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The Waukesha Fault and Its Relationship to the Michigan Basin: A Literature Compilation

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INTRODUCTION

The Waukesha Fault is located in southeastern Wisconsin, crossing through several counties including Waukesha, Washington, Ozaukee, Milwaukee, and Walworth. In the Waukesha area, increased groundwater use, due to rapid urban development, has lowered water levels in the deep sandstone aquifer by more than 500 feet. The Waukesha Fault may play a role in allowing groundwater to recharge the deep sandstone aquifer. Understanding its location and extent is essential to understanding groundwater flow in southeastern Wisconsin.

This report compiles available information on the Waukesha Fault. Much of the detailed geologic information for the southeast portion of Wisconsin is derived from earlier works, such as Thwaites (1956) and Chamberlain (1877) (Brukardt, 1983). More recent information has been pieced together using well logs, core samples from wells, quarry exposures and geophysical surveys and is available from the Wisconsin Geological and Natural History Survey. To better understand the placement and shape of the Waukesha Fault, the geologic history of the fault and its relation to adjacent regions must be understood. The Waukesha Fault is located in the southeastern portion of Wisconsin, on the western rim of the Michigan basin and adjacent to the Wisconsin arch [fig. 1]. Understanding the mechanisms that formed and control the basin are essential to understanding the formation of the Waukesha Fault.

REGIONAL SETTING

The Michigan basin is approximately 250 km in radius and nearly 5 km deep in the center (Howell & van der Pluijm, 1999). It is an intracratonic structural basin formed mainly during the Paleozoic and bordered by the Wisconsin, Kankakee, and Cincinnati arches [fig. 2]. It has a complex tectonic history of subsidence, which has been the source of study and controversy. Many theories have surfaced as to the formation of the basin, including thermal evolution with lithospheric flexure and more than one theory about episodic subsidence. However, no consensus has been reached.

SOUTHEAST WISCONSIN

The southeastern region of Wisconsin is located on the western rim of the Michigan basin but is separated from the main basinal area by Lake Michigan. As such, it is not often acknowledged as being part of the Michigan basin. The geology of southeast Wisconsin can be broken down into three packages: a Precambrian basement, overlying Cambrian to Silurian sediments, and a covering of glacial till.

STRATIGRAPHY

Much of the presently observed stratigraphy of the Eastern Interior of North America can be explained in terms of a relatively simple pattern of loads applied in the Appalachian orogen coupled with subsidence and sediment loading within the intracratonic Michigan basin (Beaumont *et al*., 1988). Although I describe the Michigan basin area, the stratigraphy of southeast Wisconsin will be the main focus [fig. 3].

Precambrian

The Precambrian rocks of southeast Wisconsin, though rarely exposed, are thought to be mostly granite and metamorphic rocks (Cohee, 1948). The Precambrian basement is depicted as being predominantly peneplain (Moll, 1987), and well logs show the contact between the Paleozoic sediments and the basement rocks dips gently eastward. The basement consists of granite, red and green slate, and pink quartzite (Foley, 1953).

Based on data gathered from isotopic dating, structural trends, and deep well samples, the basement is composed of two major structural provinces [fig. 4], the Penokean Province (1.6-1.8 b.y.) in northern Wisconsin and the granitic and felsic Central Province (1.2-1.5 b.y.) in east central Wisconsin (Moll, 1987 and Ryder, 1996). These provinces overlap, creating a transitional zone. Southern Wisconsin underwent a post-Penokean anorogenic volcanic and plutonic event that emplaced granite and rhyolite into the area. During subsequent plutonic activity, mafic and rhyolitic dikes were intruded into the Precambrian basement.

Cambrian

The Cambrian consists of two main sandstone units in southeast Wisconsin: the Mt. Simon sandstone and the Eau Claire sandstone, both of which are from the Elk Mound Group (Ostrom, 1967).

The Mt. Simon sandstone, which is the time equivalent to Jacobsville sandstone in northern Michigan (Cohee, 1948), is a fine- to coarse-grained sandstone with the occasional dolomite bed (Foley, 1953). Although it is Late Cambrian in age, it is the basal unit of the Paleozoic section in southeast Wisconsin, lying unconformably on the basement rock. Consequently, it has a relatively large variation in thickness, from 300-800 feet (Paull & Paull, 1977). Its hydrologic characteristics are important, as it is a major aquifer in the Milwaukee-Waukesha region. Although it has a high permeability overall, the local permeability varies vertically due to changes in grain size and the presence of silty and dolomitic layers (Foley, 1953).

