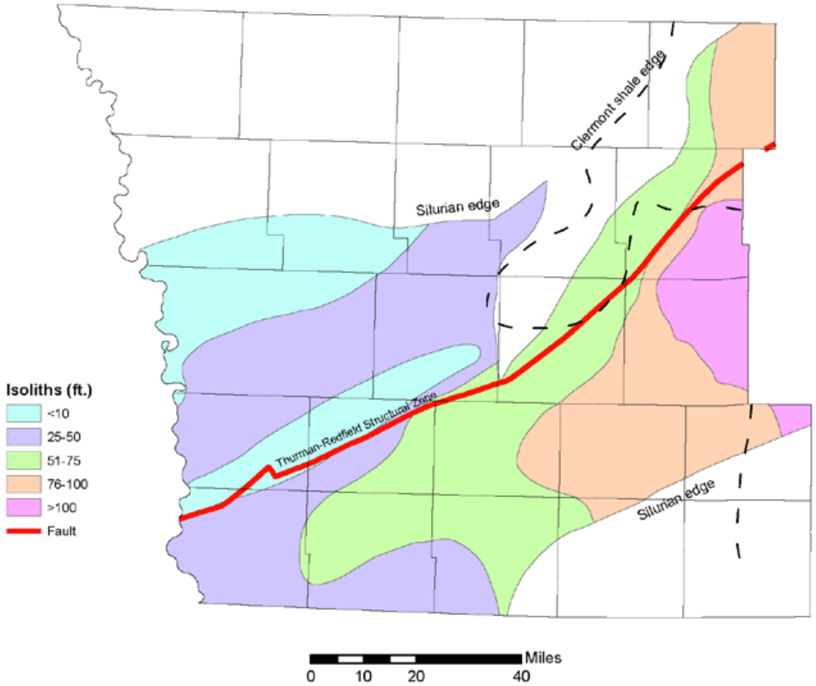


Figure 20. Cumulative thickness (isolith) of shales within the Maquoketa Formation (Upper Ordovician) of southwestern Iowa. Outside of the mapped edge of the Clermont Shale, these shales occur entirely within the Brainard-Neda interval at the top of the formation (Upper Maquoketa Aquitard). The Clermont Shale forms a local confining interval in the northeastern map area.

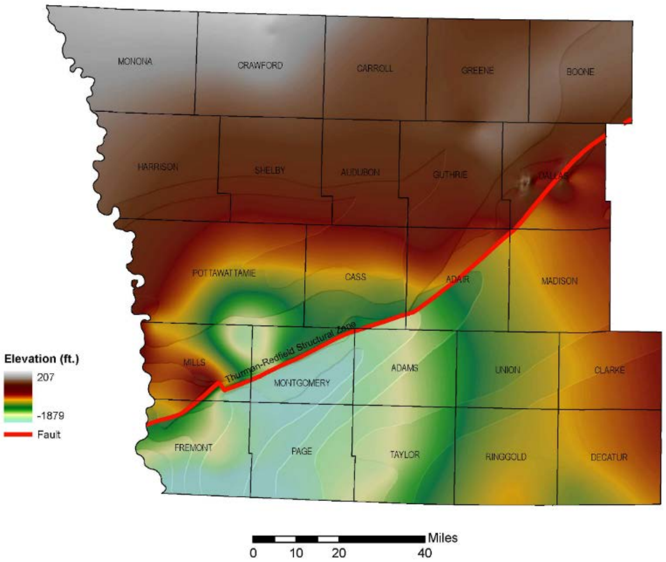


Figure 21. Elevation at top of Ordovician (Maquoketa Formation) in southwestern Iowa. This is an erosional surface variably overlain by Silurian or Devonian strata.

Matrix porosity and permeability information for Upper Ordovician strata for core samples from the Redfield gas storage structure in Dallas County is summarized here.

1) Brainard Shale: 2.3-20.2% porosity; ,0.1 mD; “impervious cap rock”
2) Fort Atkinson: 6-26.1% porosity; <0.1-392 mD, zones with high permeability; “potential storage reservoir”
3) Clermont Member: 1.8-16.2%; <0.1-6.3 mD; “impervious barrier”
4) Upper Elgin Member: 5-12.8%, average 9%; 0.1-248 mD, zones with high permeability, part “good storage reservoir”
5) Lower Elgin Member: 5.1-25.4%; <0.1-59 mD, minor zones with higher permeability
6) Basal Elgin Member: 5.5-18.7%; <0.1-2.4 mD
7) Upper Galena Group: 4.8-15.2%, average 9.5%; <0.1-600 mD, zones with high permeability
8) Decorah carbonates [shales not measured]: 2.3-11.5%, average <4%; <0.1-11.5 mD, primarily <0.1 mD
9) Platteville Formation: 1.2-9.2%, average 3.2%; <0.1-9.2 mD, primarily <0.1 mD; “permeability barrier”
10) Glenwood Shale: 10.9-21.3%; <0.1 mD.

The porous (moldic) and vuggy dolomites of the Galena-Maquoketa interval are expected to show considerably higher unit permeabilities due to pervasive fracture networks. Reports from the Redfield structure considered the Decorah-Platteville interval to be “a very distinct and definite barrier.” There are no pumping data available from the Galena-Maquoketa Aquifer, and water quality information is only available for Dallas County: Maquoketa Formation (1,870-3,161 mg/L TDS), upper Galena Group (1,556-2,932 mg/L TDS), Decorah-Platteville (1,719-1,753 mg/L TDS). The Galena-Maquoketa Aquifer is considered to be saline and non-potable throughout the study area.

Cambro-Ordovician (Jordan) Aquifer

The Cambro-Ordovician Aquifer (also known as the Jordan Aquifer) is a major and widely used regional aquifer (Horick and Steinhilber, 1978) that underlies the entire southwestern Iowa study area. It comprises a stratigraphic succession that includes in descending order the St. Peter Sandstone, the Prairie du Chien Group (Shakopee, Oneota formations), the Jordan Sandstone, and probably the St. Lawrence Formation (Fig. 22). The St. Peter Sandstone (lowest Upper Ordovician or highest Middle Ordovician) is separated from underlying strata by a major erosional unconformity (the Sauk-Tippecanoe Megasequence boundary). Nevertheless, the St. Peter is in hydrologic connection with underlying Prairie du Chien strata as no confining interval is present at its base. The Cambro-Ordovician Aquifer is confined above by the Decorah-Platteville Aquitard and below by Cambrian confining beds below (Fig. 22). The Prairie du Chien Group is entirely a Lower Ordovician interval, and the Jordan and St. Lawrence formations are known to be of Cambrian age in the Upper Mississippi Valley. Since the contained strata are known to include both Cambrian and Ordovician units, the term Cambro-Ordovician Aquifer seemed appropriate. However, recent investigations in the region have shown that the Jordan Sandstone and part of the St. Lawrence Formation in the area to the west of central Iowa (including data from Dallas County in the study area) are of Early Ordovician age (Runkle et al., 2007). Therefore, the term “Cambro-Ordovician Aquifer” may be a bit of a misnomer in the study area.

The Cambro-Ordovician Aquifer varies significantly in thickness across the study area, generally increasing in thickness to the southeast where it is known to exceed 600 ft (180 m) (Fig. 23). It is thinnest to the southwest, where sub-St. Peter erosion has beveled Prairie du Chien strata, and the St. Peter directly overlies Cambrian units in western Fremont County (Fig. 23). The St. Peter directly overlies Precambrian crystalline basement rocks a short distance to the west in southeastern Nebraska. Maximum burial depths of the aquifer are identified in the southwestern part of the study area (see elevation top of St. Peter Sandstone, Fig. 24; elevation top Jordan Sandstone, Fig. 25).

The main productive intervals within the Cambro-Ordovician Aquifer are identified within relatively homogeneous sandstone strata of the St. Peter, New Richmond (basal Shakopee Fm.; Fig. 22), and Jordan sandstones. However, zones of high permeability within the fractured Prairie du Chien dolomites add significantly to water yields within the aquifer. The entire Cambro-Ordovician Aquifer, therefore, is a mixed sandstone and carbonate aquifer system. Both the New Richmond and Jordan sandstones become more dolomitic to the west, and are replaced in some of the western counties by sandy dolomite strata.

There is considerably more information on aquifer and water properties available for this study area than there is for most of the other Paleozoic aquifers, and maps of water quality (Fig. 26) and potentiometric surface (Fig. 27) are presented. Water quality is marginally potable (<1,250 mg/L TDS) along the eastern fringe of the study area, but exceeds 2,000 mg/L TDS over large areas (Fig. 26). The potentiometric surface generally decreases eastward (Fig. 27), largely coincident with the area of maximum thickening of the aquifer (Fig. 23).

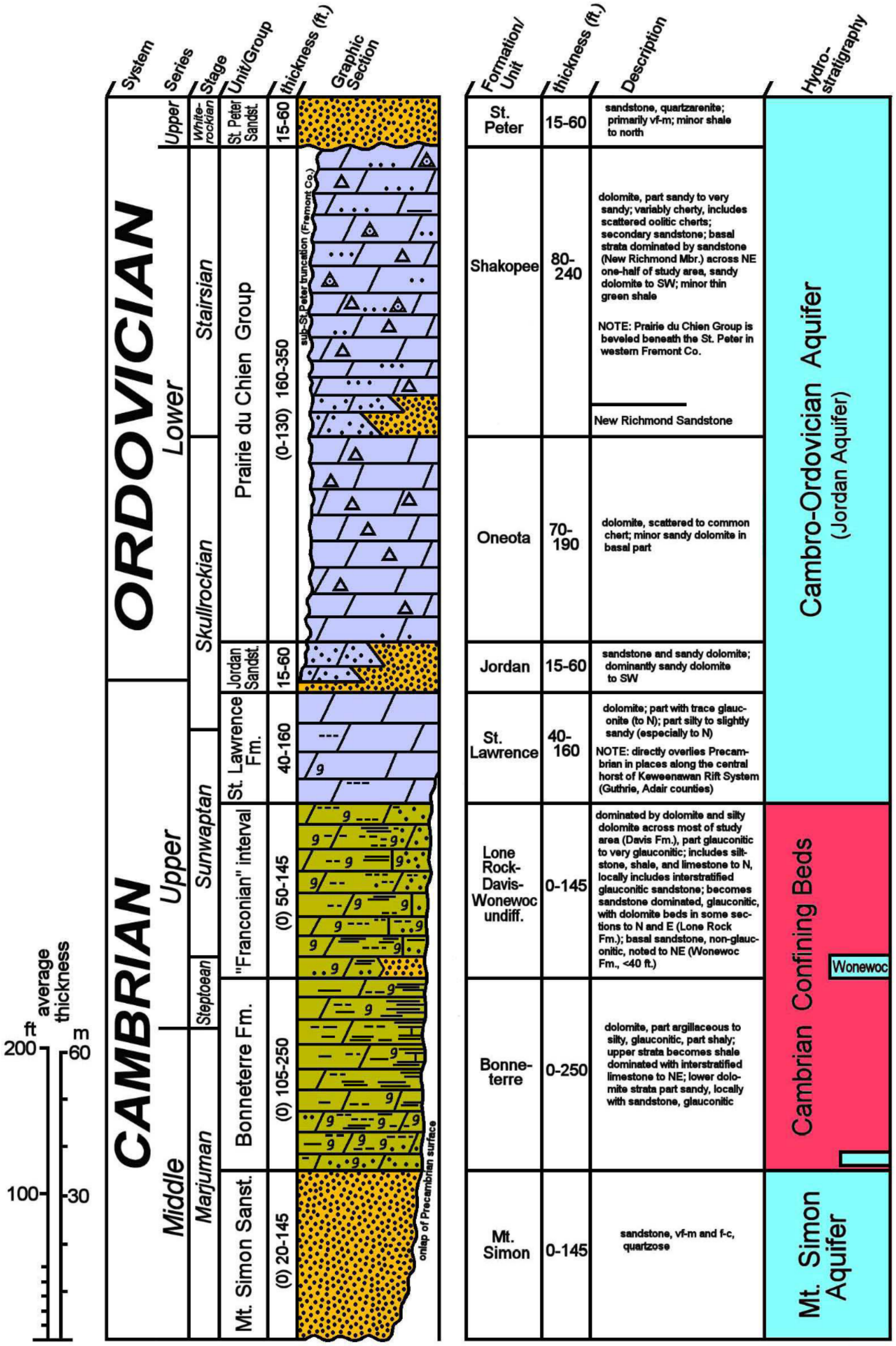
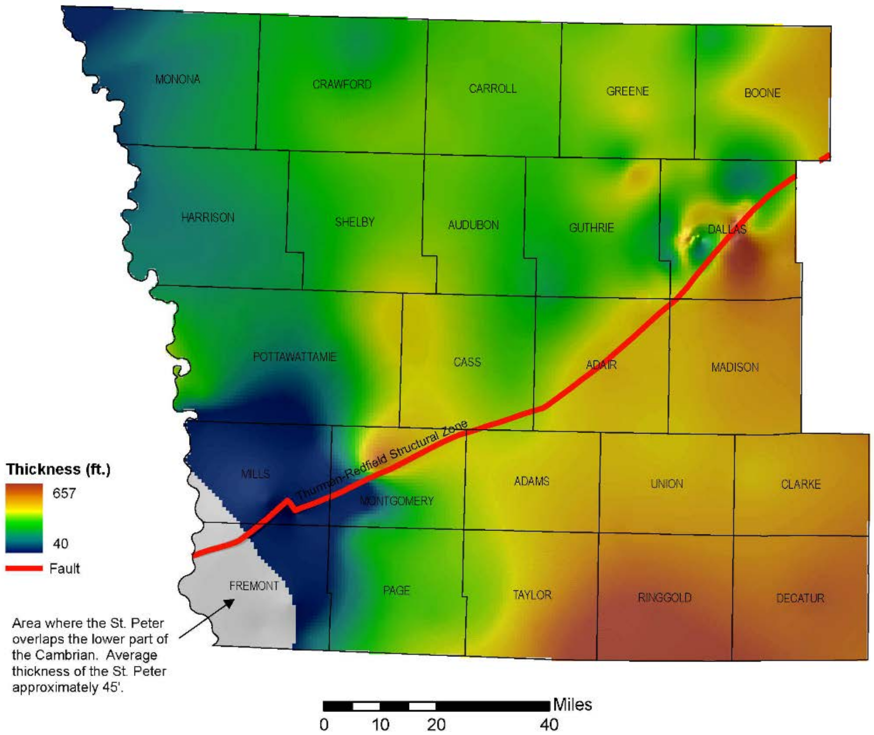


Figure 22. General summary of Cambrian and Ordovician stratigraphy and hydrostratigraphy in southwestern Iowa (Mt. Simon-St. Peter interval). Symbols shown in Figure 6.



Area where the St. Peter overlaps the lower part of the Cambrian. Average thickness of the St. Peter approximately 45'.

Figure 23. Thickness of the Cambro-Ordovician Aquifer (St. Lawrence through St. Peter formations) in southwestern Iowa. This interval significantly thins in parts of Fremont and Mills counties where the St. Peter overlies Cambrian strata.

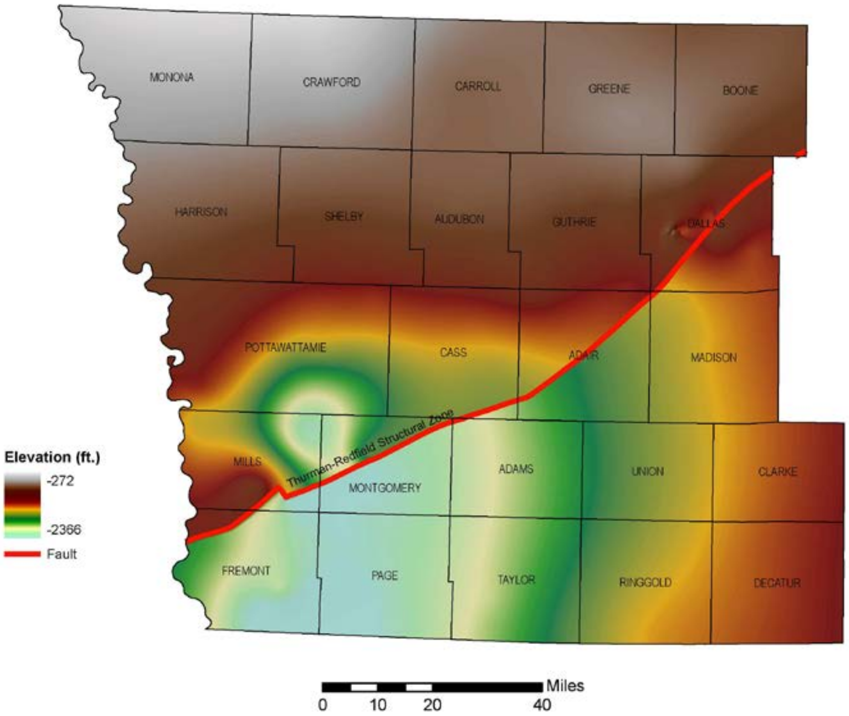


Figure 24. Elevation at the top of the St. Peter Sandstone in southwestern Iowa. This surface marks the top of the Cambro-Ordovician Aquifer.

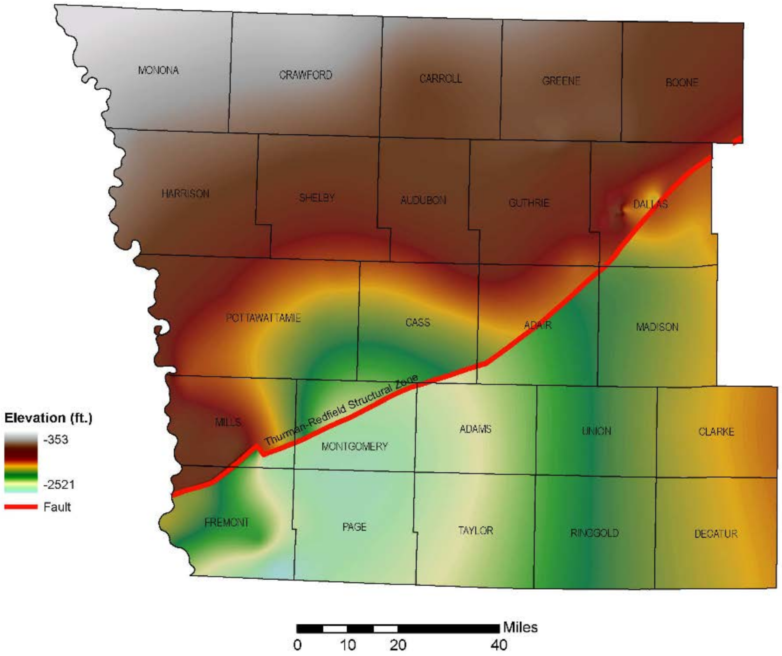


Figure 25. Elevation at the top of the Jordan Sandstone in southwestern Iowa. The Jordan occupies the lower part of the Cambro-Ordovician Aquifer.

Matrix porosity and permeability measurements are available for core samples taken from gas storage structures in Dallas and Webster counties. The contained sandstone units all show similar porosities and permeabilities: St. Peter (15.4-33.2% porosity, average 21%; 10-5,400 mD, averaging about 1,300 mD), New Richmond (20.1-23.7 %; 1350-1470 mD), Jordan (14.4-28.4%; 32-5620 mD). Data are more limited for the Prairie du Chien carbonate lithologies but available information shows highly variable matrix porosities (6.4-19.4%) and permeabilities (<0.1-2,310 mD). The fractured carbonate strata would be expected to show overall higher unit permeabilities. No information is available for carbonate strata of the St. Lawrence Formation. Total calculated results based upon a 2,700 foot depth of burial indicates a potential of approximately 23.7 billion tons of CO_2 storage capacity within the Cambro-Ordovician Aquifer of southwestern Iowa.

Cambrian Aquifers and Confining Beds

The lowest portion of the Paleozoic succession in the study area includes several Cambrian stratigraphic units that show complex lithofacies variations across the study area. Only the basal Mt. Simon Sandstone is lithologically similar across the area. Because there are fewer well penetrations through the Cambrian strata than any other portion of the Paleozoic section (since they are the deepest), these units also remain the most poorly understood in the area. Available stratigraphic and lithologic information is summarized in Figure 22. The "Franconian" interval has been given several formational names in the area, although the carbonate-dominated Davis Formation is the most widespread. Davis strata are characterized by dolomite and silty dolomite lithologies, in part highly glauconitic. Davis carbonate strata are replaced by glauconitic siltstone and fine sandstone facies, in part interstratified with shale to the north and east, where the interval is termed the Lone Rock Formation. Shaley strata of the Lone Rock Formation are known to form a relatively impermeable aquitard interval in Dallas County (gas storage structures), but the equivalent carbonate-dominated Davis Formation to the west lacks shaley units and conceivably may be part of a carbonate aquifer system that is conjoined with the overlying Cambro-Ordovician Aquifer. However, lacking any information on aquifer properties in the western area, the Davis and Lone Rock Formations are both tentatively considered to belong to the upper part of the Cambrian confining interval (Fig. 22).