The Eau Claire sandstone, which overlies the Mt. Simon sandstone, is a medium- to fine-grained light gray sandstone that also contains siltstone, glauconite, and many beds of green, red, or sandy shale, which can be up to 30 feet thick. The sandstone is commonly 220-270 feet thick, has low permeability, and is well consolidated (Foley, 1953).

The Dresbach (Galesville) sandstone, Franconia (Tunnel City) sandstone, and Trempealeau Formation are present in most other areas of the basin, but were predominantly removed from the Milwaukee-Waukesha area. There are a couple areas where these units are present: Carrollville and southwest of Pewaukee (Foley, 1953).

Ordovician

The St. Peter sandstone lies unconformably on the Eau Claire sandstone. This Middle Ordovician unit is a distinctive white, massive-bedded, well-sorted quartz sandstone. Many of the quartz grains have a frosted appearance, indicating that they were deposited as dunes (Paull & Paull, 1977). There are occasional dolomitic beds present, usually where the beds are less than 100 feet thick. The sandstone is water yielding and ranges in thickness from 80 to 357 feet (Foley, 1953).

The Platteville limestone, Decorah limestone, and Galena dolomite are commonly grouped together as the Sinnipee Group in well logs, and they overlie the St. Peter sandstone. They are described as light gray to blue-gray dolomite. The basal part of this formation is a zone of very sandy dolomite (or dolomitic sandstone) and is not classified as an aquifer (Foley, 1953). These units formed under normal marine, moderately shallow conditions (Paull & Paull, 1977).

The Maquoketa shale, which overlies the Sinnipee Group, is mostly a blue-gray dolomitic shale, which acts mainly as an aquitard between the Cambrian and Silurian aquifers. The dolomite beds may contribute small amounts of water, but it is common practice to case it out (Foley, 1953). After a minor unconformity, the seas returned with muds from the Taconic orogeny, depositing the Maquoketa shale (called the Richmond in northern Michigan). The Maquoketa is a shale with thin-bedded dolomitic limestone and interbedded nodular limestone, and it varies in thickness. The thickness and lithology varies and reflects the influence of the eastern source area; it is thickest (350 feet) in northeast Wisconsin and thins down to about 100 feet in the southwest part of the Michigan basin area (Paull & Paull, 1977). The Maquoketa shale is exposed in the Waukesha Lime & Stone Company quarries.

Silurian

Niagara dolomite is an all-encompassing term used by Foley (1953); however, Rovey (1990) broke the Silurian units down into differentiated beds.

The Mayville dolomite, the oldest Silurian bed in the Waukesha area, is a thick-bedded (~26m), vuggy dolomite with cherty intervals and argillaceous dolomite or mudstone at the base (Kluessendorf & Mikulic, 1994). The Mayville correlates with the Kankakee dolomite (Plaines Member) (Kluessendorf & Mikulic, 1994).

The Byron Formation overlies the Mayville dolomite with a "pulsating" contact (Rovey, 1990). It is a very hard, thick-bedded, very light to dark gray, dense, fine-grained dolomite mudstone that is easily recognized throughout southeast Wisconsin (Rovey, 1990).

The Franklin Member (which is eroded to the south of Franklin, WI) of the Manistique Formation lies between the Byron Formation and the Brandon Bridge Member. The Franklin Member is generally a dark gray, thin-bedded, very cherty dolomite (Rovey, 1990).

The Brandon Bridge Member contact with the overlying Byron, where the Franklin is absent, is marked by an undulating, pitted surface with concentrated glauconite. The Brandon Bridge Member is an argillaceous, fossiliferous, thin-bedded, variegated dolomite with reddish and greenish hues, generally classified as a mudstone (Rovey, 1990).

The Manistique Formation, which includes the Waukesha Member, is a light gray thin- to medium-bedded, dense, fine-grained dolomite with chert beds along bedding planes (Rovey, 1990).

Pleistocene

The glacial till varies from a few inches up to 400 feet thick and varies in composition (Brukardt, 1983).

BASIN FORMATION

Haxby *et al*. (1976) studied the thermal and mechanical evolution of the Michigan basin, proposing a model based on thermal decay of a load produced by an initially hot region in the lower crust or upper mantle. The load originated as a diapiric intrusion from the asthenospheric mantle that penetrated into the lithosphere and eventually ascended to the Mohorovicic discontinuity. The lower crust was heated by the diapir, forming a halo of gabbroic lower crustal rocks that metamorphosed into garnet eclogite. The downward buoyancy of the forming eclogite balanced the upward buoyancy of the diapir. As the diapir cooled and the upward buoyancy diminished, the lithosphere was deflected downward, consequently forming the Michigan basin [fig. 5] (Haxby *et al*., 1976).

In a study by Coakley *et al*. (1994), a different model for the formation of the Michigan basin was presented, based on the idea that intracratonic basins of North America share similar tectonic settings and have correlative sedimentary sequences of similar lithostratigraphy (Coakley *et al*. 1994 after Sloss, 1963). In order to understand the development of the basin, Coakley *et al*. (1994) focused on the response of the Michigan basin to the Appalachian Orogenies. Stratigraphic evidence suggests the Michigan basin was intermittently linked to the Appalachian foredeep, which was formed in response to thrust loading of the lithosphere in the Early Ordovician. Starting with the Ordovician St. Peter sandstone, the accumulation of sediments (mainly carbonates) in response to the Taconic orogeny spread from the Appalachian foredeep across the topographically low Findlay-Algonquin arch into the Michigan basin [fig. 6]. Further proof that the Appalachian foredeep influenced the Michigan basin lies in subsequent sedimentary packages from the Acadian and Ouachita orogenies (Coakley *et al*., 1994). Throughout the orogenic sequences, the Findlay-Algonquin arch was uplifted and relaxed several times, indicating great tectonic activity. A purely qualitative model proposed by Walker *et al*. (1983) indicates the elastic lithosphere responded to the thrust loading and basin-filling processes, and expanded and deepened the Appalachian foredeep (Coakley *et al*., 1994). However, the amount of subsidence caused by sediment loading does not account for all the subsidence that occurred in the Michigan basin. Instead, a crust or lithosphere with inhomogeneities, reactivated by periodic regional stresses, might produce a better model of basin initiation and evolution (Coakley *et al*., 1994).

Howell and van der Pluijm (1990, 1999) developed a different model for the formation of the basin using a detailed stratigraphic investigation to justify documented episodic subsidence along with a mechanism for subsidence.

The mechanisms that facilitated subsidence of the Michigan basin involve an excess mass in the upper crust and a lower viscosity lower crust [fig. 7]. The low viscosity crust serves as a crustal asthenosphere, causing a mechanical decoupling of the lower crust and upper mantle. This decoupling then leaves the excess mass supported only by a thin upper-crustal plate, thus causing the upper crust to subside into the low-viscosity zone (Howell & van der Pluijm, 1990). A large Bouger anomaly in the central Michigan basin supports the idea of an excess mass under the basin. The crustal weakening that caused subsidence may have been related to repeated orogenic stresses from the eastern margin of the North American plate or from the regional fluid-migration events associated with the same orogenic activities (Howell & van der Pluijm, 1990).

Howell and van der Pluijm (1999) have not identified a precise mechanism for subsidence; however, they do acknowledge that there is an observed temporal correlation between Appalachian orogenic activity and the subsidence history of the Michigan basin.

During Cambrian through Silurian time, there was a series of subsidence reactivations and cessations, a history not compatible with simple thermal contraction models. A series of seven sequences are presented [fig. 8] that separate the events of subsidence and the layout of deposition. These sequences outline the activities that occurred in the basin throughout the Paleozoic.

Sequence A (Cambrian-Lower Ordovician) shows the basin is open to the south in a trough shape with deposition occurring in relatively shallow water. Next, Sequence B (Lower Middle Ordovician) consists of narrow, basin-centered subsidence and separation of the Michigan and Illinois basins. Uplift and erosion was occurring on the Kankakee arch and in Wisconsin. The St. Peter Sandstone was deposited in areas where the Lower Ordovician and Upper Cambrian rocks were eroded. Sequence C (Middle Upper Ordovician) was a period of eastward tilting toward the Taconic margin of North America. The carbonate depocenters were primarily shallow-water platforms, and the Cincinnatian units (undifferentiated) were capped by a regional unconformity that is found throughout the basin and its margins. Sequence D (Lower Upper Silurian) consisted of broad basin-centered subsidence that filled the topographic lows left by the Taconic disconformity. Sequence E (Uppermost Silurian-Middle Devonian) returns the basin to a narrow basin-centered subsidence. Toward the central basin area, evaporates grade upward into nonfossiliferous carbonates and quartzose sandstones, which are distinct along the basin margins. There is an extensive unconformity present on the basin margins near the Silurian-Devonian boundary that is not recognized in the central basin. Sequence F (Uppermost Middle Devonian) is a period of broad basin-centered subsidence with deposition occurring in shallow water, marine environments. Sequence G (Upper Devonian-Mississippian) reverts the basin back to a time of eastward tilting. This sequence marked a time of extensive erosion around the basin margin. (Howell & van der Pluijm, 1999)