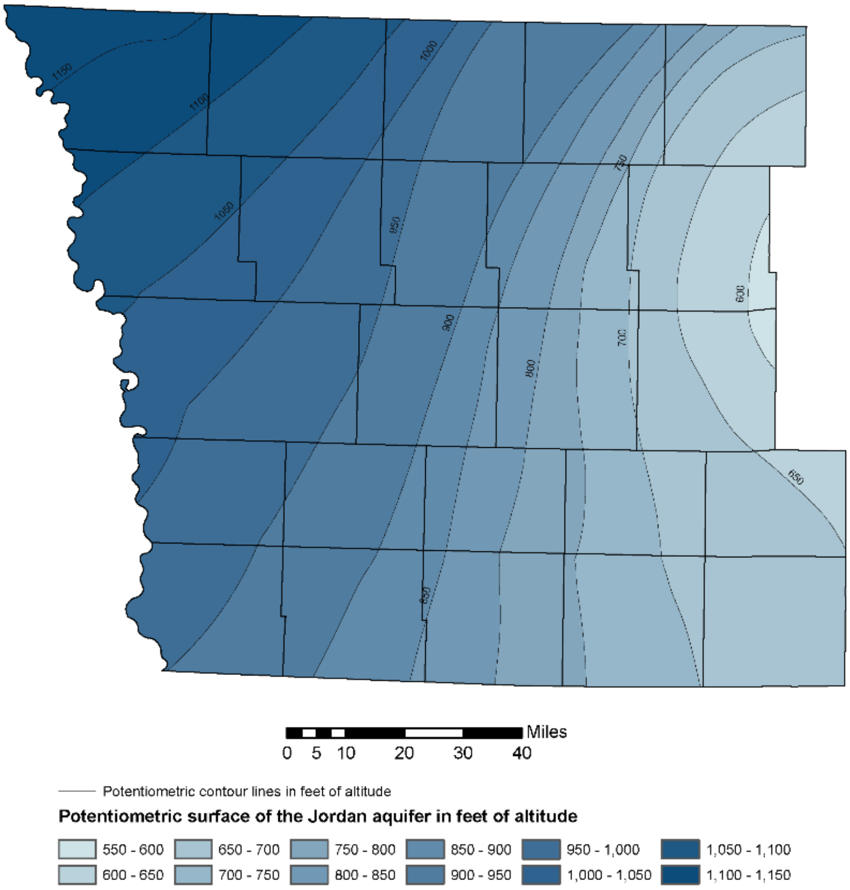


Figure 26. Map showing the distribution of TDS (mg/L) in waters from the Cambro-Ordovician (Jordan) Aquifer in southwestern Iowa. Data are insufficient in the southern map area.

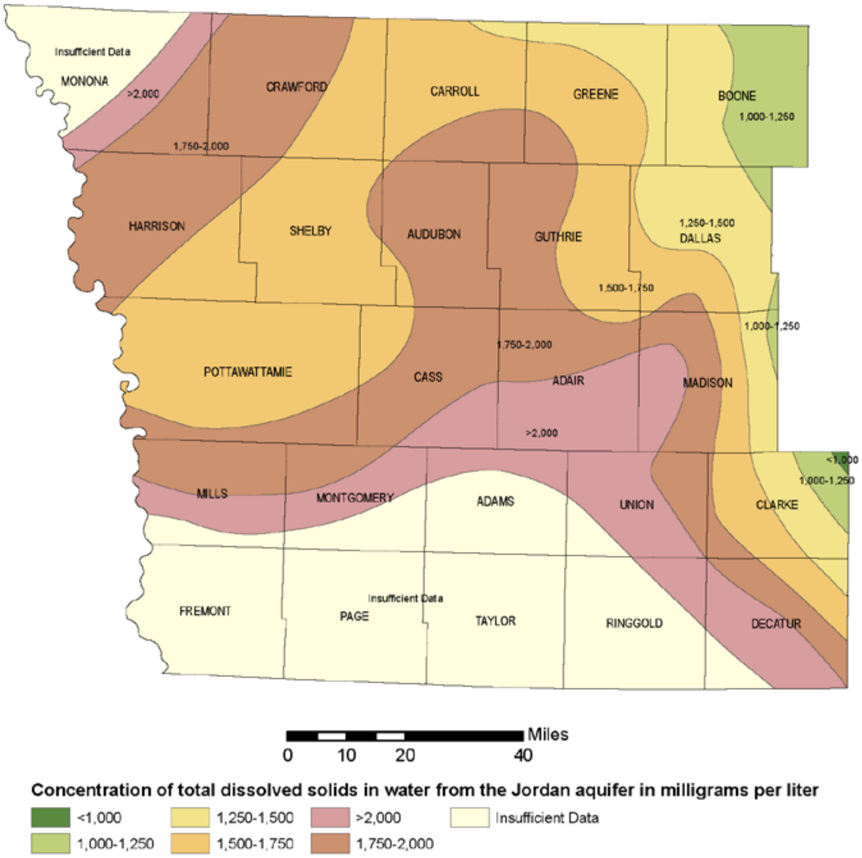


Figure 27. Potentiometric surface (ft of altitude) of the Cambro-Ordovician (Jordan) Aquifer in southwestern Iowa.

The basal part of the “Franconian” interval in the northeastern corner of the study area includes the distal (southwestern) edge of the Wonewoc Sandstone (Fig. 22). The Wonewoc is a sandstone aquifer in eastern Iowa and the Upper Mississippi Valley, and this sandstone remains part of a productive aquifer into the northeastern part of the study area (including gas storage structures in Dallas County). However, the Wonewoc Sandstone is not recognized across most of the study area, where it is apparently replaced by dolomite strata.

The underlying Bonneterre Formation is dominated by dolomite, commonly argillaceous to shaley and, in-part, glauconitic. Shale and siltstone content generally increases to the northeast in the study area, especially in the upper part, and limestone is also present in that area. The Bonneterre Formation is laterally equivalent to the Eau Claire Formation of the Upper Mississippi Valley, which is dominated by fine sandstone. The shaley character of the Bonneterre identifies it as an aquitard, and it forms a caprock for the lower gas storage reservoirs in Dallas and Webster counties. However, the lower part of the Bonneterre in the northeastern study area includes a porous glauconitic sandstone interval (probably a southwestern tongue of Eau Claire sandstone). This interval is part of the lower gas storage reservoir in Dallas and Webster counties that is separated from underlying Mt. Simon Sandstone by a thin, shaley, dolomite zone. This interval has been termed the “lower Eau Claire storage zone” in these gas storage structures.

The Mt. Simon Sandstone, a major sandstone aquifer of regional extent, forms the basal Cambrian interval across most of the study area. It directly overlies an eroded Precambrian surface, variably overlying crystalline basement lithologies (igneous and metamorphic rocks including Keweenawan volcanic rocks) or Proterozoic sedimentary rocks (Keweenawan "red clastics" of the Midcontinent Rift System). The Mt. Simon is a primary storage interval in the gas storage structures of Iowa. The Mt. Simon aquifer may be conjoined in parts of the study area with groundwater systems in the underlying Keweenawan "red clastics."

Interpreted thicknesses of sub-St. Lawrence Cambrian strata (the interval below the Cambro-Ordovician Aquifer) show significant variations across the study area (Fig. 28). These variations likely result from three factors: 1) progressive Cambrian onlap of Precambrian paleotopographic/structural highs, especially the "Central Iowa Arch" (northwestern Adair, western Guthrie, and Green counties) and the "Southeast Nebraska Arch" (noted by the westward thinning of Cambrian units in Fremont Co.). Sub-St. Lawrence Cambrian strata are completely absent along the crest of the Central Iowa Arch (Fig. 28); 2) westward depositional thinning of Cambrian formations; 3) Cambrian down-dropping south of the TRFZ leading to increased thicknesses in that area. Subsequent Paleozoic displacements along the TRFZ likely have disrupted regional continuity of the Mt. Simon Aquifer and overlying Cambrian strata, separating groundwater systems to the north and south. These discontinuities are evident on the elevation of the Precambrian surface (Fig. 29).

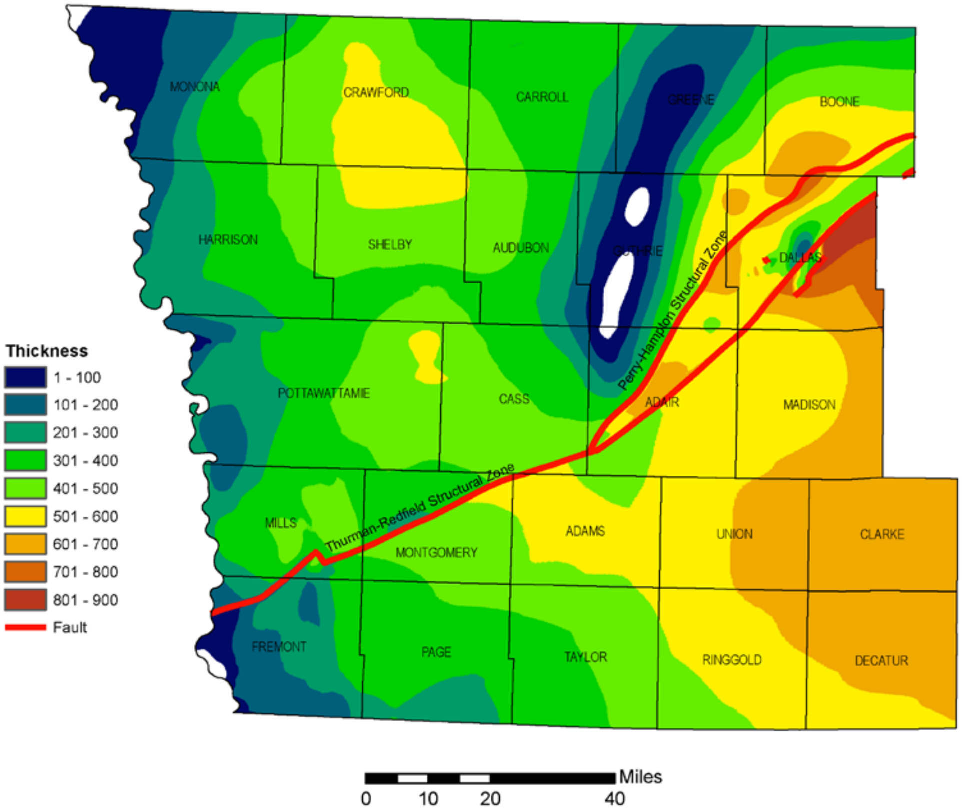


Figure 28. Interpreted thickness (in ft) of the Cambrian succession below the St. Lawrence Formation in southwestern Iowa.

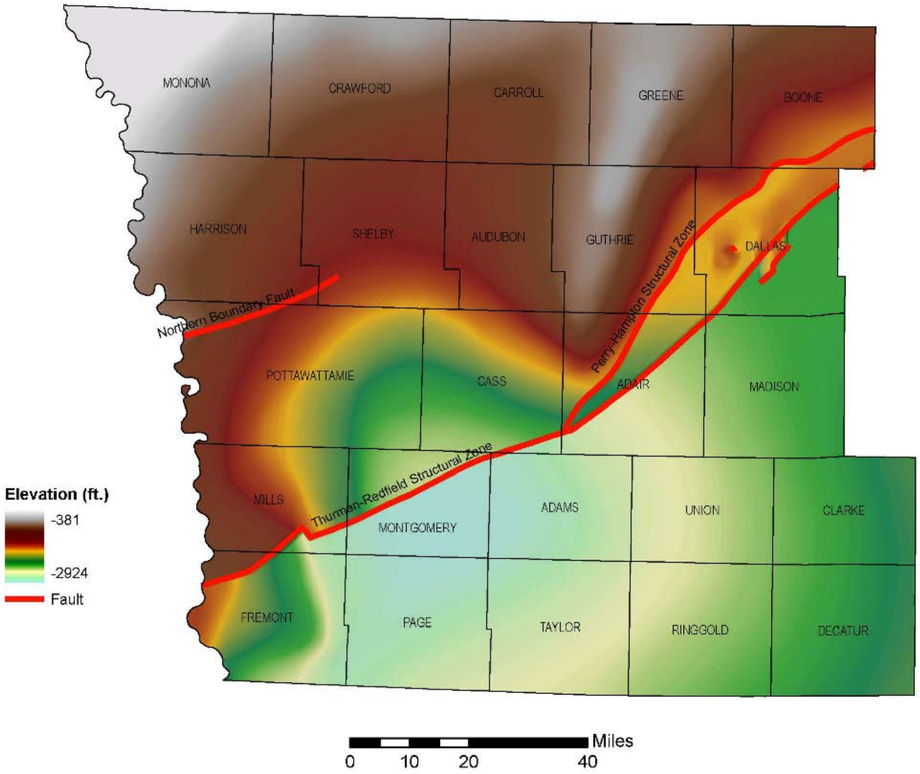


Figure 29. Elevation of Precambrian (basement) surface in southwestern Iowa. Interpreted basement faults are displayed.

Matrix porosity and permeability data are available for core samples from the sub-St. Lawrence Cambrian succession in the gas storage structures of Dallas and Webster counties, as summarized here:

1) Lone Rock Formation: 3.3-8.9% porosity; permeabilities <0.1-4.3 mD; “excellent caprock” 2) Wonewoc Sandstone: 16.5-26.5%; 0.3-1033 mD.
2) Bonneterre Formation (highly variable porosities 1.8-30%; variable permeabilities mostly very low, <0.1-75.4 mD; “excellent caprock”).
3) Basal Bonneterre/Eau Claire sandstone: 6.2-21.3%; mostly “good permeability” but variable <0.1-3133 mD; “storage zone.”
4) Mt. Simon Sandstone: 11-38%; 26-1459 mD, some “low permeability lenses <0.1-5.6 mD; “storage zone.”

There is some available water quality information for the Cambrian aquifers, primarily from the Redfield gas storage structure in Dallas County. A single sample from the Wonewoc Sandstone in this structure noted 2,249 mg/L TDS. The basal Eau Claire sandstone unit yielded two values of 1,761 and 2,022 mg/L TDS. Files from the Vincent structure in Webster County (north of the study area) recorded water from this interval with 4,122 mg/L TDS. A number of water samples from the Mt. Simon Aquifer in the Redfield structure have recorded values of 1,588 to 1,782 mg/L TDS. However, one Mt. Simon sample from the Dallas Center structure of Dallas County was recorded as 8,320 mg/L TDS. An additional sample from the Mt. Simon Aquifer from the Ogden town well in Boone County was noted at 1,510 mg/L TDS. Since dissolved solids generally increase southwestward in all Paleozoic aquifers, the Mt. Simon Aquifer is considered to be slightly too moderately saline across the entire study area. A water sample taken from Precambrian “red clastics” in Page County, an interval that likely is in hydrologic connection with the Mt. Simon, is reported at 8,480 mg/L TDS, whereas “red clastics” waters from the Redfield structure vary between 1,709 and 1,917 mg/L (similar to values noted in the overlying Mt. Simon Aquifer).

Conclusions

Carbon sequestration within saline aquifers is considered a possibility for several Paleozoic aquifer systems in southwestern Iowa. Only those aquifers that occur at burial depths in excess of 2,700 ft (820 m) are considered potentially viable for storage, which excludes Pennsylvanian, Mississippian, and most of the Devonian aquifers from further consideration in southwestern Iowa. However, several aquifers cover at least part of the study area at appropriate depths, including the basal Cedar Valley, Silurian, Galena-Maquoketa, Cambro-Ordovician, and Mt. Simon aquifer systems. Of these, the Cambro-Ordovician and Mt. Simon aquifers provide the best targets for further investigation. These two aquifers both contain intervals of high porosity (>20-25%) and high permeabilities (>500-1,000 mD), and both are bounded by effective confining beds. Because these two aquifers are in the deeper part of the stratigraphic section, they also have the widest geographic distribution at appropriate depths. These depths are achieved for the Cambro-Ordovician Aquifer over much of the southern half of the study area, and for the Mt. Simon Aquifer over an even broader region that covers greater than three-quarters of the study area (see Fig. 5). Of note, water quality is saline and non-potable throughout these areas (>1,500 mg/L, probably much higher in the southern area).

Further investigations of the Paleozoic bedrock aquifers are needed to fully characterize the groundwater systems and aquifer properties. Nevertheless, there is sufficient data available to provide basic information on porosities and matrix permeabilities of individual aquifers as well as the three-dimensional distribution and stratigraphic container for each major aquifer system.

PENNSYLVANIAN STRATA OF SOUTHWESTERN IOWA: POTENTIAL FOR COAL BED CARBON SEQUESTRATION

Virtually the entire 24-county study area of southwestern Iowa is underlain by coal-bearing Pennsylvanian strata at relatively shallow depths. There are numerous surface exposures of Pennsylvanian strata in the study area, and the maximum depth to the base of Pennsylvanian section is noted in the far southwestern study area of southern Page and Fremont counties (>1,900 ft; 580 m). Therefore, the depth of burial of Pennsylvanian strata varies between 0 and about 1,900 ft (580 m). The study area has included historic coal mining activity, especially in the early 20th century, but at present there are no operating coal mines in Iowa. In addition, there have been no attempts to evaluate or develop coal bed methane in the area. The Pennsylvanian stratigraphic section in Iowa comprises a succession of "cyclothems," which are cyclic depositional units that record the frequent rise and fall of sea level during the Pennsylvanian. The basal unit of many cyclothems includes coal beds of varying thickness, generally capped by marine deposits (limestone and/or shale). A stratigraphic summary of known coal beds in Iowa is shown in Figure 30.

Most historic coal-mining activity in Iowa had concentrated on several beds within the Middle Pennsylvanian Cherokee Group (Fig. 30), which contains eight or more widely traceable and potentially mineable coal beds. Some Cherokee coals locally exceed 5 ft (1.5 m) in thickness, primarily the Black Oak and Cliffland coals (Fig. 30). However, additional widespread coals in overlying Pennsylvanian strata, some of which have been mined, are generally thinner and most are not known to exceed 1 to 2 ft (30-60 cm) in thickness. Based on a regional evaluation of coal resources across southwestern and south-central Iowa undertaken for this report, a map displaying a conservative estimate of cumulative coal thicknesses was compiled based largely on the distribution of coal-bearing stratigraphic units across the study area (Fig. 31). Only those coals that average about 12 inches (30 cm) or more in thickness were used for this compilation. Because many coal units are concentrated in relatively thin stratigraphic intervals within the Cherokee Group, an irregular contour interval was used for those intervals in compiling the cumulative coal thickness map (Fig. 31). Coal-bearing stratigraphic intervals and their contained coal beds are summarized below.

The lower Cherokee Group (strata below the Whitebreast Coal) contains the best development of coal beds greater than 12 inches (30 cm) in thickness, primarily the Black Oak, Cliffland, Laddsdale, and Carruthers coals (Fig. 30). The first three of these coal units are locally split into two or more individual coal beds. This interval is assigned a cumulative coal thickness of 4 ft (1.2 m), although in many sections this value would be expected to be considerably greater, especially when the many additional thinner coals are included. Lower Cherokee Group strata are found throughout the study, except in two areas: 1) few small Mississippian windows in the northern study area (Fig. 31); and 2) a sizeable portion of Mills County north of the TRFZ where the Cherokee Group is greatly thinned (probably a broad Pennsylvanian uplift in that area). Cherokee strata are also greatly thinned to absent along the crest of the nearby Nemaha Uplift immediately west of the study area in eastern Nebraska. Lower Cherokee strata vary significantly in thickness in the study area, generally averaging about 400 ft (120 m) but reaching greater thicknesses (to about 600 ft, 180 m) southwestward into the deeper parts of the Forest City Basin.

The upper Cherokee Group includes three widespread coal horizons (Whitebreast, Wheeler, and Bevier) each averaging about 12 inches (30 cm) in thickness. The cumulative thickness of coal in this interval is conservatively estimated to be 2 ft (60 cm). The overlying Middle Pennsylvanian Marmaton Group is subdivided for the cumulative coal map (Fig. 31) into two coal-bearing intervals: the lower Marmaton (which includes the closely-spaced Mystic and Marshall coals) and upper Marmaton (including the Mulberry coal; Fig. 30). Additional thinner coals occur within the interval, and the Mulky coal (at the Cherokee-Marmaton contact) and Imes coal locally reach thicknesses to 6 inches (15 cm) or more. Cumulative coal thicknesses for both the upper and lower Marmaton are each conservatively estimated at 1 foot (30 cm). The Mystic Coal is known to locally reach thicknesses to 34 inches (86 cm), and the Mulberry Coal to 21 inches (53 cm).

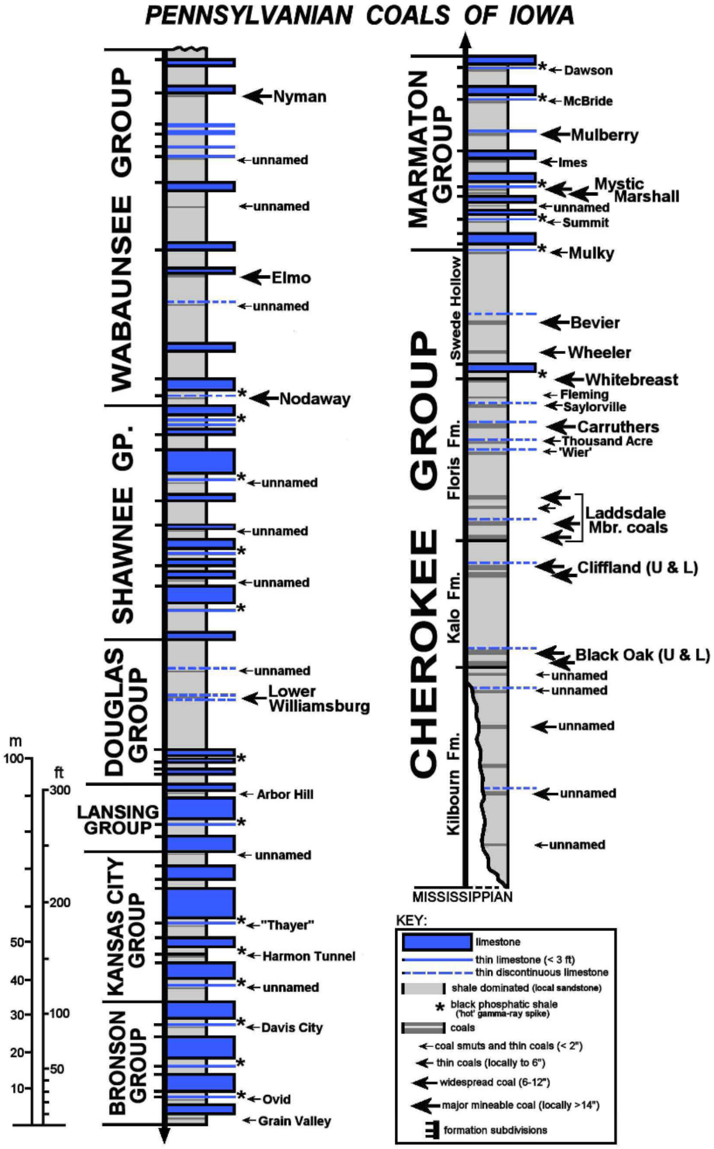


Figure 30. Stratigraphic distribution of coal units in the Pennsylvanian succession of Iowa. Named and unnamed coals are labeled, and the position of limestone units within the succession are shown in blue. Variations in coal thicknesses are largely derived from unpublished records at the IGS. Scaled to reflect average thicknesses of stratigraphic units in southwestern Iowa.

The limestone-dominated Upper Pennsylvanian (Missourian) succession of the Bronson, Kansas City, and Lansing groups (Fig. 30) contains a number of coals, but none of these are known to exceed 2 inches (5 cm) in thickness and, therefore, are excluded from the cumulative coal thickness map. Likewise, the Upper Pennsylvanian (Virgilian) succession of the Douglas, Shawnee, and Wabaunsee groups contains a number of thin coal units (Fig. 30), although several widespread and mineable coal units are recognized within the Virgilian interval each averaging about 12 inches (30 cm) in thickness. The Lower Williamsburg Coal (6-16 inches; 15-41 cm) in the middle Douglas Group is added to the cumulative coal thickness map (Fig. 31), as are the lower Wabaunsee Nodaway (9-24 inches; 23-61 cm) and Elmo (9-12 inches; 23-30 cm) coals and the upper Wabaunsee Nyman coal (6-18 inches; 15-46 cm). The greatest cumulative coal thickness in the study area is interpreted to occur where upper Wabaunsee strata are identified, estimated at 11 ft (3.4 m) (Fig. 31). This value is considered to be conservative, with actual cumulative coal thicknesses likely higher (perhaps locally by as much as 50%).

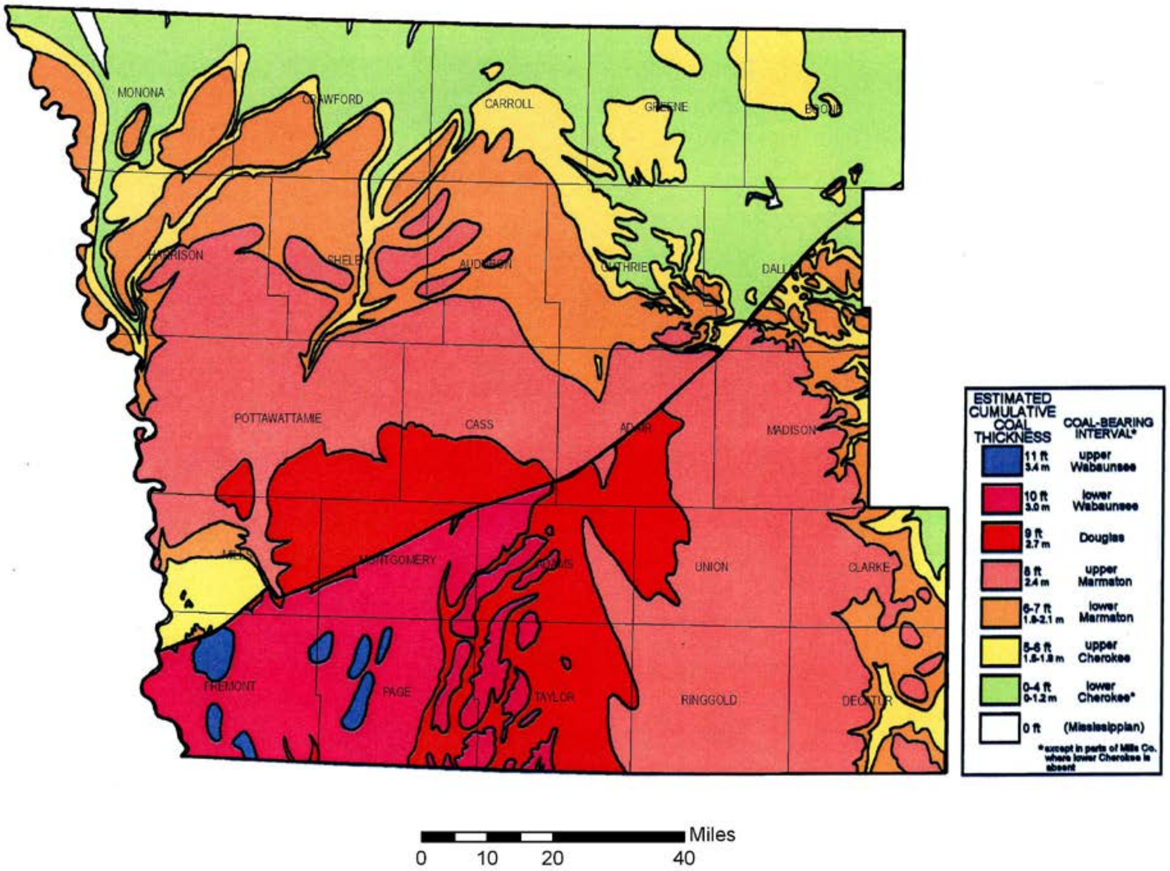


Figure 31. Estimated cumulative thicknesses of mineable coal beds in southwestern Iowa. Only widespread coal beds with thickness of 12 inches (30 cm) or more were used in this compilation (see Figure 27). Numerous thinner coal beds were not included. Estimates are considered to be conservative, and total coal thicknesses are probably greater than shown for many areas.

The Cherokee Group buries a major regional unconformity surface developed on Mississippian carbonate strata, with about 300 ft (90 m) of erosional relief identified across this surface in the southwest Iowa study area. Because the Cherokee Group is dominated by relatively impermeable shale and mudstone strata, this interval serves as the upper confining beds for the underlying Mississippian bedrock aquifers across most of the study area. However, locally the Cherokee Group includes significant thicknesses of porous and permeable sandstone (mostly as elongate channel-sandstone bodies) at several stratigraphic positions, and these units undoubtedly contain sandstone aquifers (some of which have been locally used for water supply in the study area). In addition, porous and permeable sandstone units are also known to occur in the study area within the Marmaton, Douglas, and Wabaunsee groups, and some of these have also been utilized for local (farm) water supply. Some of the thicker limestone units in the Kansas City and Shawnee groups have also been developed for local water supplies. The most widespread (but still discontinuous) Cherokee sandstone interval is identified at the base of the Cherokee Group; it is generally less than 50 ft (15 m) thick, but is known to reach thicknesses to 340 ft (104 m) in southern Fremont County. Where present, the basal Cherokee sandstone interval would be expected to be in direct hydrologic connection with the underlying Mississippian aquifer. There is little information on water quality, hydrostatic head, or porosity/permeability for any of the discontinuous (and marginally utilized) Pennsylvanian sandstone aquifers in southwest Iowa. Available data indicates highly variable water quality within the Pennsylvanian aquifers: 295-2,330 mg/L TDS in the northeast (Guthrie, Green, and Dallas counties), 532-1,600 mg/L TDS to the northwest (Monona Co.), 1,940-2,070 mg/L east-central (Madison Co.), and 675-4,010 mg/L TDS in the southern counties (Clarke, Page, and Decatur counties).

Summary Statement. A number of widespread and historically mined bituminous coal beds (from 1 to 14 coal units) are known to occur in Pennsylvanian strata across virtually all of the southwestern Iowa study area (Fig. 30). These coal beds average about 12 inches (30 cm) in thickness, but locally achieve greater thicknesses (in some cases exceeding 5 ft thick). The distribution of coal-bearing strata was used to conservatively estimate cumulative coal thicknesses of 0 to 11 ft (3.4 m) across the study area (Fig. 31). However, the exact thickness and number of coal beds would need to be evaluated on a site specific basis for future study of possible carbon sequestration potential. Numerous thinner coal beds are also recognized in the area, varying between about 0 and 6 inches (15 cm) thick, but because of the unlikelihood of being used for potential carbon sequestration, were excluded from the cumulative thickness estimates in this report. The potential for coalbed methane and carbon sequestration within the study area has not yet been adequately evaluated, but because the area contains significant thicknesses of coal, further study may be warranted. All coal beds in the study area occur at depths of less than 1,900 ft (580 m), most at considerably shallower depths.

SUITABILITY OF MIDCONTINENT RIFT SYSTEM CLASTIC ROCKS IN IOWA FOR THE SEQUESTRATION OF CO_2

The MRS in Iowa

The Midcontinent Rift System (MRS) of North America (Fig. 32) is a failed rift that formed in response to region-wide stresses associated with the Grenville Orogeny about 1,100 million years ago. In Iowa, the MRS is buried by thick sequences of Paleozoic and Mesozoic sedimentary rocks and Quaternary glaciogenic deposits, ranging in thickness from about 1,700 ft near the Minnesota border to in excess of 5,000 ft in southwest Iowa.

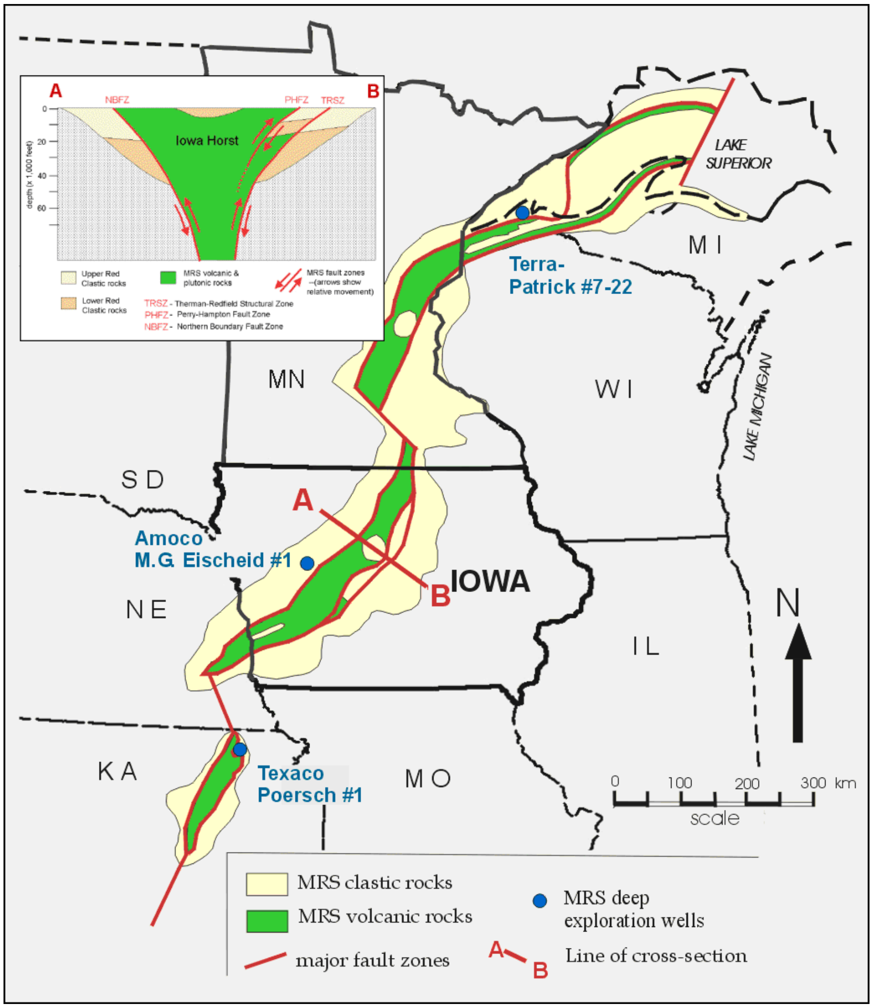


Figure 32. Location map of the MRS showing major lithologic packages, the locations of major petroleum industry exploration wells, and a generalized cross-section of the feature.

The presence of the MRS in Iowa was first identified by Lyons (1950) who described a linear gravity anomaly extending from the Lake Superior area southward across Iowa, southeastern Nebraska, and into central Kansas. He called the geophysical feature the Greenleaf anomaly, but the anomaly's name soon evolved to the Midcontinent Gravity Anomaly, and finally to the Midcontinent Geophysical Anomaly.

Since its origin as a failed rift system was identified, the physical feature that produces the anomaly has been known as the Midcontinent Rift (Black, 1955), the Central North American Rift System (Ocola and Meyer, 1973), the Keweenawan Aulacogen (Milanovsky, 1981), the Mid-Continent Rift System (Chandler et al., 1989), and its most widely-used name, the Midcontinent Rift System (Wold and Hinze, 1982). Building on a large body of work on the MRS in its Lake Superior exposure area (summarized by Wold and Hinze, 1982), and early studies of the feature in Iowa (e.g., Coons, 1966; Cohen, 1966; Fischer, 1982), Anderson (1992) produced the most comprehensive description of the MRS in Iowa.

The structural configuration, nature of the major lithologic packages, and geologic history of the MRS in Iowa was interpreted by examination of the limited number of well samples of MRS rocks in the state, visual interpretation of gravity (Fig. 33a) and magnetic (Fig. 33b) anomaly maps, and interpretation of six petroleum industry seismic reflection profiles (Fig. 34) over the MRS. These interpretations were used as controls for modeling a series of 2-dimensional gravity profiles across the MRS, including profiles coincident with the seismic profiles. Interpretations from these models were used to construct 3-dimensional models of each unit and structural packages within the MRS of Iowa (Fig. 35). Model lithologies, densities, and general structural configurations were constrained by examination and sampling of MRS rocks exposed in the Lake Superior region, and the examination of core and cutting samples of MRS rocks from every state along the trend of the structure. These interpretations were compared and contrasted with previous investigations of the MRS in Iowa and from the Lake Superior region where MRS rocks are exposed.

These models reveal the MRS in Iowa to be characterized by a central horst (the Iowa Horst), dominated by mafic volcanic rocks, and thrust over younger clastic rocks in flanking sedimentary basins. At upper crustal depths, the MRS displays a relatively symmetrical structure, unlike the half-graben structural configurations that characterize interpretations of the MRS in the Lake Superior area (e.g. Chandler et al., 1989) and many modern rifts. Sedimentary basins on both flanks of the central horst are similar in depth and configuration, and the volcanic rocks that comprise the Iowa Horst are generally sub-horizontal. The lavas flows associated with the early stages of the development of the Iowa segment of the MRS were apparently mostly contained within a slowly-subsiding rift-axial graben (Anderson, 1992). In a later stage of MRS evolution the central graben was forced upward, reversing the displacements along the graben bounding fault zones, producing the Iowa Horst. The clastic rocks filling the deep horst-flanking basins are apparently dominated by two major depositional sequences; 1) the Lower Red Clastic Series, deposited shortly after the cessation of rift volcanism, and 2) the Upper Red Clastic Series, deposited during and shortly after the uplift of the Iowa Horst. These clastic sequences correspond respectively to the Oronto Group and Bayfield Group of Michigan (Fig. 36)

In its final configuration (Fig. 37) the rift-axial Iowa Horst of the MRS in Iowa is flanked on the east and west by a series of connected clastic rock-filled basins. The western flanking basins include the Wellsburg (north) and Defiance (south) basins, and to the east the Wellsburg (north), Ankeny (central), and Shenandoah (south) basins flank the horst. In addition, three smaller clastic rock-filled basins are preserved on the Iowa Horst. The elliptical Stratford Basin lies on the horst axis near the center of Iowa. Modeling suggests this basin is filled with Lower Red Clastic Series rocks. The Jewell Basin is connected on the west to the Stratford Basin and bounded on the east by the Perry-Hampton Fault Zone (PHFZ). Gravity modeling demonstrates this basin is also filled with Lower Red Clastic Series rocks. Near the southern end of the Iowa Horst, at the Nebraska border, lies the Mineola Basin. This basin appears to be the product of late graben activity and models suggest it is filled with Upper Red Clastic Series rocks. One other area of the MRS where clastic rocks are preserved on the Iowa Horst is the Ames Block. The Ames Block is a sliver of the Iowa Horst that sheared from the main body of the horst as it was being uplifted. Centrally located along the eastern edge of the Iowa Horst, modeling indicates both Lower and Upper Red Clastic Series rocks are structurally preserved on the Ames Block.

The MRS is of interest as a possible repository for sequestered CO_2 because of its exceedingly thick sequences of clastic sedimentary rocks (sandstones, siltstones, and shales) and depth of burial. MRS clastic rocks underlie over 16,000 square mi of Iowa (about 28% of the state), with the vast majority of these rocks lying below the 2,700 foot optimal sequestration depth.

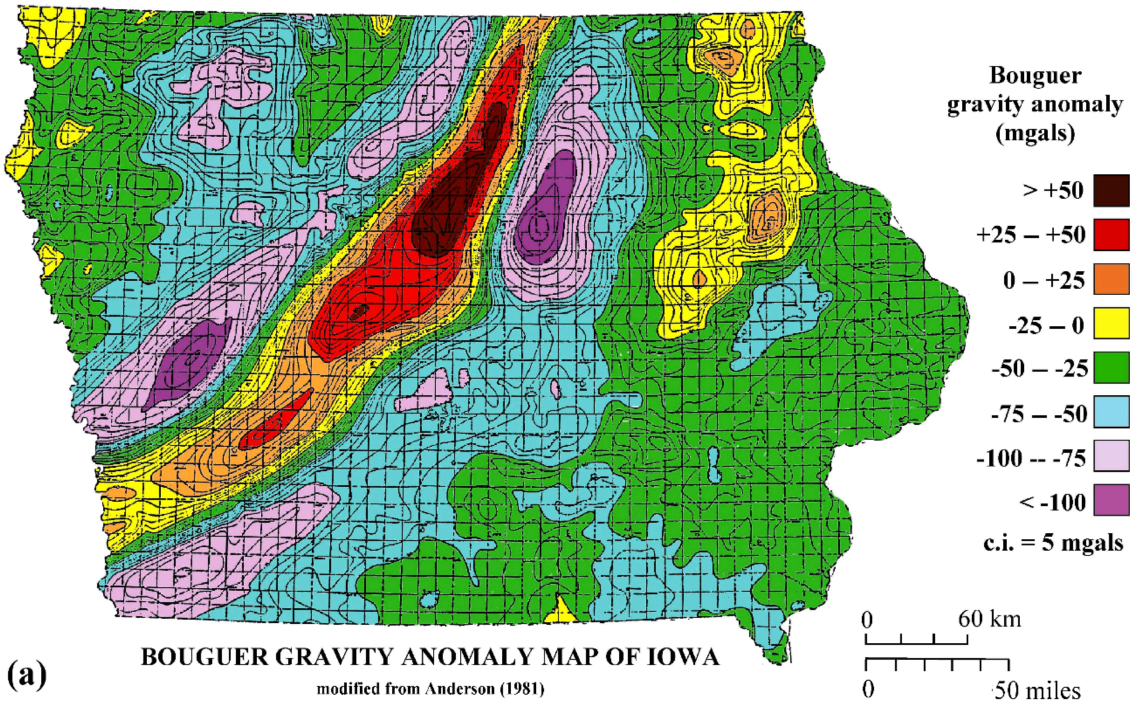
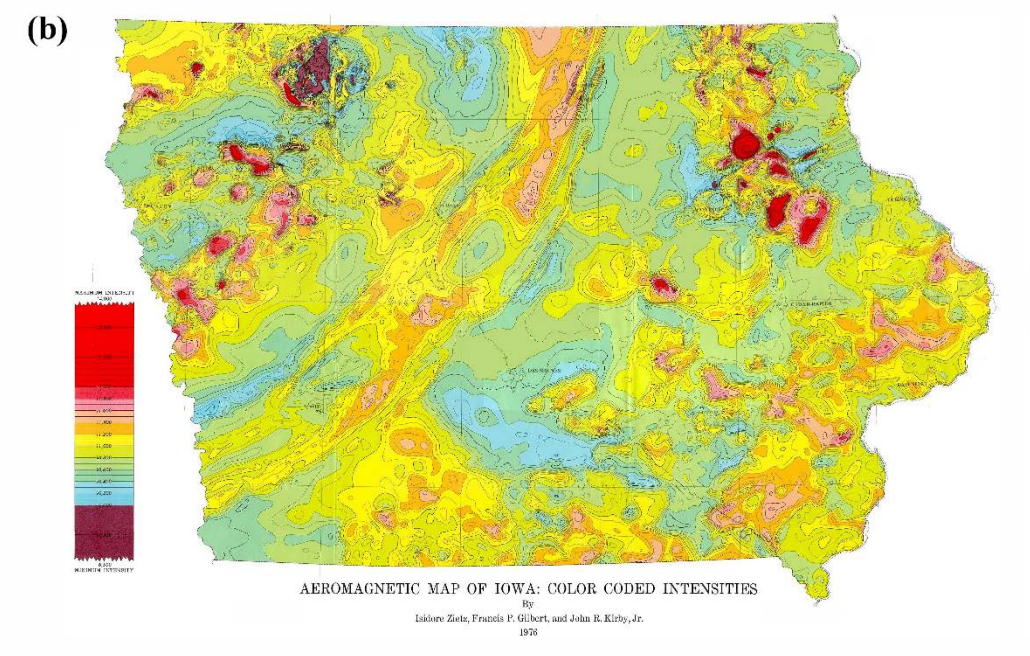


Figure 33. (a) Gravity (modified from Anderson, 1981) and (b) aeromagnetic anomaly maps of Iowa showing the MRS as a prominent northeast-trending feature across the state.



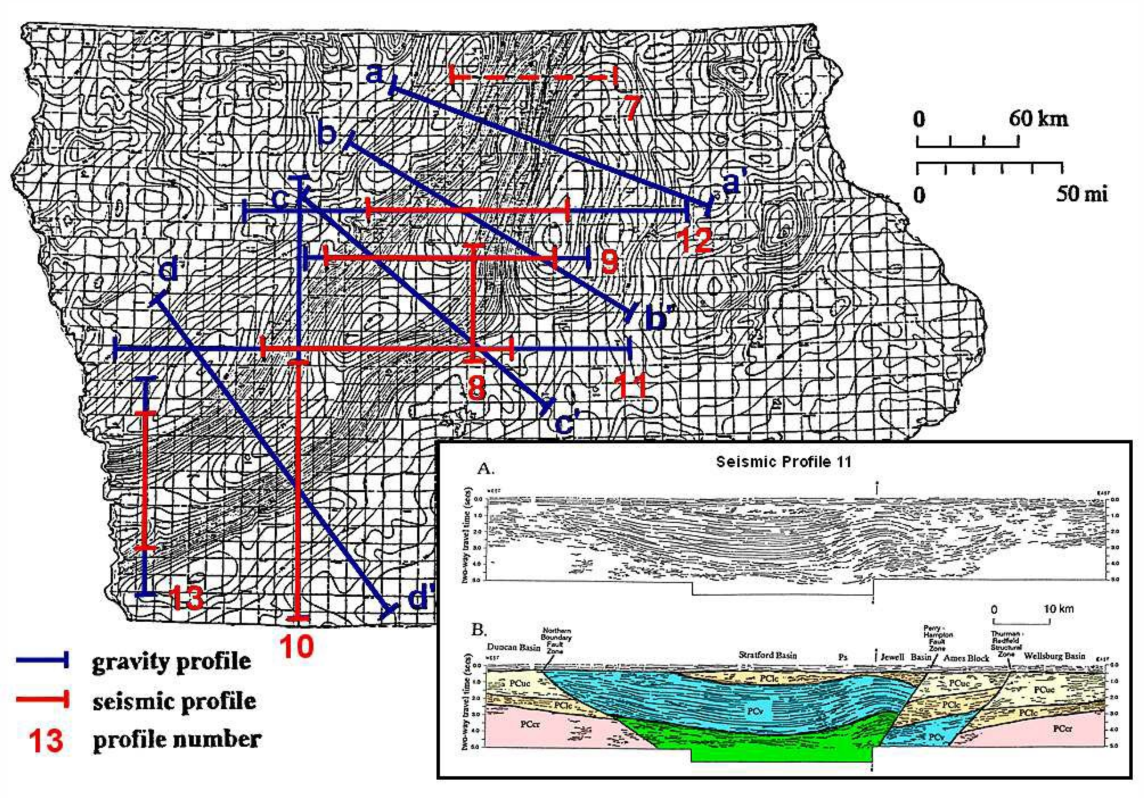
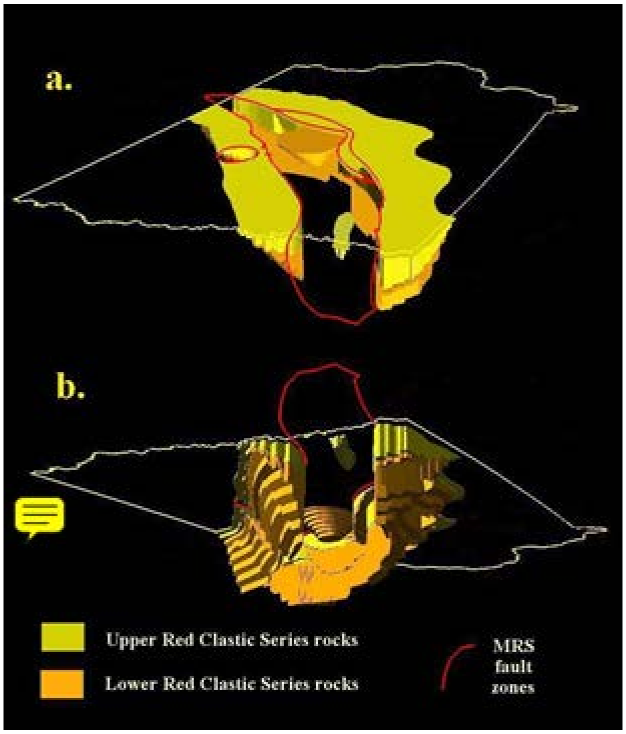


Figure 34. Bouguer gravity anomaly map of Iowa displaying petroleum industry seismic lines (red) and gravity model profiles (Anderson, 1992). Inset shows uninterpreted (a) and interpreted (b) stick drawings of seismic reflectors from Profile 11 (Anderson, 1992).

Figure 35. 3-D model of the clastic rocks of the MRS in Iowa, viewed from southwest of Iowa looking in a northeasterly direction. Image (a) views the clastic rocks from above looking downward, and (b) views the rocks from below looking upward.



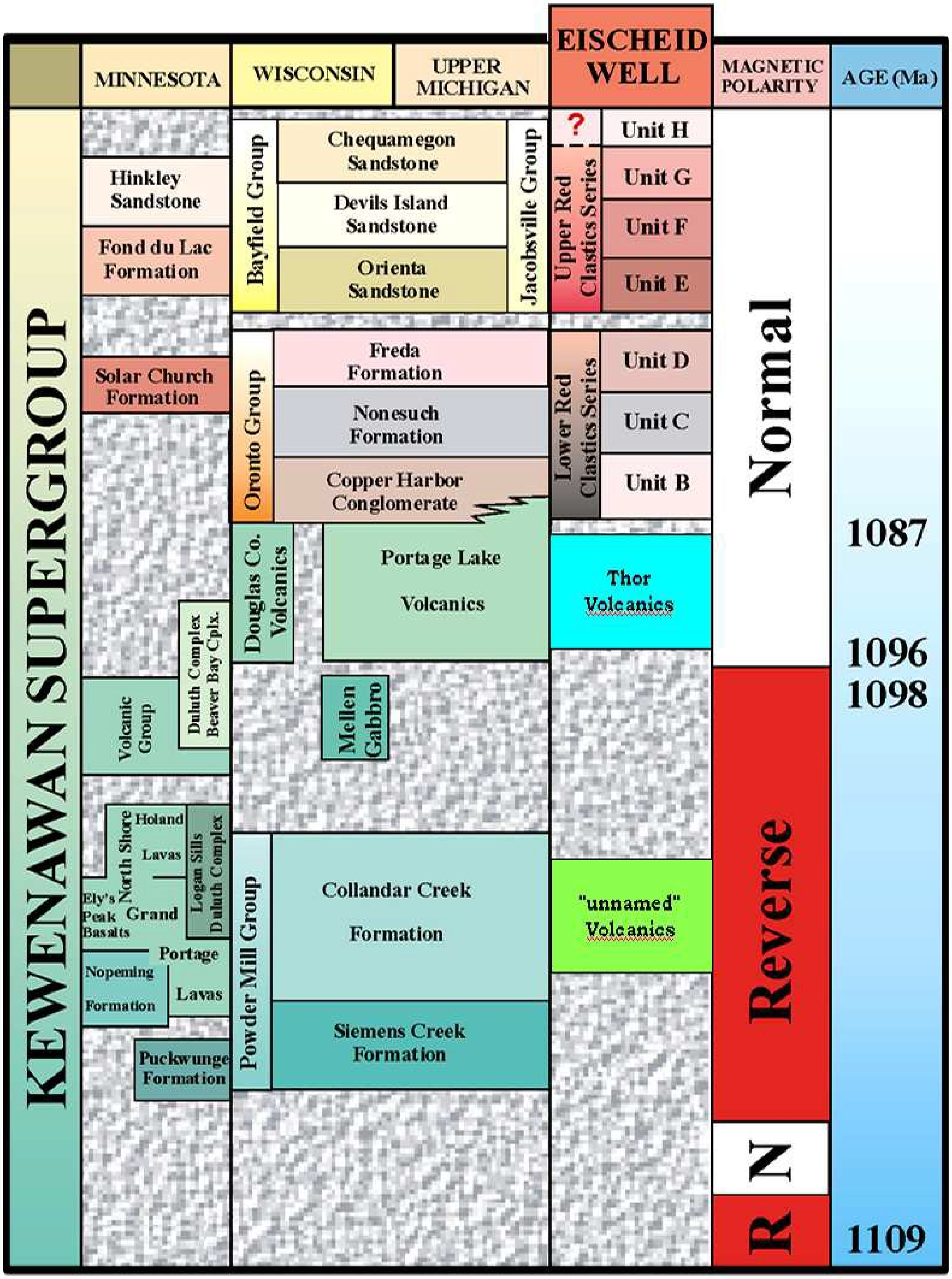


Figure 36. Comparative stratigraphy of the MRS in Iowa as observed in the M.G. Eischeid #1 well and unit names in areas of exposure around Lake Superior.

Goals of This Study

There are three principal goals of this investigation of the MRS in Iowa as a potential repository for sequestered CO_2.

1. **Compile all available information related to the suitability of MRS clastic rocks in Iowa for sequestering CO_2:**

   All available information on the physical properties of MRS clastic rocks in Iowa relating to their suitability for sequestering CO_2 was investigated and tabulated. This limited information included data from the drilling of several oil exploration wells, especially the Amoco M.G. Eischeid deep petroleum test, information from subsurface natural gas storage structures (where gas is stored in lower Paleozoic strata just above MRS rocks), tests on several deep cores, and parameters used in gravity modeling projects.
2. **Revise interpretations of the location of major Iowa Horst bounding fault zones:**

   Anderson (1992) identified the general locations of the two major faults that bound the Iowa Horst, the TRFZ on the south and the Northern Bounding Fault Zone (NBFZ) on the north, as a part of his modeling of Bouguer gravity anomaly data over the MRS in Iowa, and a third major fault, the PHFZ, by interpretation of petroleum industry deep seismic data and 100 gamma contour interval aeromagnetic maps (Zietz et al., 1976) and data. The principal new data used in this reinterpretation was a large 20 gamma contour interval aeromagnetic map published by the U.S Geological Survey (Henderson and Vargo, 1965). This map was scanned and georeferenced for use as a GIS coverage.
3. **Review of gravity models for the geometry of the MRS clastic rock-filled basins:**

   A major goal of this investigation was to review previous gravity models of the clastic rock-filled basins associated with the MRS in Iowa. This modeling was originally accomplished over a multi-year time frame in the late 1980s and early 1990s by Anderson (1992). It was anticipated that the application of new data and interpretations would improve the earlier models.

INVESTIGATION OF THE MRS IN IOWA FOR CO_2 SEQUESTRATION

The initial phase of this study included a detailed review of well folders, oil and gas files, and technical files at the IGS for geotechnical information related to the suitability of MRS rocks in Iowa for CO_2 sequestration. Information collected during this study included locations, depths, lithologies, hydrologic information (e.g. porosity, permeability, and pump test information), logs, and related information. This information was tabulated in a series of spreadsheets (see example in Table 1).

Well penetrations of MRS rocks in Iowa

A total of 71 wells are known to penetrate into MRS clastic or igneous rocks (Table 1). These include water wells, oil exploration wells, and gas storage structure exploration and development wells. MRS igneous rocks were most frequently penetrated, with 58 wells encountering primarily basaltic rocks. Most wells penetrated less than 20 ft into basement rocks. The deepest penetration of MRS igneous rocks was by the Sharp #1 well (W-15523, IGS well identification number) in Webster County which cored 107 ft of basalt including all or parts of three basalt flows. The Olson #1 (W-17028) well in Webster County penetrated 106 ft of basalt but only chip samples were collected and, as of yet, have not been microscopically studied. MRS clastic rocks were encountered by 15 wells. Of these wells, by far the deepest penetration was by the Amoco M.G. Eischeid #1 well (W-27933) in Carroll County that completely penetrated the northern end of the Defiance Basin (chip samples and limited core), passing through 14,085 ft of the clastic rocks (as well as 813 ft of overlying Precambrian clastic rocks interpreted as younger than the MRS clastics). The Wilson #1 well (W-17) in Page County penetrated 1,605 ft of MRS clastic rocks in the Shenandoah Basin (chip samples), and the #1 Huntly well (W-14428) in Butler County penetrated 1,290 ft of the rocks in the Wellsburg Basin (chip samples). MRS clastic rocks in basins on the Iowa Horst were encountered in only 2 wells, both very shallow penetrations of the Stratford Basin. The Boone City Well #1 (W-32431) penetrated 300 ft into the Lower Red Clastic rocks in the basin while the Ogden City Well #1 (W-5) bottomed at the surface of the clastic rocks. Both wells were deep water wells, and no samples are available for either well. Of these wells only the Amoco M.G. Eischeid #1 well had significant data related to CO_2 sequestration, specifically an extensive suite of down-hole geophysical logs.

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

The Amoco M.G. Eischeid #1 well was the second of three deep petroleum test wells drilled by major petroleum exploration companies along the trend of the MRS between 1986 and 1992 (Fig. 32). Samples and information collected during the drilling of the Eischeid #1 well in Carroll County in 1987 have provided by far the best information on the Midcontinent Rift clastic rocks in Iowa. The well penetrated 14,898 ft of Precambrian clastic rocks with cutting samples collected at 10 foot intervals, but less than 50 ft of drill core was retrieved. Fortunately, Amoco provided IGS staff geologists almost unlimited access to their drilling operation, and released samples and logs to outside researchers shortly after drilling. Consequently, the IGS was able to assemble an experienced working group of scientists to analyze data, compile information, and publish a Special Report on the geologic materials encountered in the well (Anderson, 1990). A graphic log of the Eischeid well was prepared by Witzke (1990) (Fig. 38) with variations in the grain size of the clastic rocks with depth determined by Ludvigson et al. (1990) (Fig. 39).

Table 1. Wells that penetrate into MRS rocks in Iowa. Wells highlighted in green penetrate into mafic igneous rocks. The list is sorted alphabetically by county (PC-Precambrian, SEQ-Sequence, S ELEV-surface elevation, EL-elevation, PEN-penetration depth, TD-total depth).

SEQ	W#	WELL NAME	DATE	COUNTY	T	R	SEC	S ELEV	PC EL	PC PEN	TD	PC LITHOLOGY
1	20388	ADAIR, CITY OF	1968	ADAIR	77	33	4	1391	2690	30	2720	GABBRO
2	5	OGDEN, CITY OF #2	1929	BOONE	84	27	32	1095	2852	0	2852	CLASTICS
3	32431	BOONE, CITY #1	1898	BOONE	84	26	22	1140	2700	300	3OOO	CLASTICS
4	14428	#1 HUNTLEY	1963	BUTLER	90	15	15	830	2320	1275	3595	CLASTICS
5	27933	M.G.EISCHEID#1	1987	CARROLL	83	35	6	1387	2802	14898	17851	CLASTICS
6	115	MASON CITY, CITY #8	1912	CERRO GORDO	96	20	3	1098	1698	67	1765	ULTRAMAFIC
7	2971	MASON CITY, CITY #12	1947	CERRO GORDO	96	20	16	1164	1567	18	1585	DIABASE
8	26850	M.G.AUGUSTINE	1982	CRAWFORD	85	38	35	1360	2505	1355	3860	CLASTICS
10	23106	BERDIE LEHMAN #1	1971	DALLAS	79	27	18	890	2924	40	2964	CLASTICS
11	23289	RHINEHART A-1	1973	DALLAS	80	27	28	1046	3066	16	3082	CLASTICS
12	26683	PAMETICKY #1	1974	DALLAS	79	28	6	973	2911	9	2920	MAFICS
13	16522	BRODERICK #6	1958	DALLAS	79	28	7	1031	2801	12	2813	CLASTICS
14	27044	MAHER #7	1974	DALLAS	79	28	7	1029	2911	13	2924	MAFICS
15	33240	BRODERICK #12	1969	DALLAS	79	28	7	1023	2808	19	2827	MAFICS
16	27281	HILL #1	1973	DALLAS	79	28	12	1045	2906	10	2916	MAFICS
17	6903	HUMMELL #1	1954	DALLAS	79	28	18	1016	2778	11	2789	DIABASE
18	26703	HUMMELL #11	1954	DALLAS	79	28	18	1043	2906	10	2916	MAFICS
19	6579	MAHER #1	1953	DALLAS	79	29	1	1012	2913	3	2916	DIABASE
20	26565	CRASE #1	1974	DALLAS	79	29	1	1028	2865	12	2877	MAFICS
21	26580	TURNER #1	1973	DALLAS	79	29	2	1024	2952	27	2979	MAFICS
22	27279	EMMERT #1	1974	DALLAS	79	29	2	1031	2910	10	2920	MAFICS
23	27252	EMMERT #2	1974	DALLAS	79	29	2	1018	2886	14	2900	MAFICS
24	26338	FITCH #2	1974	DALLAS	79	29	11	1023	2930	59	2989	MAFICS
25	6804	WALKER #1	1954	DALLAS	79	29	11	1048	2899	1	2900	DIABASE
26	26976	KNAPP #3	1973	DALLAS	79	29	11	1047	2880	7	2887	MAFICS
27	33241	MAHER #5	1968	DALLAS	79	29	12	1033	2856	19	2875	MAFICS
28	16533	HAGERMAN #3	1968	DALLAS	79	29	12	1021	2833	5	2838	BASALT
29	21284	DAVIS #12	1967	DALLAS	79	29	12	1024	2828	22	2850	QUARTZITE
30	6686	DAVIS #1	1954	DALLAS	79	29	12	1045	2884	2	2886	DIABASE
31	16570	DAVIS #4	1957	DALLAS	79	29	12	1042	2851	5	2856	BASALT
32	6365	NELSON #1	1954	DALLAS	79	29	12	1027	2823	18	2841	DIABASE
33	26581	PITSENBARGER #17	1974	DALLAS	79	29	13	1039	2868	12	2880	MAFICS
34	26889	ELLIS #1	1973	DALLAS	79	29	14	1049	2905	0	2905	MAFICS
35	33243	HENNING #3	1969	DALLAS	79	29	14	1053	2888	7	2895	MAFICS
36	26972	JONES #1	1973	DALLAS	79	29	15	1037	2965	20	2985	MAFICS
37	27207	BURRIS #3	1974	DALLAS	79	29	15	986	2877	2	2879	MAFICS
38	26702	KEERAN #1	1973	DALLAS	79	29	22	972	2892	20	2912	MAFICS
39	21308	HILL #1	1967	DALLAS	79	29	23	1045	2906	10	2916	MAFICS
40	26336	MORRISON #1	1973	DALLAS	79	29	23	1082	2925	16	2941	MAFICS
41	33244	KIPPING #5	1968	DALLAS	79	29	24	1070	2907	8	2915	MAFICS
42	33245	KIPPING #6	1968	DALLAS	79	29	24	1080	2911	11	2922	MAFICS
43	7203	MONCELLE #1	1954	DALLAS	79	29	26	1076	2985	0	2985	DIABASE
44	26663	PITSENBARGER #16	1973	DALLAS	79	29	35	1070	2973	12	2985	MAFICS
45	26799	KARST #1	1973	DALLAS	80	28	31	984	2946	16	2962	MAFICS
9	27172	McCALLUM A-1	1972	DALLAS	79	27	5	1024	2990	20	3010	CLASTICS
46	26582	POETKER, MERLE	1982	FREMONT	67	40	16	1098	3845	80	3925	CLASTICS
47	1386	WISNOM #1		FREMONT	68	41	23	937	3278	100	3378	CLASTICS
48	27272	FINNEGAN A-1	1973	GUTHRIE	81	30	17	1117	2636	72	2708	MAFICS
49	26322	KINNEY A-1	1974	GUTHRIE	81	31	1	1102	2311	51	2362	ULTRAMAFIC
50	18670	NESSA #2	1966	HUMBOLDT	91	27	34	1143	2285	25	2310	DIABASE
51	17799	NESSA #1	1965	HUMBOLDT	91	27	34	1148	2250	0	2250	BASALT
52	27220	WOODFILL #3-19	1984	MILLS	71	40	19	1120	3787	3	3790	BASALT
53	27213	FITZGERALD #1	1984	MILLS	71	41	21	970	2600	5	2605	BASALT
54	27233	CODDINGTON #3-24	1984	MILLS	71	41	24	1150	3790	33	3823	BASALT
55	17	JAMES J. WILSON #1	1934	PAGE	68	37	35	967	4600	705	5305	CLASTICS
56	3218	FT. DODGE, CITY #15	1949	WEBSTER	89	28	19	980	2290	17	2307	BASALT
57	17797	SCHAEFERLE #1	1965	WEBSTER	90	27	2	1130	2259	11	2270	BASALT
58	27206	ANDERSON #3	1966	WEBSTER	90	27	3	1149	2199	11	2210	BASALT
59	27204	ANDERSON #2	1971	WEBSTER	90	27	3	1139	2176	24	2200	BASALT
60	16939	ANDERSON #1	1965	WEBSTER	90	27	3	1142	2141	10	2151	BASALT
61	17038	HOFMANN #2	1964	WEBSTER	90	27	4	1130	2171	4	2175	BASALT
62	18690	HOFMANN #3	1965	WEBSTER	90	27	4	1140	2196	54	2250	BASALT
63	16964	HOFMANN #1	1964	WEBSTER	90	27	4	1140	2285	25	2310	DIABASE
64	17028	OLSON #1	1964	WEBSTER	90	27	8	1146	2379	6	2385	BASALT
65	17798	SHARP #3	1965	WEBSTER	90	27	9	1143	2149	21	2170	BASALT
66	18703	SHARP #4	1966	WEBSTER	90	27	9	1143	2150	20	2170	BASALT
67	11749	PETERSON #1	1963	WEBSTER	90	27	10	1130	2166	20	2186	BASALT
68	15523	SHARP #1	1963	WEBSTER	90	27	10	1132	2156	57	2213	BASALT
69	22315	DERSCHEID #1	1966	WEBSTER	90	27	11	1138	2180	20	2200	BASALT
70	31753	WILLEY #1	1966	WEBSTER	90	27	11	1136	2177	23	2200	BASALT
71	17036	HODGSON #1	1964	WEBSTER	90	27	11	1134	2191	8	2199	BASALT

Porosity and Permeability of MRS Clastic Rocks in Iowa

Due to the low number and poor distribution of well samples of the clastic rocks of the MRS in Iowa it is impossible to obtain an accurate determination of the variability of the physical characteristics of these rocks units. However, we have investigated the few rocks that have been sampled. The porosities of the Proterozoic Red Clastic rocks in the M.G. Eischeid #1 well were studied by Schmoker and Palacas (1990) and Ludvigson et al. (1990). Schmoker and Palacas (1990) utilized a variety of downhole geophysical logs to calculate the porosity of sandstones between 11,450 and 17,340 ft (3,435 and 5,202 m), units B and C, and the lower portion of Unit D of the Lower Red Clastics Series (Fig. 40). They identified porosities ranging from 1 to 6% (averaging 2.3%) in this interval, with "better" porosity (3.5% or more) in about 14% of the section and distributed in the upper (Unit D) and lower (Unit B) zones. Ludvigson et al. (1990) (Fig. 41) and Barnes (1990) noted, however, that optically-resolvable porosity was not observed in samples below 8,000 ft (2,400 m). The disparity between the low porosity reported by Schmoker and Palacas (1990) and the virtual absence of porosity noted by Ludvigson et al. (1990) and Barnes (1990) may be due to the presence of microporosity (not observable by optical microscopic techniques), or porosity as gas and/or liquid filled inclusions in calcite and quartz veins and calcite cements. Also, cutting samples from many intervals in the Eischeid well included abundant loose (uncemented) grains (Fig 37), possible areas of incomplete cementation, and higher porosity.

Additional porosity and permeability measurements were conducted with the assistance of the Minnesota Geological Survey as a part of this investigation. Drill core recovered during the drilling of the M.G. Eischeid #1 well (W-27933) was sampled, with rock collected for analyses from 28 intervals between 8,835 ft and 15,105 ft. One sample was collected from 3,013 ft from Ray McCallum A-1 (W-27172), three samples from 2,945 ft to 2,960 ft in the Birdie Lehman #1 well (W-23106), and four samples from 3,068 ft to 3,080 ft in the Rhinehart Farms Inc. A-1 well (W-23289), the last three wells being located in Dallas County. Analyses of these samples by Core Laboratories, Inc. (Table 2) identified porosities of 6.29% to 11.55% in the Dallas County samples retrieved from depths of less than 3,100 ft. Samples from the M.G. Eischeid #1 well showed much lower porosities, ranging from 3.81% to 0.26% and generally decreasing with depth. Permeability measurements on all samples were less than 0.001 mD (millidarcies).

Reinterpretation of the MRS Bounding Fault Zones

The availability of a detailed scanned and georeferenced aeromagnetic anomaly map of the MRS in Iowa (Henderson and Vargo, 1965) (Fig. 42) and GIS software (ArcMap) provided an opportunity to reinterpret the location and nature of the major fault systems that bound the Iowa Horst as a part of this project. The new interpretations of the locations of these fault zones (the Northern Boundary Fault Zone (NBFZ) on the northwest and the TRFZ and PHFZ on the southeast; Fig. 43) closely parallel earlier interpretations (e.g., Anderson, 2006). These faults separate highly magnetic basaltic rocks that dominate the Iowa Horst from the non-magnetic clastic sedimentary rocks filling the deep flanking basins. Aeromagnetic surveys essentially measure the magnetite content of crystalline basement rocks. Magnetite's high susceptibility causes it to react strongly with the earth's magnetic field, producing strong anomalies. Since the overlying sedimentary rocks contain very little magnetite, it can be considered magnetically invisible. Also, since the strength of a magnetic field diminishes with the cube of the distance from the detector, the strength of the anomalies in the magnetic field produced by magnetite-bearing crystalline rocks forming the floors of the clastic basins, thousands of ft below the Precambrian surface, is much weaker than the adjacent horst basalts which lie at the Precambrian surface. This difference in the strength of the magnetic anomalies with depth is expressed in the contours of the aeromagnetic anomaly map, with the contours over the highly magnetic basalts of the horst displaying high relief and often tightly-contorted aspects as opposed to the contours over the low field strength basins that are more widely spaced and gently curving. The generally linear fault zones that bound the horst are usually expressed by bundles of linear, parallel contours. The more detailed contouring of the 20 gamma contour interval (c.i.) aeromagnetic map of Henderson and Vargo (1965) permitted a more detailed and accurate interpretation of the location of these faults (Fig. 43) than the 100 gamma c.i. aeromagnetic map employed by Anderson (2006).

Although the newly interpreted fault traces is in general agreement with the previous fault locations (e.g., Anderson, 2006) the new, more detailed mapping has identified apparent irregularities in the original fault traces. Figure 44 shows a larger scale view of the previous and current interpretations of the location of the TRFZ at the Precambrian surface in southwestern Iowa. The sub-linear trend of closely spaced bundles of contours, trending in a generally northeasterly direction, can be interpreted as Iowa Horst basalts with high magnetic susceptibilities. The gently curving, more widely spaced contours to the southeast of these basalts are easily interpreted as representing the deeply buried crystalline rocks that floor the flanking clastic basins.

Table 2. Porosity, permeability, and densities from plug tests of selected samples from MRS clastic rock cores in Iowa.

Iowa Geological Survey
Multiple Well Study

Iowa

CL File No.:
Date: 15
A

CMS - 300 CORE ANALYSIS DATA

Sample Number	Depth (ft)	Net Confining Stress (psig)	Porosity (%)	Permeability Klinkenberg (mD)	Permeability Kair (mD)	Saturation Oil % Pore Volume	Saturation Water % Pore Volume	Grain Density g/cm3	Description
Eischeid w-27933									
2	8835.50	1500	3.27	.001	.003	***	***	2.684	Sst, lt red, vfg, w cem, lam (1), py
3	8836.50	1500	3.81	.002	.005	***	***	2.709	Sst, lt red, vfg, w cem, py
4	8837.50	Ambient	1.92	***	***	***	***	2.666	Sst, lt red, vfg, w cem, py
5	11382.80	1500	2.96	.002	.004	***	***	2.731	Sst, red, vfg, wcem, py
6	11383.80	1500	3.25	.002	.005	***	***	2.746	Sst, red, vfg, wcem, py
7	11385.50	1500	3.24	.0003	.001	***	***	2.726	Sst, red, vfg, wcem, lam (1), py
8	11386.30	Ambient	1.90	***	***	***	***	2.718	Sst, red, vfg, wcem, lam (1), py
9	11387.80	1500	2.60	.002	.004	***	***	2.726	Sst, red, vfg, wcem, lam (2), py
10	11387.90	1500	3.54	1.52	1.60	***	***	2.729	Sst, red, vfg, wcem, lam (2), py, frac
11	11388.30	1500	3.00	.001	.004	***	***	2.710	Sst, red, vfg, wcem, lam (2), py
12	15108.50	Ambient	0.40	***	***	***	***	2.697	Sst, gry, vfg, wcem, sl calc, calc frac
13	11389.20	1500	2.33	.000	.001	***	***	2.716	Sst, red, vfg, wcem, py
14	11389.80	1500	2.41	.001	.002	***	***	2.706	Sst, red, vfg, wcem, py
15	11390.20	Ambient	1.67	***	***	***	***	2.699	Sst, red, vfg, wcem, py
16	11391.50	1500	2.06	***	***	***	***	2.715	Sst, red, vfg, wcem, py
17	11391.80	1500	2.84	.001	.002	***	***	2.704	Sst, red, vfg, wcem, py
18	11392.60	1500	2.24	.001	.003	***	***	2.708	Sst, red, vfg, wcem, lam (2), py
19	11393.00	1500	1.38	***	***	***	***	2.7527	Sst, red, vfg, wcem, py
20	15119.00	1500	1.79	***	***	***	***	2.705	Sst, gry, vfg, wcem, lam (2), calc, py
21	15119.30	1500	0.36	***	***	***	***	2.717	Sst, gry, vfg, wcem, lam (2)
22	15108.30	1500	0.51	***	***	***	***	2.694	Sst,lt gry - dk gry, vfg - fg, wcem, lam (2)
23	15110.00	1500	0.29	***	***	***	***	2.693	Sst, gry, fg, wcem
24	15112.00	1500	0.38	***	***	***	***	2.669	Sst, gry, fg, wcem
25	15115.00	1500	0.26	***	***	***	***	2.702	Sst, lt gry - dk gry, vfg-fg, wcem, lam (2)
26	15096.20	1500	0.45	***	***	***	***	2.709	Sst, dk gry, vfg, wcem
27	15101.30	1500	0.46	.001	.002	***	***	2.655	Sst, dk gry, fg, wcem
28	15105.00	1500	0.78	.00005	.0002	***	***	2.695	Sst, dk gry, fg, wcem, lam (2)
McCallum w-27172									
29	3013.60	1500	8.47	.001	.003	***	***	2.673	Sst, tan, fg, wcem
Lehman w-23106									
32	2945.20	1500	10.52	.001	.002	***	***	2.740	Sst, red-tan, vfg-fg, wcem, mott, lam (2)
33	2951.20	1500	10.52	.001	.004	***	***	2.744	Sst, red-tan, vfg-fg, wcem, mott, lam (1)
34	2960.00	1500	8.87	.0003	.001	***	***	2.679	Sst, gry-tan, vfg-fg, wcem, mott
Rhinehart w-23289									
35	3068.50	1500	6.29	.0004	.001	***	***	2.704	Sst, gry-tan, fg-mg, wcem, mott
36	3074.50	1500	7.71	.007	.016	***	***	2.714	Sst, gry-tan, vfg-fg, wcem, mott
37	3078.50	1500	11.55	.040	.053	***	***	2.668	Cgl, gry, vfg-cg, wcem
38	3079.80	1500	11.04	.001	.002	***	***	2.677	Cgl, red-tan, vfg-cg, wcem

Footnotes :

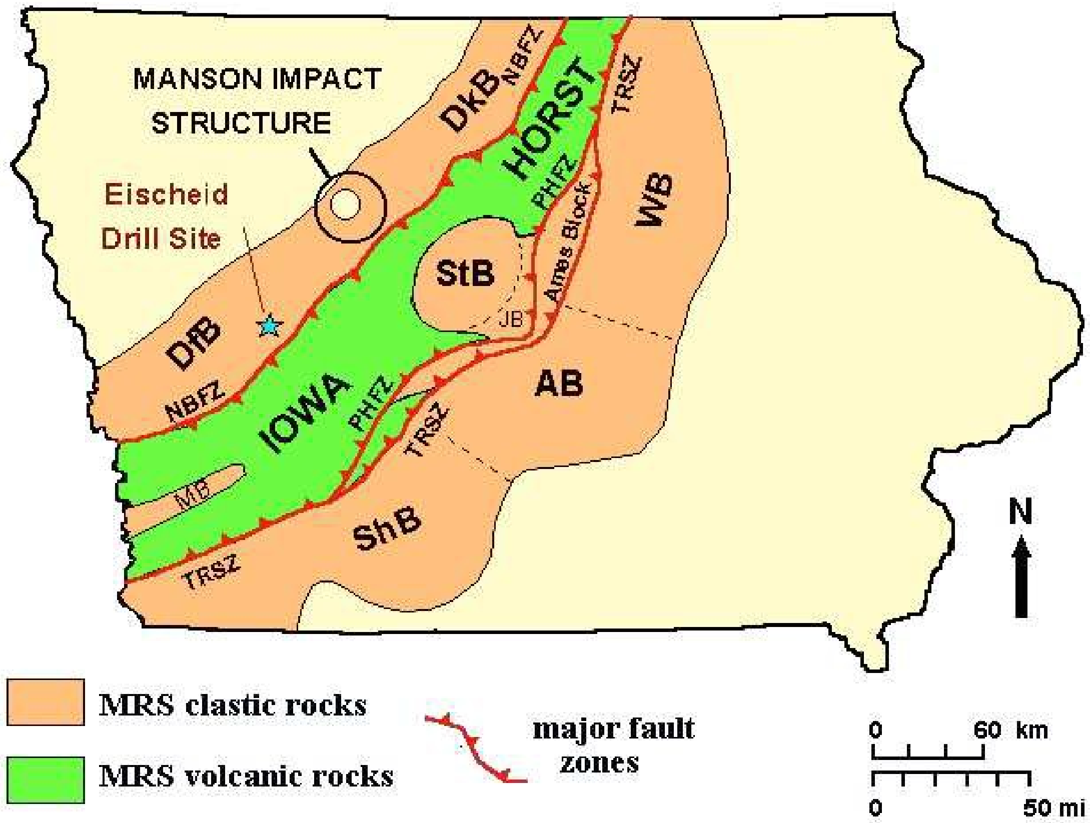


Figure 37. Map showing the structural features identified with the Midcontinent Rift System in Iowa. Clastic rock-filled basins include DfB-Defiance Basin, DkB-Duncan Basin, ShB-Shenandoah Basin, AB-Ankeny Basin, WB-Wellsburg Basin, StB-Stratford Basin, JB-Jewell Basin, and MB-Mineola Basin. Fault zones include the NBFZ-Northern Boundary Fault Zone, TRFZ-Thurman-Redfield Fault Zone, and PHFZ-Perry-Hampton Fault Zone.

The largest area of discrepancy between the older interpretation of the MRS bounding fault locations and the new interpretation using the more detailed aeromagnetic map lie on and along the northern portions of the Ames Block (Fig. 45) and north from there along the TRFZ to the Minnesota border. Interpretations of four petroleum industry speculative seismic profiles (produced by Petty-Ray Geosource in the early 1970s) in that area (lines 8, 9, 11, and 12) demonstrate that most of the newly interpreted faults delineate the juxtaposition of two blocks of MRS basalt with differing magnetic susceptibility characteristics, with little or no displacement of the crystalline surface. However, the location and trend of the PHFZ is revised in some areas. These interpretations modify only slightly the interpreted distribution of MRS clastics on the Precambrian surface and the volumes of these clastics in rift basins.

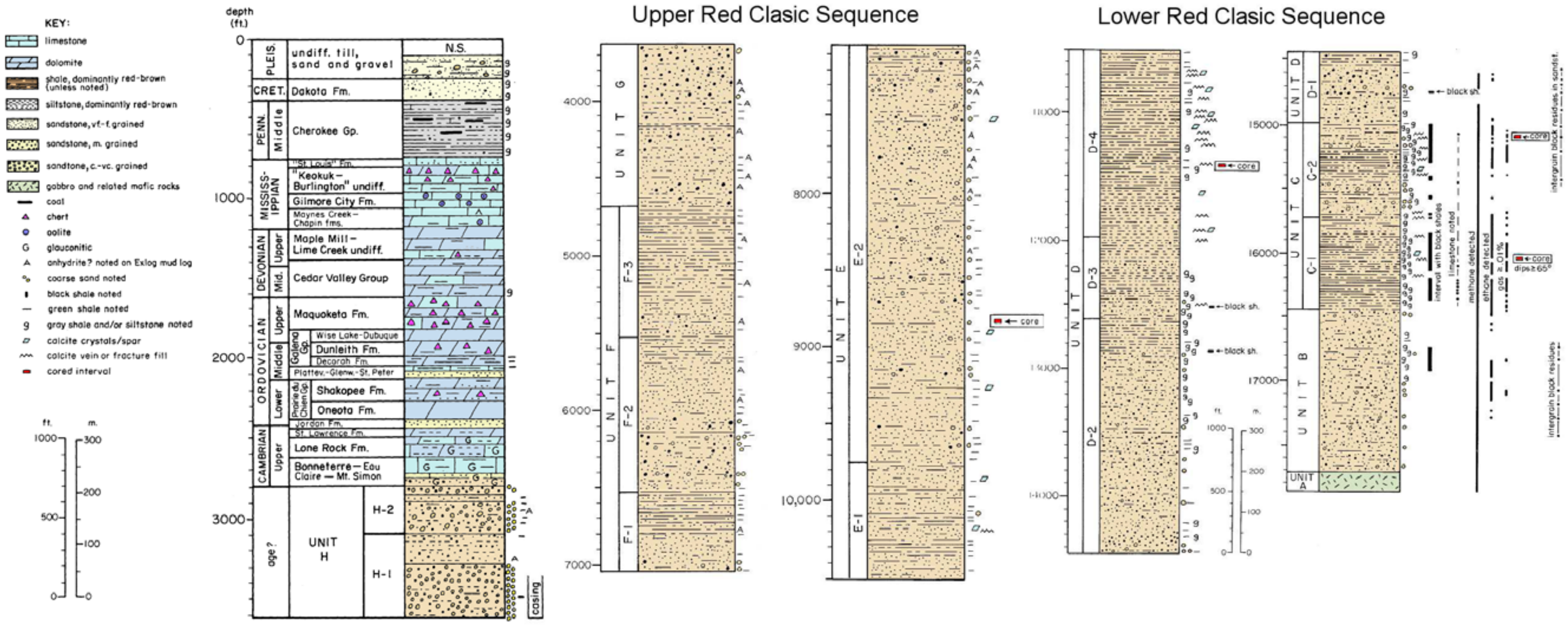


Figure 38. Graphic log of the Amoco M.G. Eischeid #1 deep petroleum test well drilled in Carroll County, Iowa (modified from Witzke, 1990).

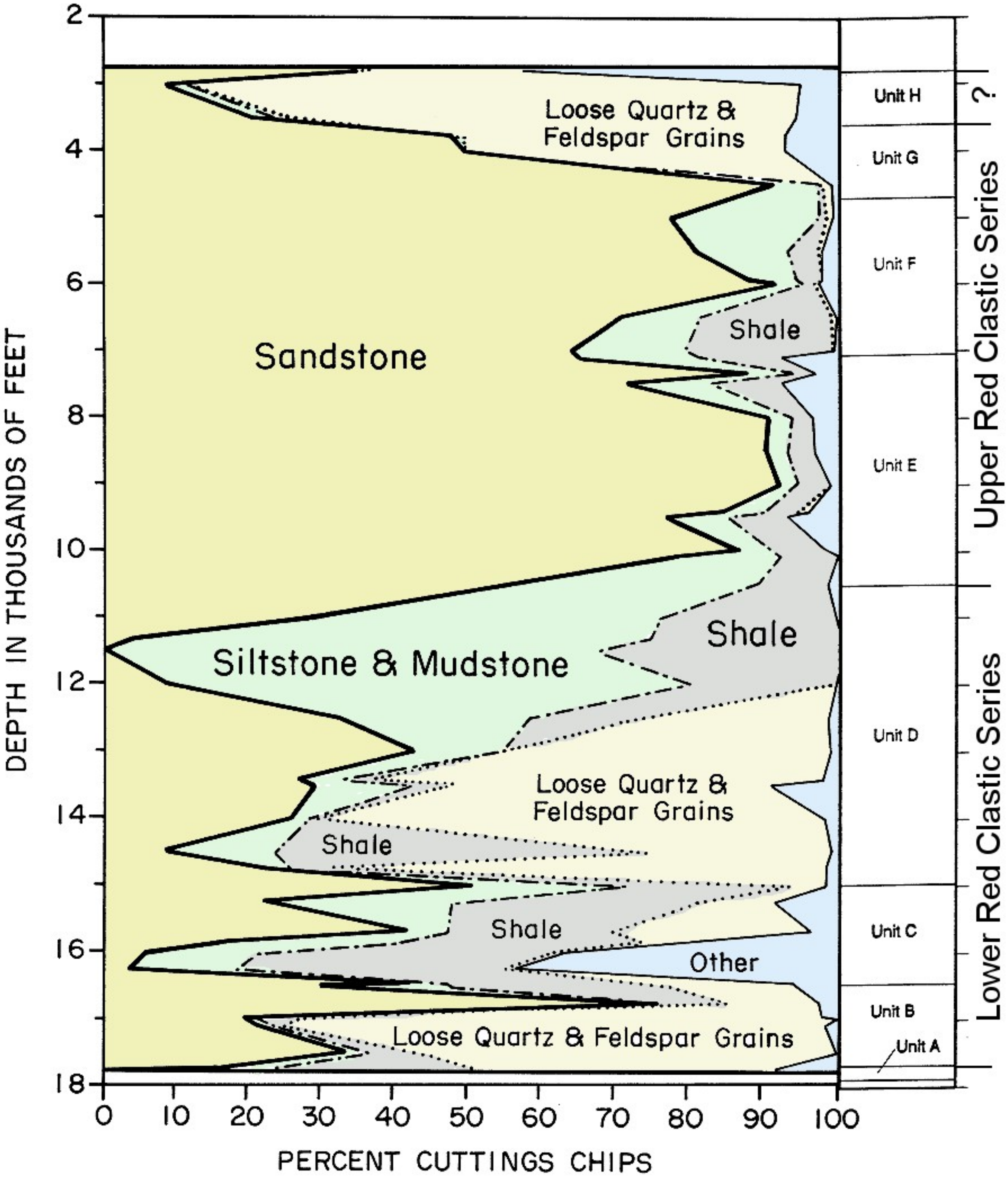


Figure 39. Variation of clastic rock lithologies with depth in Amoco M.G. Eischeid #1 chip samples (Ludvigson et al., 1990).

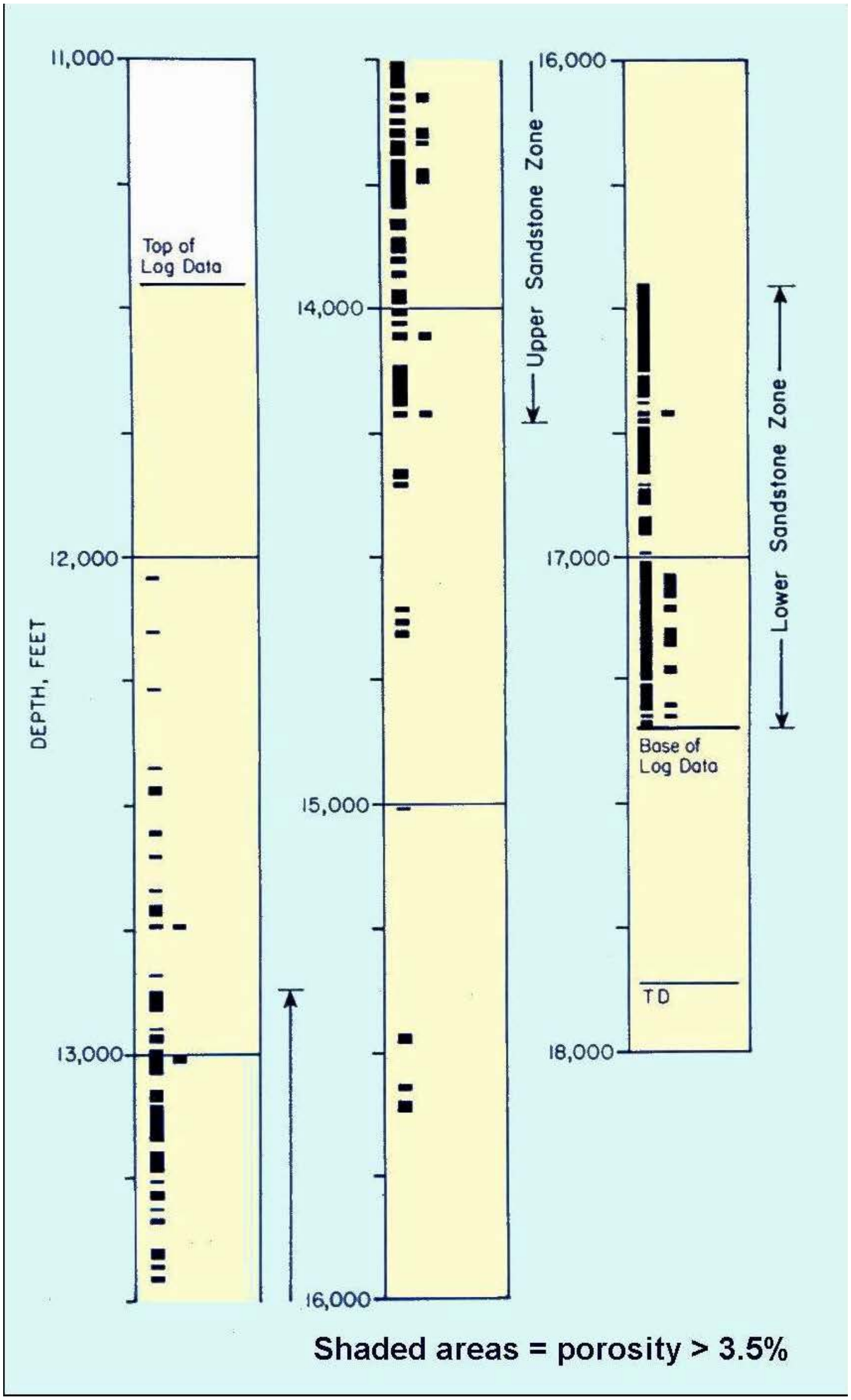


Figure 40. Porosity in Lower Red Clastic Group rock as interpreted from geophysical logs in the M. G. Eischeid #1 well (Schmoker and Palacas, 1990).

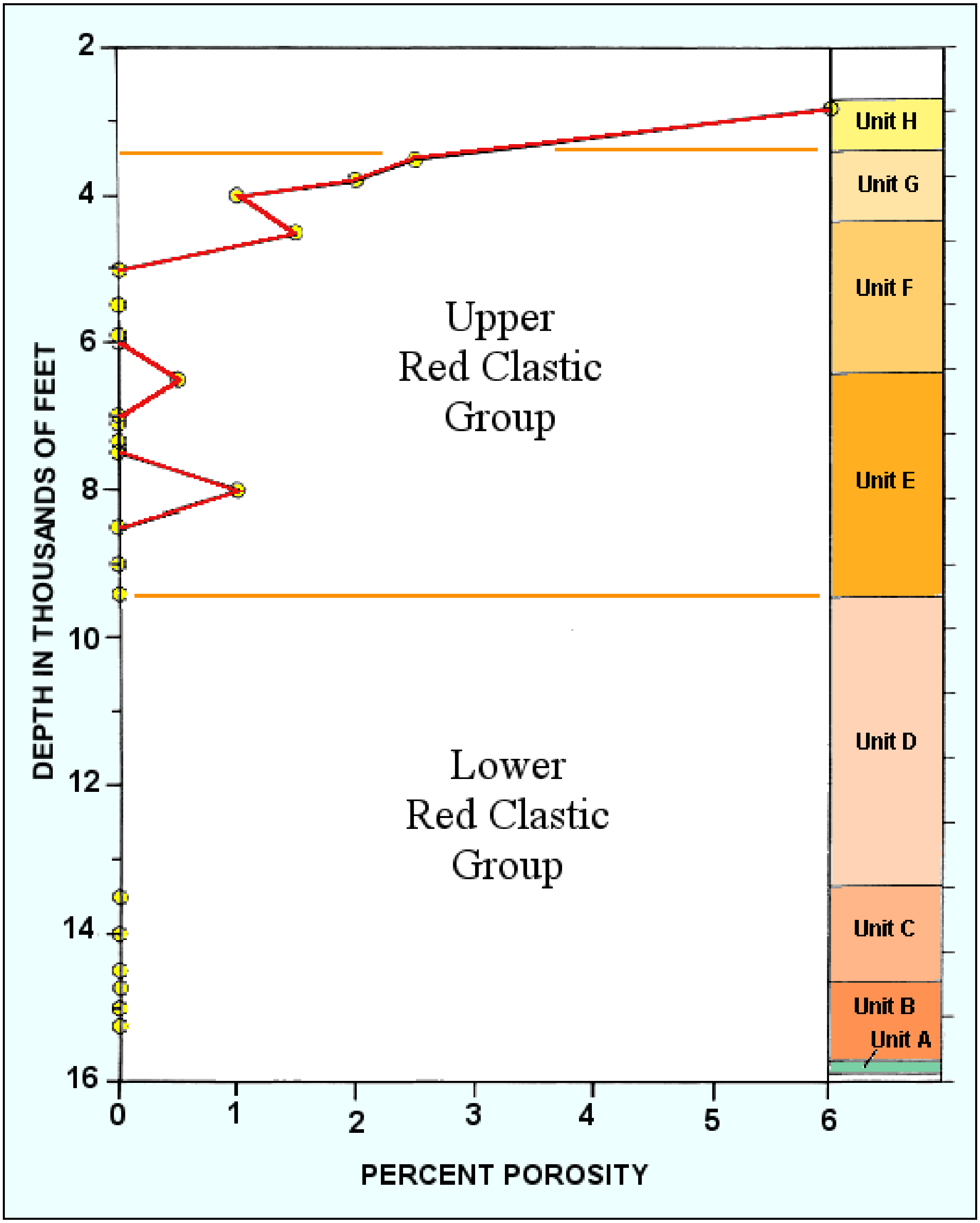


Figure 41. Porosity in clastic rocks in the M.G. Eischeid #1 well as interpreted from petrographic analysis of chip samples (Ludvigson et al., 1990).

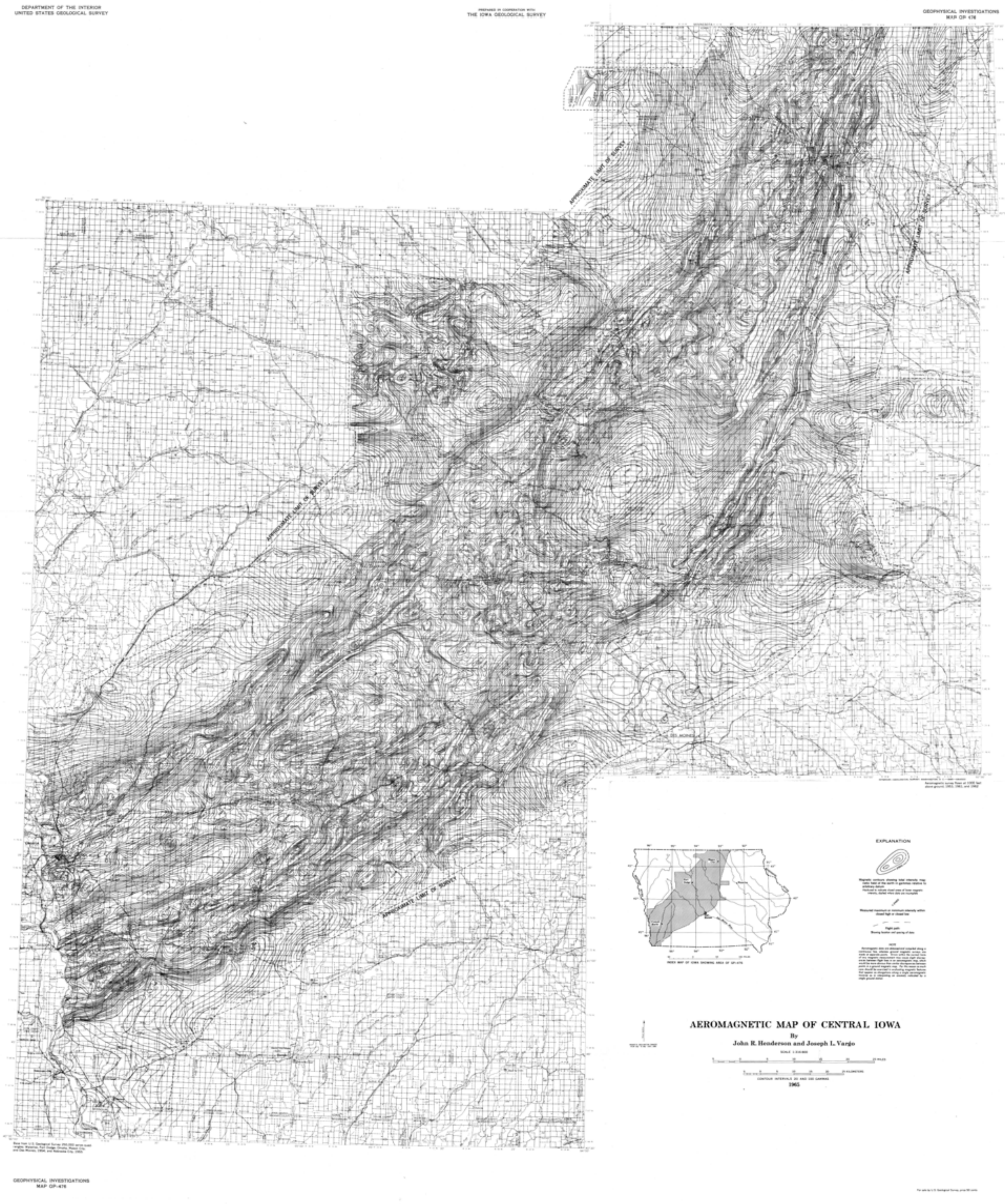


Figure 42. Scanned map of the aeromagnetic anomaly of the MRS in Iowa (Henderson and Vargo, 1965).

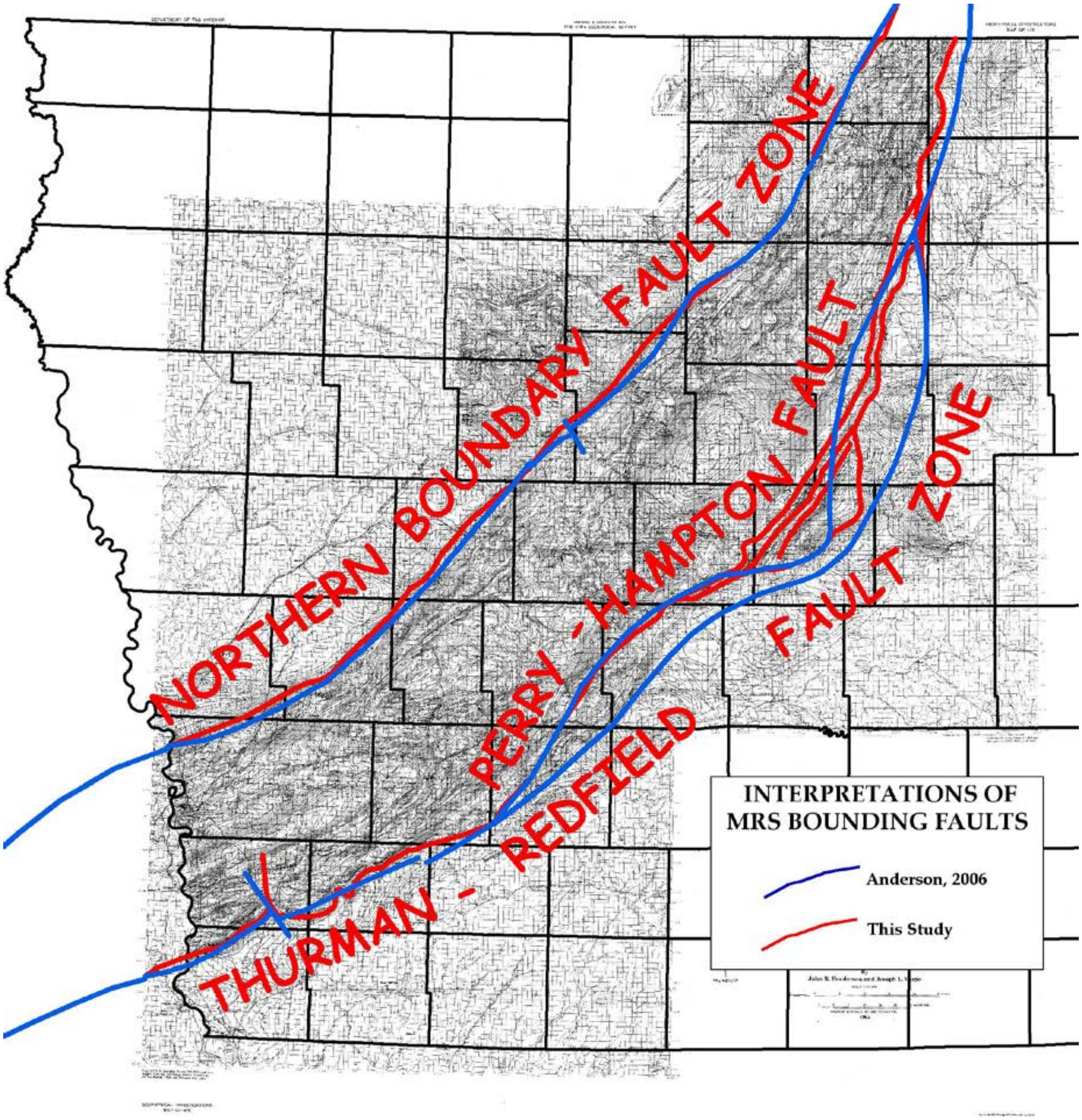


Figure 43. Old (Anderson, 2006) and new (this study) interpretations of the Precambrian surface locations of the major fault zones that bound the MRS in Iowa, displayed on the 20 gamma contour interval (c.i.) map of the aeromagnetic anomaly of the feature (Henderson and Vargo, 1965).

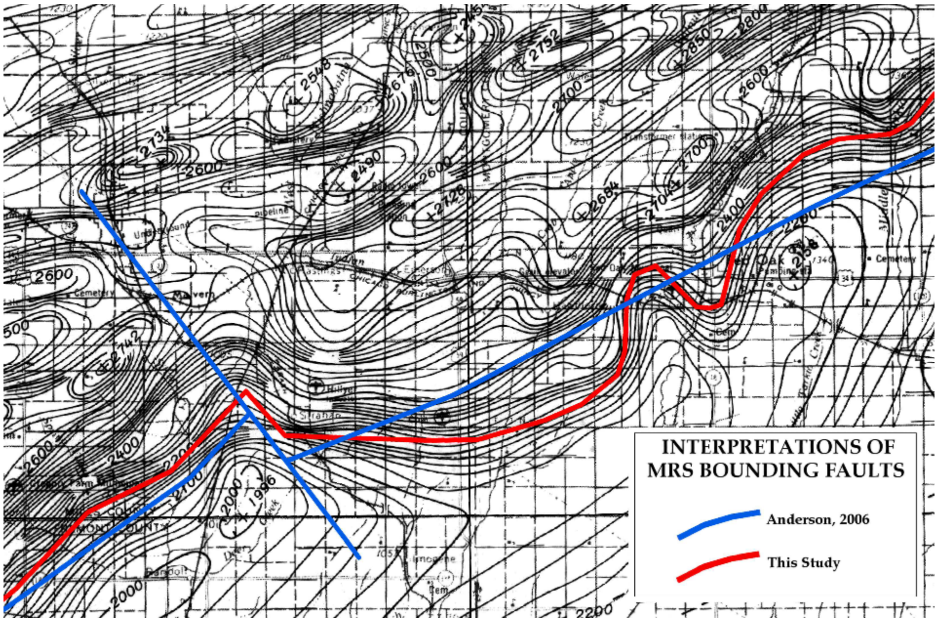


Figure 44. Larger scale comparison of the old (Anderson, 2006) and new (this study) interpretations of the locations of the major fault zones that bound the MRS in southwest Iowa. This area lies immediately above the "URM" of the TRFZ on Figure 39. The fault locations are displayed on the 20 gamma contour interval (c.i.) map of the aeromagnetic anomaly of the feature (Henderson and Vargo, 1965).

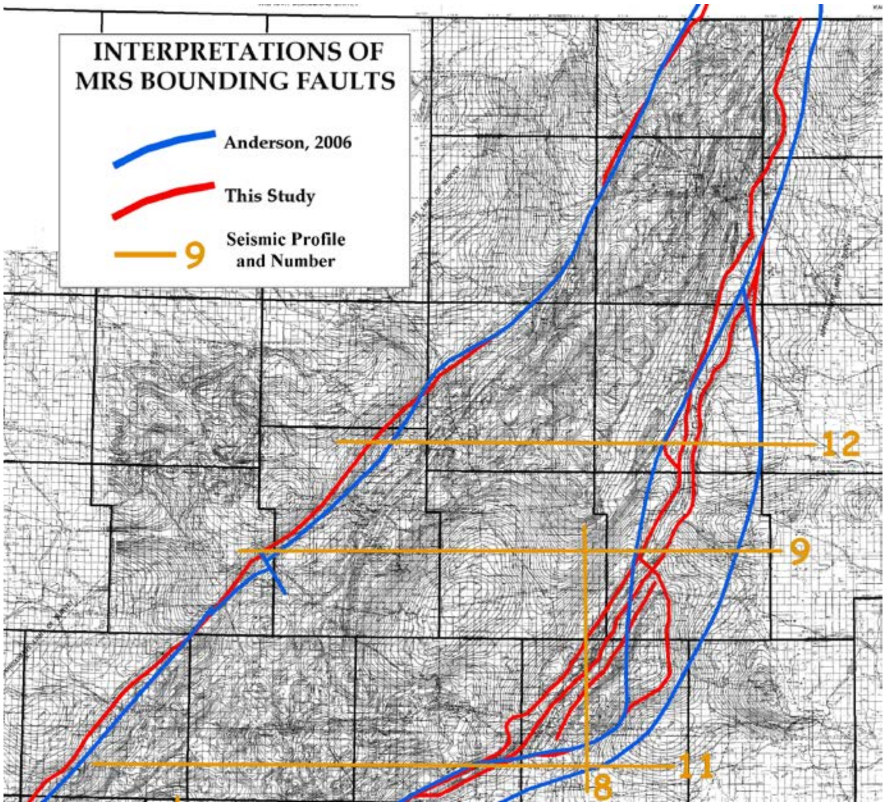
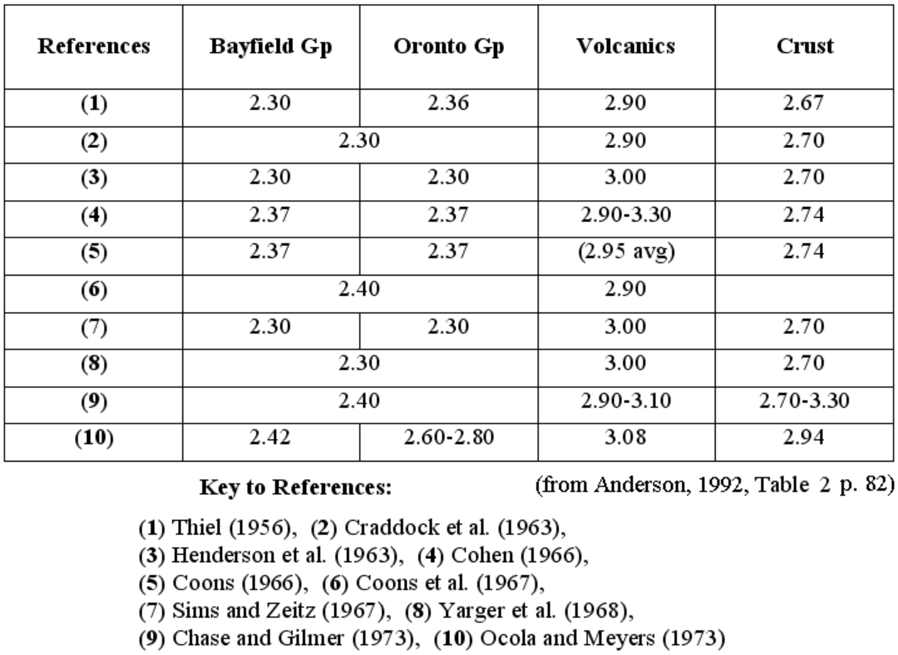


Figure 45. Comparison of the locations of the major fault zones associated with the Iowa Horst of the MRS in the northern half of Iowa, as interpreted by Anderson (2006; blue) and this study (red). Fault locations for this study are principally based on interpretation of the 20 gamma contour interval (c.i.) aeromagnetic anomaly map (Henderson and Vargo, 1965) shown in background, controlled by interpretations of Petty-Ray Geosource reflection seismic data.

Review of Gravity Models of the MRS Clastic Rock-Filled Basins

The use of gravity anomaly modeling to delineate the structure and geometry of the MRS began in 1950 when Lyons first used the technique to discover the feature he called the Greenleaf Anomaly. Since then, many other workers have used the technique, initially in the outcrop area of the MRS around and south of Lake Superior (see partial list of early gravity workers in references for Table 3). Several workers used gravity modeling in studies of various areas of the MRS in Iowa (e.g., Coons, 1966; Cohen, 1966, and Coons et al., 1967) but the most comprehensive modeling of gravity data over the MRS in Iowa was accomplished in several generations over a multi-year time frame in the late 1980s and early 1990s as a part of dissertation work by Anderson (1992). A comparison of the geometry of the northern end of the Defiance Basin as modeled by Anderson (1992) with the rock units encountered during the drilling of the Amoco M.G. Eischeid #1 well (Fig. 38) showed a thinner sequence of Lower Red Clastic Series rocks than modeled by Anderson (1992). This implies that the model densities for the Lower Red Clastics used in Anderson's model were denser than the actual rock densities. In determining model densities, Anderson reviewed densities used in earlier gravity models of the MRS (Table 3) then adjusted density values to produce models that were consistent with interpretations of speculative seismic reflection survey data (Table 4). As a part of this study, a new gravity model was produced along several of Anderson's (1992) profiles using lower density values for the Lower Red Clastic Series (Table 5). The new models were run using a Gravmag program from a Field Geophysics Software Suite (licensed by W.W. Norton and Company, Inc.) included with Introduction to Applied Geophysics (Burger et al., 2006). The thickness of the Lower Red Clastic Series rocks in the MRS basins was reduced as a result of this modeling and new information and interpretations. The revised basin thicknesses were mapped and modeled in 3-D (ArcScene).

Table 3. Densities (g/cm3) assigned to Keweenawan rocks by early gravity modelers.



References	Bayfield Gp	Oronto Gp	Volcanics	Crust
(1)	2.30	2.36	2.90	2.67
(2)	2.30		2.90	2.70
(3)	2.30	2.30	3.00	2.70
(4)	2.37	2.37	2.90-3.30	2.74
(5)	2.37	2.37	(2.95 avg)	2.74
(6)	2.40		2.90	
(7)	2.30	2.30	3.00	2.70
(8)	2.30		3.00	2.70
(9)	2.40		2.90-3.10	2.70-3.30
(10)	2.42	2.60-2.80	3.08	2.94

Key to References: (from Anderson, 1992, Table 2 p. 82)

(**1**) Thiel (1956), (**2**) Craddock et al. (1963),
(**3**) Henderson et al. (1963), (**4**) Cohen (1966),
(**5**) Coons (1966), (**6**) Coons et al. (1967),
(7) Sims and Zeitz (1967), (**8**) Yarger et al. (1968),
(**9**) Chase and Gilmer (1973), (**10**) Ocola and Meyers (1973)

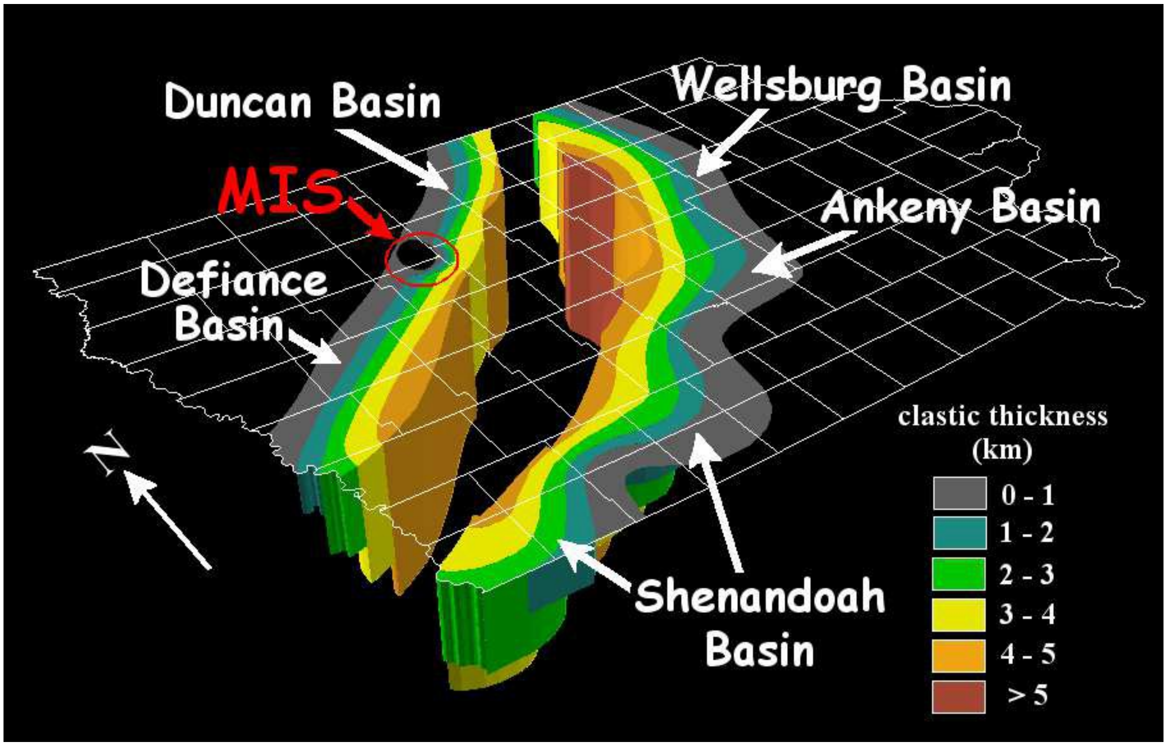


Figure 46. **3**-D model of the thickness of clastic rocks in basins flanking the central horst of the Midcontinent Rift System in Iowa. MIS identifies the Manson Impact Structure.

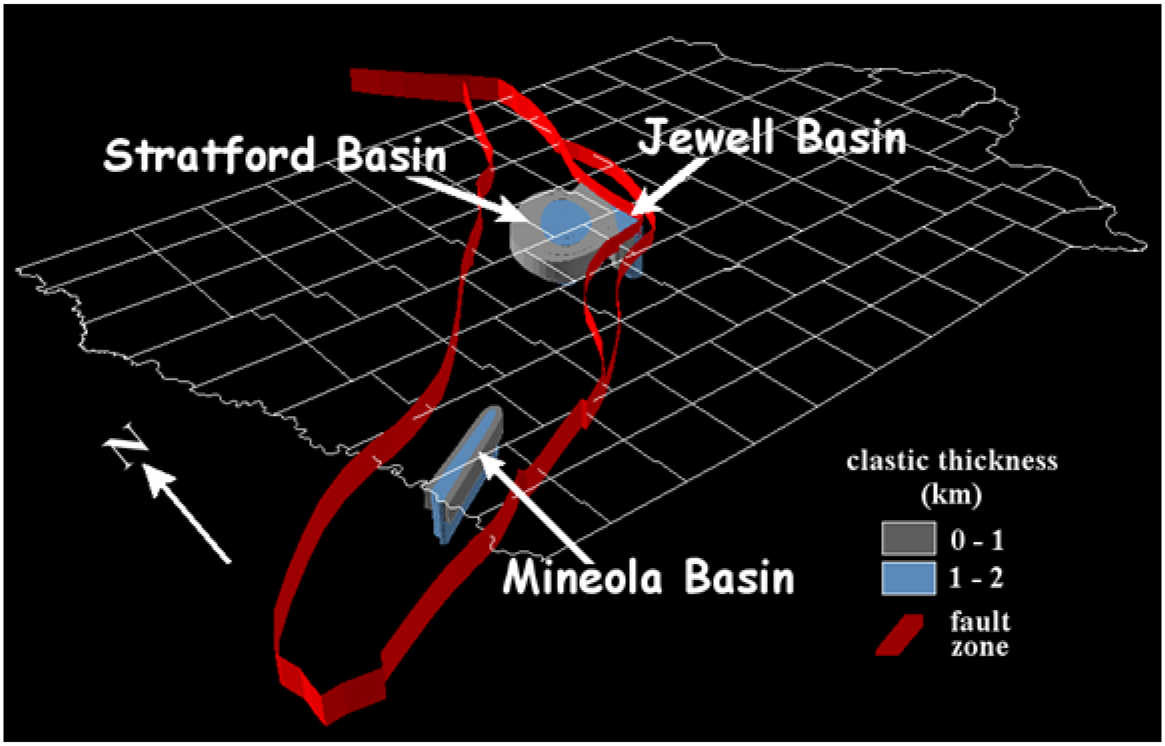
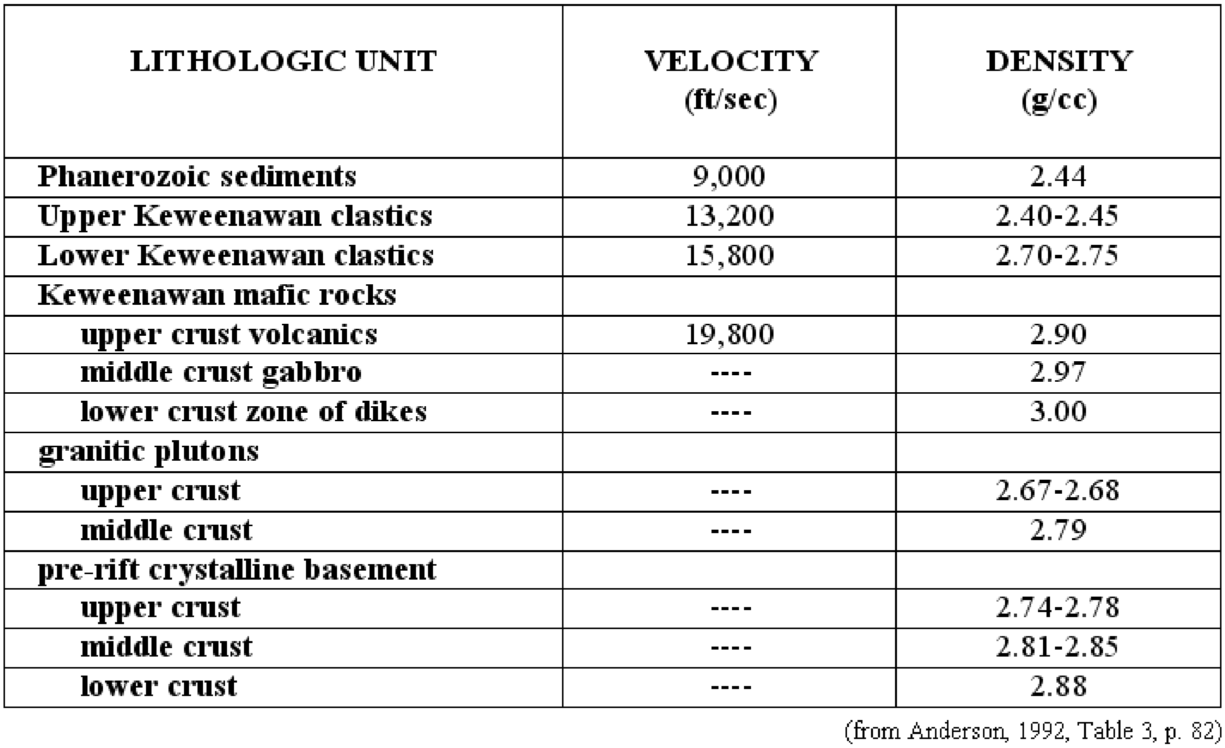


Figure 47. 3-D model of the thickness of clastic rocks in preserved in the Stratford, Jewell, and Mineola basins on the central horst of the Midcontinent Rift System in Iowa.

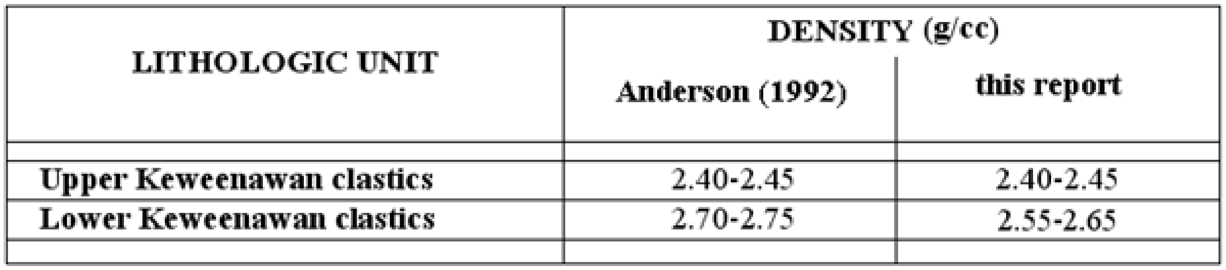
Table 4. Densities (g/cm^3) and velocities (ft/sec) assigned to Keweenawan rocks for gravity modeling in Iowa by Anderson (1992).



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

(from Anderson, 1992, Table 3, p. 82)

Table 5. Comparison of densities assigned to Keweenawan Clastic rocks in Iowa for gravity modeling in Iowa by Anderson (1992) and in this report.



LITHOLOGIC UNIT	DENSITY (g/cc)	
	Anderson (1992)	this report
Upper Keweenawan clastics	2.40-2.45	2.40-2.45
Lower Keweenawan clastics	2.70-2.75	2.55-2.65

The clastic-filled basins that bound the Iowa Horst on the east and west (Fig. 47) include multiple connected depositional centers, each of which has been designated as an individual basin. All of these basins include thick accumulations of Lower and Upper Red Clastic Series rocks. Additional clastic rock filled basins are preserved on the Iowa Horst.

Western Horst-Flanking Basins

The western flanking basins, separated from the Iowa Horst by the NBFZ (Fig. 37), includes the Duncan Basin which stretches from the Minnesota border for 68 mi (110 km) nearly half-way across the state where the basin was penetrated by the Late Cretaceous Manson Impact Structure. It reaches a maximum width of about 20 mi (32 km). The Duncan Basin contains maximum model thicknesses of clastic rocks where it abuts the Iowa Horst in Wright and Hancock counties, with about 7,200 ft (2.2 km) of Lower Red Clastics and about 8,800 ft (2.7 km) of Upper Red Clastics, totaling almost 16,000 ft (5 km) of MRS clastic sedimentary rocks (see Table 6). The total volume of MRS clastic rocks in the Duncan Basin is estimated at about 1,800 mi^3 (7,500 km^3). The southern-most of the western clastic basins is called the Defiance Basin. It stretches from the Manson Impact Structure on the north to the Iowa-Nebraska border and into Nebraska on the west. It preserves maximum thickness of clastic rocks where it abuts the Iowa Horst in Shelby and Carroll counties. In this area modeling suggests the presence of clastic rock thicknesses similar to those in the Duncan Basin, about 7,200 ft (2.2 km) of Lower Red Clastics and about 9,200 ft (2.8 km) of Upper Red Clastics, totaling 16,000 ft (5 km) of MRS clastic sedimentary rocks. This produces a model volume of about 2,900 mi^3 (12,100 km^3) of MRS clastic rocks in the basin.

Eastern Horst-Flanking Basins

On the eastern margin of the Iowa Horst, the TRFZ separates the clastic basins from the Iowa Horst. The northernmost of the eastern basins (Fig. 46) is the Wellsburg Basin. This basin reaches its maximum depth where it abuts the Iowa Horst in western Floyd and Butler counties, preserving about 9,000 ft (2.7 km) of Lower Red Clastic Series rocks and about 11,000 ft (3.4 km) of Upper Red Clastic Series rocks (Table 6), totaling a maximum of almost 19,000 ft (6 km). The total volume of MRS clastic rocks preserved in the basin is about 5,000 mi^3 (21,000 km^3). The Ankeny Basin lies south of the Wellsburg Basin, near the center of the state. This basin preserves about 7,000 ft (2.2 km) of Lower Red Clastic Series rocks and about 8,000 ft (2.5 km) of Upper Red Clastic Series rocks, totaling a maximum of almost 14,900 ft (4.7 km) where it abuts the Iowa Horst. The volume of MRS clastic rocks in the basin is about 3,800 mi^3 (15,800 km^3). The southernmost of the eastern flanking basins, the Shenandoah Basin, is also the aerially largest of the MRS flanking basins, covering almost 3,900 mi^2 (10,000 km^2) of the Precambrian surface of Iowa. The basin is partially separated into two sub-basins by a north-trending high on the crystalline basement surface known as the Central Iowa Arch Granite. Clastic rocks in the Shenandoah Basin reach a maximum thickness of about 16,200 ft (5.1 km) where it abuts the Iowa Horst, near the common corner of Fremont, Page, Mills, and Montgomery counties. At this location, modeling suggests there are about 6,000 ft (1.9 km) of Lower Red Clastic rocks and about 10,000 ft (3.2 km) of Upper Red Clastics, the thickest in Page County. The modeling yields an approximate total volume of MRS clastic rocks in the basin of 4,700 mi^3 (19,600 km^3).

Clastic Basins on the Iowa Horst

On the Iowa Horst, the Stratford Basin (Fig. 47) is an elliptical basin, extending for about 34 mi (56 km) along the axis of the horst with a width of about 23 mi (37 km), in Hamilton County. Modeling indicates that the basin is filled with Lower Red Clastic Series rocks reaching a maximum thickness of about 6,000 ft (2 km) and contains about 2,000 mi^3 (8,400 km^3) of clastic rock strata (Table 6). Its location and geometry closely resembles the Twin City Basin on the MRS central horst in Minnesota. The Jewell Basin is an asymmetric basin that abuts the eastern edge of the Stratford Basin and extends generally in a northerly direction for about 36 mi (60 km), reaching a maximum width of about 12 mi (20 km). The maximum thickness of clastic rocks in the basin is about 6,000 ft (2 km) where it is truncated by the PHFZ. This basin is filled about 400 mi^3 (1,700 km^3) of what modeling indicates is Lower Red Clastic Series rocks. The Mineola Basin (Fig. 47) is an elongate, graben-controlled basin that lies along the axis of the Iowa Horst just east of Iowa's western border. The basin, which trends in an east-northeasterly direction, runs for about 39 mi (65 km) along the axis of the Iowa Horst, reaching a maximum width of about 8.4 mi (14 km). Modeling indicates that the Mineola Basin contains Upper Red Clastic Series rocks with a maximum thickness of about 4,800 ft (1.5 km) and contains about 120 mi^3 (500 km^3) of clastic rocks.

Ames Block

The Ames Block (Fig. 48) is a fragment of the Iowa Horst, located along its eastern margin, separated from the main body of the horst by the PHFZ. When the MRS axial horst was being uplifted, the Ames Block was not thrust up as far as the rest of the Iowa Horst, so it structurally preserves both Upper and Lower Red Clastic Series rocks over much of its length. The clastic rocks on the Ames Block extend for about 126 mi (210 km) along the Iowa Horst (Table 6) and reach a width of about 18 mi (30 km). An estimated 2,400 mi^3 (10,000 km^3) of MRS clastic rocks are preserved on the Ames Block, which is bounded on the east by the TRFZ.

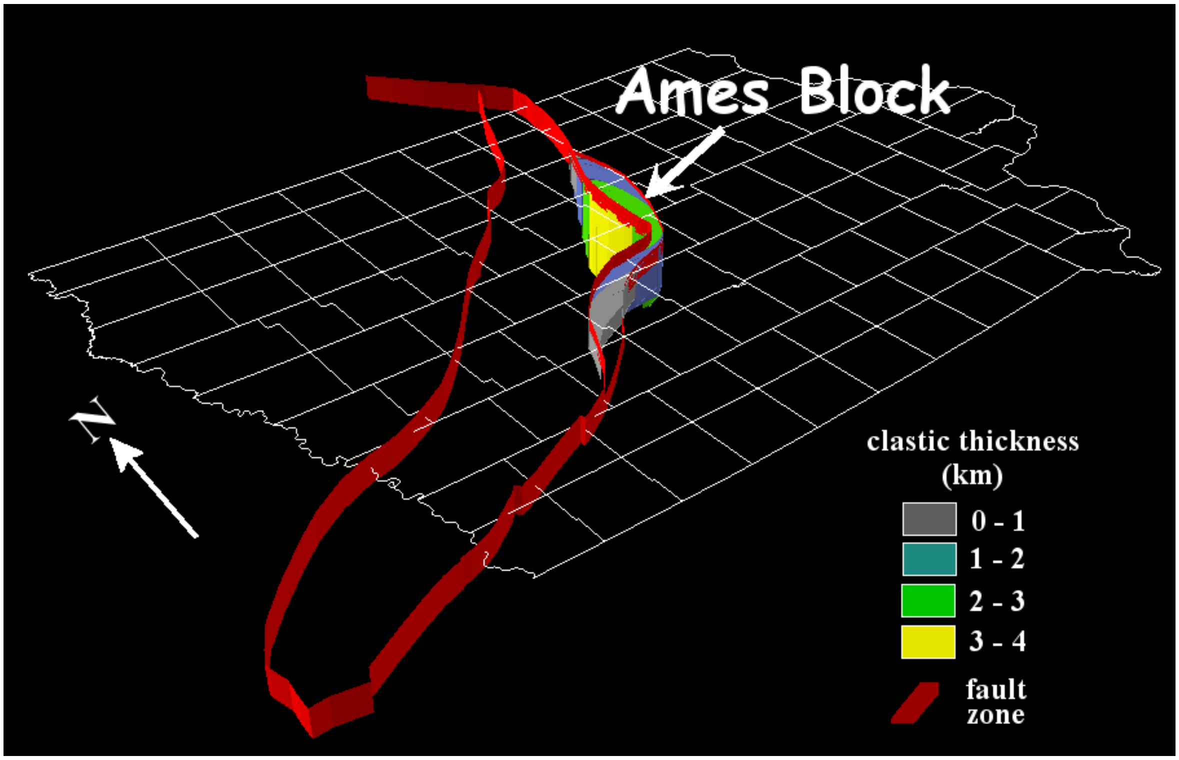
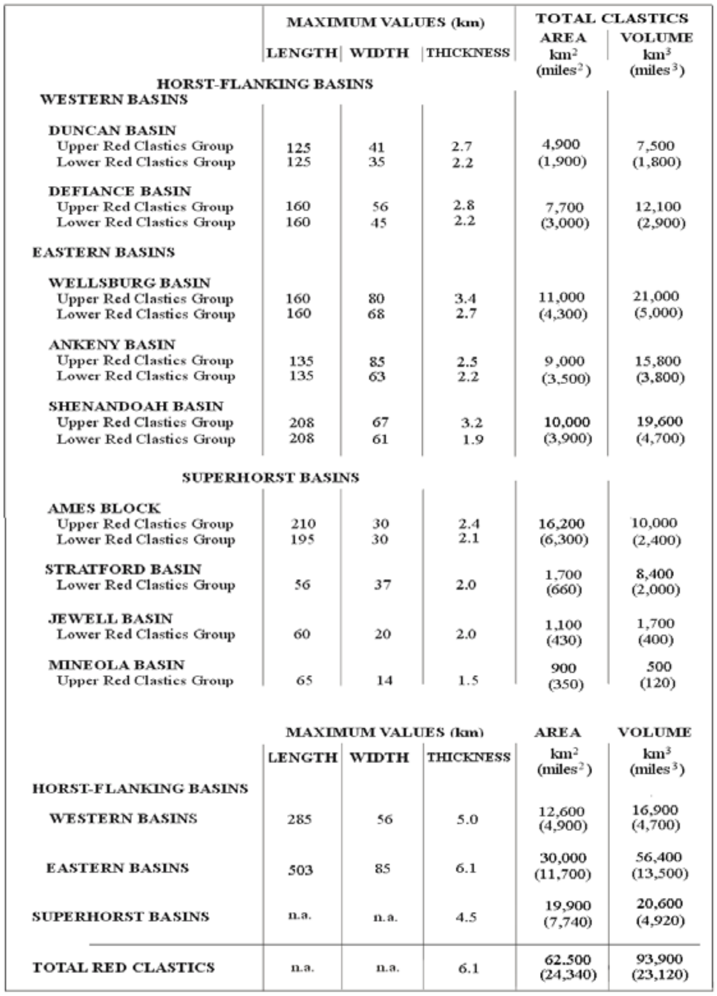


Figure 48. 3-D model of the thickness of clastic rocks structurally preserved on the Ames Block of the Midcontinent Rift System in Iowa.

Discussion and Conclusions

The Midcontinent Rift System (MRS) in Iowa is characterized by the Iowa Horst (an axial uplifted block dominated by MRS basaltic volcanic rocks) that is capped by four structural basins that preserve MRS clastic sedimentary rocks. The horst is flanked on the east and west by five additional basins filled with MRS clastic sedimentary rocks. These MRS clastic sedimentary rocks, which include conglomerates, sandstones, siltstones, and shales, are promising targets for the future sequestration of CO_2. They cover over 16,000 square mi of the Precambrian surface of Iowa (about 28% of the state) and are overlain by 1,700 to <5,000 ft of younger geologic strata. Gravity modeling, controlled by seismic interpretations, suggest that about 23,100 mi^3 (93,900 km^3) of MRS clastic sedimentary rocks are preserved in these seven basins, and most of this volume lies below the 2,700 foot depth of burial that provides the hydrostatic pressure critical to containing CO_2 in its liquid state. Review of previous interpretations of the thicknesses of clastics rocks in the seven MRS basins and the locations of key fault zones Anderson (1992; 2006) using newly available aeromagnetic maps, gravity modeling, and well information has somewhat modified the interpreted locations of some fault zones and reduced the estimated volume of MRS clastic rocks in Iowa by almost 40%. However, the lack of an appropriate number of well distributed drill samples makes characterizing the suitability of these rocks for CO_2 sequestration very difficult.

Table 6. Dimensions and volumes of MRS clastic basins in Iowa.



	MAXIMUM VALUES (km)			TOTAL CLASTICS	
	LENGTH	WIDTH	THICKNESS	AREA km^2 (miles^2)	VOLUME km^3 (miles^3)
HORST-FLANKING BASINS					
WESTERN BASINS					
DUNCAN BASIN					
Upper Red Clastics Group	125	41	2.7	4,900 (1,900)	7,500 (1,800)
Lower Red Clastics Group	125	35	2.2		
DEFIANCE BASIN					
Upper Red Clastics Group	160	56	2.8	7,700 (3,000)	12,100 (2,900)
Lower Red Clastics Group	160	45	2.2		
EASTERN BASINS					
WELLSBURG BASIN					
Upper Red Clastics Group	160	80	3.4	11,000 (4,300)	21,000 (5,000)
Lower Red Clastics Group	160	68	2.7		
ANKENY BASIN					
Upper Red Clastics Group	135	85	2.5	9,000 (3,500)	15,800 (3,800)
Lower Red Clastics Group	135	63	2.2		
SHENANDOAH BASIN					
Upper Red Clastics Group	208	67	3.2	10,000 (3,900)	19,600 (4,700)
Lower Red Clastics Group	208	61	1.9		
SUPERHORST BASINS					
AMES BLOCK					
Upper Red Clastics Group	210	30	2.4	16,200 (6,300)	10,000 (2,400)
Lower Red Clastics Group	195	30	2.1		
STRATFORD BASIN					
Lower Red Clastics Group	56	37	2.0	1,700 (660)	8,400 (2,000)
JEWELL BASIN					
Lower Red Clastics Group	60	20	2.0	1,100 (430)	1,700 (400)
MINEOLA BASIN					
Upper Red Clastics Group	65	14	1.5	900 (350)	500 (120)

	MAXIMUM VALUES (km)			AREA	VOLUME
	LENGTH	WIDTH	THICKNESS	km^2 (miles^2)	km^3 (miles^3)
HORST-FLANKING BASINS					
WESTERN BASINS	285	56	5.0	12,600 (4,900)	16,900 (4,700)
EASTERN BASINS	503	85	6.1	30,000 (11,700)	56,400 (13,500)
SUPERHORST BASINS	n.a.	n.a.	4.5	19,900 (7,740)	20,600 (4,920)
TOTAL RED CLASTICS	n.a.	n.a.	6.1	62.500 (24,340)	93,900 (23,120)

Porosity in MRS Clastic Rocks

Study of the chip samples by Ludvigson et al. (1990) identified sandstone in over 85% of samples examined (Fig. 39) of Upper Red Clastic Series rocks (from 3,615 to 10,510 ft) and sandstone or loose quartz and feldspar grains comprising even greater percentages of units D and B in the Lower Red Clastic Series samples (from 10,510 to 17,700 ft). The presence of so much sandstone in the Upper Red Clastic Sequence strongly suggests that some zones with porosity and permeability suitable for CO_2 injection must exist. In addition, the large percentage of free quartz and feldspar grains in Lower Red Clastic Series samples implies poor cementation and possibly high porosity and permeability in this these rocks. This possibility, however, is at odds with work by Schmoker and Palacas (1990) who studied a variety of downhole geophysical logs to calculate the porosity of sandstones in units B and C (11,450 to 17,340 ft). Although Ludvigson et al. (1990) identified greater than 50% loose quartz and feldspar grains in most sections of these units, Schmoker and Palacas (1990) determined porosity ranging from 1 – 6% (averaging 2.3%) in this interval (Fig. 40), with values greater than 3.5 % in 14% of the sequence. An even bleaker picture was presented by Ludvigson et al. (1990) who reported no optically-resolvable porosity in samples that they studied below 8,000 ft (including 6 samples from units B and C) in the Eischeid well (Fig. 41). Anderson (1990b) suggested the disparity between the porosity identified in the logs by Schmoker and Palacas (1990) but not optically resolved by Ludvigson et al. (1990) might have originated in microporosity or gas and/or liquid filled inclusions in calcite and quartz veins and calcite cements. Samples from three cored intervals below 8,000 ft in the Eischeid well were tested for porosity (Table 2) by Core Labs, Inc. as a part of this study. Measured porosities ranged from 0.26% to 3.81% (averaging 1.6%). Two samples from the interval 8835.5 to 8836.5 ft averaged 3.54% porosity, and seven samples from the interval 11,382.8 to 11,388.3 ft averaged 2.93% porosity. Porosities were also measured from eight samples taken from cores collected very near the Precambrian surface in three wells in the Redfield Gas Storage Structure in Dallas County (Table 2). These included Ray McCallum A-1 (W-27172) - one sample from 3013.6 ft (about 0.5 ft below the Precambrian surface), Birdie Lehman #1 well (W-23106) - three samples from 2,945.2, 2,951.2, and 2,960.0 ft (Precambrian surface at 2,924 ft), and Rhinehart Farms Inc. A-1 well (W-23289) - four samples from 3,068.5, 3,074.5, 3,078.5, and 3,079.8 ft (Precambrian surface at 3,066 ft). These eight samples displayed porosities ranging from 11.6% to 6.3% (averaging 9.4%). Greater porosities were also optically observed by Ludvigson et al. (1990) at shallower depths in units E, F, and G (Fig. 41). In six samples studied from 8,000 ft and above, porosities ranged from 0.5% to 2.5%, suggesting greater porosities may exist in MRS clastic rocks that are not so deeply buried.

Permeability of MRS Clastic Rocks

Extremely limited data exists on the permeability of MRS clastic rocks in Iowa. Permeability tests were conducted by Core Labs, Inc. as a part of this study for 28 samples from three intervals of core from the Amoco M.G. Eischeid #1 petroleum test well (Table 2), and 8 samples from three shallow core penetrations of the MRS clastics in the Redfield Gas Storage Structure in Dallas County. Both air and Klinkenberg corrected permeabilities were reported, but only the air values are discussed here. Of the 28 samples tested, 13 (46%) displayed no measurable porosity. Of the 15 samples having measurable porosity, values ranged from 0.0002 to 1.50 mD (an apparently anomalous measurement) and averaged

0.102 mD (0.003 mD omitting the anomalous value). Permeabilities measured in the 8 samples from three cored wells in Dallas County ranged from 0.001 to 0.052 mD, averaging about 0.01 mD. The 0.052 value is about three times higher than any other measured value and may be erroneous. Excluding that high value, the next highest measured permeability is 0.016 mD and the average permeability of the remaining seven samples is 0.004 mD.

Ludvigson et al. (1990, p. 82) reported that “shrinkage cracks are perhaps the most common sedimentary deformation structures” in the MRS clastic rock cores they examined from the M.G. Eischeid #1 well. They noted these cracks cross cut horizontally-laminated shale and siltstone and are filled with poorly-sorted materials including silt to coarse sandstone and sometimes connect to overlying sandstones. Such cracks may provide permeability to such horizontally laminated units.

Water Quality in MRS Clastic Rocks

Water quality analysis is known from only one well that penetrated MRS clastic rocks in Iowa. This sample was taken from the James J. Wilson #1 well (W-17). The Wilson well was completed to 5,305 ft (including about 1,600 ft of MRS clastic rocks) in 1930 but the water sample was not collected until 1940. Records indicate that the well was cased to 4,708 ft (about 1,000 ft into MRS clastic rocks), and the water analysis report indicates that the well was flowing when sampled, presumably from the MRS clastics rocks below the casing depth. The records also indicates TDS in the water as 6,018 ppm, sodium as 2,207 ppm, and chlorine as 2,900 ppm. Calculated hardness was analyzed as 158 ppm and the pH was listed as 7.6. The Wilson #1 well was observed to still be flowing as late as 2007 but has subsequently been destroyed. When observed in 2007 by an IGS geologist, the water flowing from the well displayed very high levels of iron oxide, suggesting that the water may have been sourced in Pennsylvanian strata (which are very pyritic), suggesting that the casing had deteriorated.

Suitability of MRS Clastic Rocks for CO_2 Sequestration

Randolph and Saar (2008) modeled the potential for CO_2 sequestration in MRS clastic rocks in Minnesota. They stated (ibid. p. 114) that “Our modeling indicates that the matrix permeability of potential caprock in the rift is sufficiently low, 10-21 m2 (1.0 x 10-6 mD) to 10-18 m2 (1.0 x 10-3 mD), to serve as an effective reservoir caprock (without consideration of fractures that would, however, increase caprock permeability). We also find that deep geologic sequestration would be possible in the strata of the rift if large sandstone bodies with porosities in the range 0.04 to 0.20 (i.e., 4% to 20%) and permeabilities in the range 10-15 m^2 (1.0 mD) to 10-13 m^2 (100 mD) (with uncertainty of approximately one order of magnitude) are eventually located in the rift at depths greater than 800 m below a caprock with the above-described properties.” These parameters would also apply to sequestration of CO_2 in MRS clastic rocks in Iowa. Many of the rock sequences encountered in the extremely limited number of penetrations of MRS clastic rocks in Iowa would fit their requirements as potential caprock, but no units with sufficient porosity or permeability have yet been encountered. However, it must be considered that all of the information that has been presented about the geotechnical characteristics of the MRS clastic rocks in Iowa for CO_2 sequestration comes from four wells, one deep penetration (Eischeid) and three closely spaced very shallow penetrations (McCallum, Lehman, and Rhinehart Farms) of a sequence of rocks that cover 16,000 mi^2 of Iowa. These wells are all located within 5 mi of the Iowa Horst-bounding faults, an area that was subjected to higher heat flow and related fluid movement from the thick sequence of volcanic and plutonic rocks that filled the rift-axial graben (and later horst). It is reasonable to suggest MRS clastic rocks were deposited farther from the rift axis and may yet retain suitable porosities and permeabilities for sequestration. The quality of the water in the MRS clastics, as indicated by the single analysis from the Wilson #1 well, is so saline as to classify it as not potable, but the fact that it produced a flowing well demonstrates a reasonable permeability at that location.

Future Work

Some additional information on the porosity of the upper-most Red Clastics rocks in other wells in the Redfield Gas Storage Structure may exist in various geophysical logs but these wells were very shallow penetrations of the MRS rocks and lie very near the wells sampled for porosity measurements, so it was determined that these additional data would be of only limited value. Also, limited chip samples from the Wilson #1 well (W-017) in Page County (which penetrated 1,605 ft of MRS clastic rocks in the Shenandoah Basin) and the #1 Huntly well (W-14428) in Butler County (which penetrated 1,290 ft of the rocks in the Wellsburg Basin) could be studied for possible porosity and permeability information. However, the relatively low potential for useful data and limited time available precluded those investigations for this study.

Exploration for MRS clastic rocks in Iowa exhibiting suitable porosities and permeabilities for CO_2 sequestration and an acceptable cap rock will be difficult. Drilling to the depths required to properly sample these rocks would be expensive and geophysical techniques would not provide definitive information. A future exploration plan would probably begin with the identification of an appropriate CO_2 producer with capture capabilities in an area above MRS clastic rocks. A high resolution reflection seismic survey in the area could be used to identify potential targets for the drilling of a test well with the coring of critical caprock and reservoir rocks for geotechnical analysis. If appropriate rocks were encountered, several additional drill holes would be required before sequestration activities could begin.

REFERENCES

Anderson, R.R. 1981. Bouguer gravity anomaly map of Iowa. Miscellaneous Map Series No. 7, scale 1:1,000,000, Iowa Geological Survey, Iowa City.

Anderson, R.R. (ed.) 1990. The Amoco M.G. Eischeid #1 deep petroleum test Carroll County, Iowa. Iowa Geological Survey Special Report Series No. 2, 185 p .

Anderson, R.R. 1990b. Review of the current studies of Proterozoic rocks in the Amoco M.G. Eischeid #1 petroleum test well, Carroll County, Iowa. In: Anderson, R.R. (ed.), The Amoco M.G. Eischeid #1 deep petroleum test Carroll County, Iowa. Iowa Geological Survey Special Report Series No. 2, p. 175-184.

Anderson, R.R. 1992. The geology of the Midcontinent Rift System in Iowa. Unpublished PhD dissertation, University of Iowa, Iowa City, IA, 324 p.

Anderson, R.R. 2006. Geology of the Precambrian surface of Iowa and surrounding area, Open File Map 06-7, Iowa Geological Survey.

Arrhenius, S. 1896. On the influence of carbonic acid in the air upon the temperature of the ground. London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science (fifth series), v. 41, p. 237–275.

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. Iowa Geological Survey Special Report Series No. 2, p. 113-118.

Black, W.A. 1955. Study of the marked positive gravity anomaly in the northern midcontinent region of the United States (abs.). Geological Society of America Bulletin, v. 66, p. 1531.

Bunker, B.J., Witzke, B.J., Watney, W.L. And Ludvigson, G.A. 1988. Phanerozoic history of the central midcontinent, United States. In: Sloss, L.L. (ed.), Sedimentary Cover--North American Craton: U.S.: Geol. Soc.
Amer., Geology of North America, v. D-2, p. 243-260, p. 4.

Burger, R.H., Sheehan, A.F. and Jones, C.H. 2006. Introduction to applied geophysics. W.W. Norton and Company,
554 p.

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.

Chase, C.G. and Gilmer, T.H. 1973. Precambrian plate tectonics: the midcontinent gravity high. Earth and Planetary Science Letters, v. 21, p. 70-78.

Cohen, T.J. 1966. Explosion seismic studies of the Mid-Continent Gravity High. Unpublished PhD dissertation, University of Wisconsin, Madison, WI, 215 p.

Coons, R.L. 1966. Precambrian basement geology and Paleozoic structures of the Midcontinent Gravity High. Unpublished PhD dissertation, University of Wisconsin, Madison, WI, 296 p.

Coons, R.L., Woollard, G.P. and Hershey, H.G. 1967. Structural significance and analysis of the Midcontinent gravity high. Bulletin of the American Association of Petroleum Geologists, v. 51, p. 2381-2399.

Craddock, C., Thiel, E.C. and Gross, B. 1963. A gravity investigation of the Precambrian of southeastern Minnesota and western Wisconsin. Journal of Geophysical Research, v. 68, p. 6016-6032.

Fischer, L.E. 1982. Geological interpretation of an aeromagnetic anomaly southwest of Boone in west central Iowa.
Unpublished MS thesis, University of Iowa, Iowa City, IA, 234 p.

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

Henderson, J.R., White, W.A. and Zietz, I. 1963. Preliminary interpretation of an aeromagnetic survey in north-central Iowa. U.S. Geological Survey Report, 27 p.

Hershey, H.G., Brown, C.N., Van Eck, O. and Northup, R.C. 1960. Highway construction materials from the consolidated rocks of southwestern Iowa. Iowa Highway Research Board, Bulletin no. 15, 151 p.

Herzog, H. and Golomb, D. 2004. Carbon capture and storage from fossil fuel use. In: Cleveland, C.J. (ed.), Encyclopedia of Energy, Elsevier Science Inc., New York, NY, p. 277-287.

Horick, P.J. 1984. Silurian-Devonian Aquifer of Iowa. Iowa Geological Survey, Miscellaneous Map Series 10, 4 sheets.

Horick, P.J. and Steinhilber, W.L. 1973. Mississippian Aquifer of Iowa. Iowa Geological Survey, Miscellaneous Map Series 3, 3 sheets.

Horick, P.J. and Steinhilber, W.L. 1978. Jordan Aquifer of Iowa. Iowa Geological Survey, Miscellaneous Map Series 6, 3 sheets.

IPCC 2007. Summary for policymakers. In: Solomon, S., Qin, D. and Manning, M. (eds.), Climate Change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change.

Landis, E.R. and Van Eck, O.J. 1965. Coal resources of Iowa. Iowa Geological Survey, Technical Paper no. 4, 141 p., 1 plate.

Libra, R.D., Hallberg, G.R., Ressmeyer, G.G. and Hoyer, B.E. 1984. Part 1: Groundwater quality and hydrogeology of Devonian-carbonate aquifers in Floyd and Mitchell counties, Iowa, p. 1-106, 20 figs., 15 tables, 2 appendices. Witzke, B.J., and Bunker, B.J., Part 2: Devonian stratigraphy of north-central Iowa, p. 107-149, 6 figs., 1 appendix: Iowa Geological Survey, Open-File Report 8 4 -2.

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. Iowa Geological Survey Special Report Series No. 2, p. 77-112.

Lyons, P. 1950. A gravity map of the United States. Tulsa Geological Society Digest, v. 18, p. 33-43.

Metz, B., Davidson, O., de Coninck, H., Loos, M. and Meyer, L. (eds.) 2005. IPCC Special Report on Carbon Dioxide Capture and Storage, Cambridge University Press, 431 p.

Milanovsky, E.E. 1981. Aulocogens of ancient platforms: problems of their origin and tectonic development. Tectonophysics, v. 73, p. 213-248.

Ocola, L.C. and Meyer, R.P. 1973. Central North American Rift System: 1. Structure of the axial zone from seismic and gravimetric data. Journal of Geophysical Research, v. 78, n. 23, p. 5173-5194.

Pacala, S. and Socolow, R. 2004. Stabilization wedges - solving the climate problem for the next 50 years with current technologies. Science, v. 305, p. 968-972.

Pope, J.P, Witzke, B.J., Anderson, R.R., Ludvigson, G.A., Bunker, B.J. and Greeney, S. 2002. Bedrock geology of south-central Iowa; digital geologic map of Iowa, phase 4. Iowa Geological Survey, Open File Map 02-2.

Randolph, J.B. and Saar, M.O. 2008. Preliminary numerical modeling of CO_2 injection and storage in deep saline aquifers: current research scenarios, and required data. In: Thorleifson, L.H. (ed.), Potential capacity for geologic carbon sequestration in the Midcontinent Rift System in Minnesota. Minnesota Geological Survey Open File Report OFR-08-01, p. 100-118.

Runkle, A.C., Miller, J.F, McKay, R.M., Palmer, A.R. and Taylor, J.F. 2007. High-resolution sequence stratigraphy of lower Paleozoic sheet sandstones in central North America: the role of special conditions of cratonic interiors in development of stratal architecture. Geological Society of America Bulletin, v. 119, p. 860-881.

Schmoker, J.W. and Palacas, J.G. 1990. Porosity of Precambrian sandstones in the lower portion of the Eischeid #1 well, Carroll County, Iowa. In Anderson, R.R. (ed.), The Amoco M.G. Eischeid #1 deep petroleum test Carroll County, Iowa. Iowa Geological Survey Special Report Series No. 2, p. 135-142.

Schrag, D.P. 2007. Preparing to capture carbon. Science, v. 315, p. 812-813.

Schroeder, K., Ozdemir, E. and Morsi, B.I. 2002. Sequestration of carbon dioxide in coal seams. Journal of Energy and Environmental Research, v. 2, n. 1, p. 54–63, U.S. Department of Energy, National Energy Technology Laboratory, First National Conference on Carbon Sequestration, 2001.

Sims, P.K. and Zietz, I. 1967. Aeromagnetic and inferred Precambrian paleogeologic map of east-central Minnesota and part of Wisconsin. U.S. Geological Survey, Map G.P. 563.

Thiel, G.A. 1956. Correlation of gravity anomalies with the Keweenawan geology of Wisconsin and Minnesota. Geological Society of America Bulletin, v. 67, p. 1079-1100.

Witzke, B.J., Anderson, R.R., Bunker, B.J. and Ludvigson, G.A. 2003. Bedrock geologic map of southwest Iowa; Digital geologic map of Iowa, phase 5. Iowa Geological Survey, Open File Map 03-1, map with text.

Witzke, B.W. 1990. General stratigraphy of the Phanerozoic and Keweenawan sequence, 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. Iowa Geological Survey Special Report Series No. 2, p. 39-58.

Wold, R.J. and Hinze, W.J. (eds.) 1982. Geology and tectonics of the Lake Superior Basin. Geological Society of America, Memoir 156, 280 p.

Yarger, H.L., Robertson, R., Wentland, R. and Zeitz, I. 1968. Recent aeromagnetic and gravity data in northeastern Kansas.

Zietz, I., Gilbert, F.P. and Kirby, J.R Jr. 1976. Aeromagnetic map of Iowa: color coded intensities. U.S.G.S. Geophysical Investigations Map GP-911, 1:1,000,000 scale.