Although the current shape of the Michigan basin is well established, the origin of the basin remains to be mysterious. One prevalent theory points to the midcontinent rift system [fig. 4] as contributing to the original trough shape in the Precambrian basement. Predominantly noticed as a geophysical anomaly stretching from central Kansas to Lake Superior and then turning southward through central Michigan, the midcontinent rift creates a structural trough below the Phanerozoic sedimentary rocks of the Lower Peninsula of Michigan (Van Schmus & Hinze, 1985). This anomaly is easily discernable from gravity and magnetics surveys. The gravity anomaly of the mid-Michigan geophysical anomaly is continuous across the state of Michigan, but the associated magnetic anomaly only occurs along segments of the feature, suggesting discrepancies in the underlying volcanic rocks (Van Schmus & Hinze, 1985). Regardless of compositional variations, the interpretation of geophysical surveys, including seismic reflection surveys, indicates that the principal shallow manifestation of the midcontinent rift system is a trough that initially filled with interbedded volcanic and clastic rocks that were later covered by more clastic sediments (Van Schmus & Hinze, 1985).

WAUKESHA FAULT

The Waukesha Fault is a normal fault, trending approximately northeast-southwest. The precise location, extent, and shape of the Waukesha Fault have been a source of controversy for over 70 years [fig. 9]. Early studies of the fault were a result of poorly constrained data from shallow wells and the one known exposure located in the Waukesha Lime & Stone quarry [fig.10] (Sverdrup *et al*., 1997).

The relaxation of the lithospheric stress set up by the Appalachian orogen, the Michigan basin, and the Illinois basin produced flexural uplift and erosion patterns across the adjacent arches: Wisconsin, Cincinnati, Findlay, and Kankakee (Beaumont *et al*., 1988, Quinlan & Beaumont, 1984). The Wisconsin arch, a broad, 160° trending fold that extends from central Wisconsin southeastward into Illinois (Pirtle, 1932), forms the far western edge of the Michigan basin. The Waukesha Fault lies between the Wisconsin arch and the main depositional center of the Michigan basin. There was undoubtedly intermittent movement along the axis of the fold throughout Paleozoic time (Pirtle, 1932).

In a study by Kuntz and Perry (1976), past reports of the Waukesha and other faults from southern and eastern Wisconsin were discussed, showing the inconsistent interpretations that have emerged. Kuntz and Perry (1976) highlight the work of F.T. Thwaites, who cited three different interpretations of the Waukesha Fault in three separate papers [fig. 11]. Thwaites (1937) showed the fault starting at the Illinois border and continuing northeastward through Waukesha and Ozaukee counties into Lake Michigan with an overall length of 84 miles. Later, Thwaites (1940) showed two faults in the Waukesha area, but in 1957, Thwaites reverted back to one major fault. The shortest reported length, 38 ½ miles, was mapped by the USGS and AAPG (1962) [fig. 12]. It was later mapped by the USGS in 1968, where it was a maximum at 133 miles long [fig. 13] (Kuntz & Perry, 1976). The reports all varied on where the fault starts, in Wisconsin or Illinois, and where it ends, near or in Lake Michigan. There has also been some confusion as to the amount of displacement on the northwest vs. the southeast side of the fault. Thwaites (1931) reported that there is about 1000 feet of downward displacement of the Precambrian surface on the southeast side; however, there have been reports by Heyl *et al.* (1959) and Rudman *et al.* (1965) that showed the downward displacement to be on the northwest side of the fault, both of which are speculated to be the result of drafting errors [fig. 14] (Kuntz & Perry, 1976).

The Waukesha Lime & Stone Company quarry, located in Waukesha County, has the only known exposure of the Waukesha Fault [fig. 10]. At the quarry, the fault offsets the Silurian beds by 26 feet, with the downthrown side to the southeast. Even though this outcropping is often referred to as the Waukesha Fault, it is not certain as to whether this is the main fault or a splay of the of the main fault.

TECTONIC THEORIES AND POSSIBLY ANALOGOUS FRACTURES, JOINTS, AND FEATURES

The Waukesha Fault is located in southeastern Wisconsin on the western rim of the Michigan basin. Since the fault is located within the basin, it is possible for the formation of the fault to be related to the tectonic activity that impacted the Michigan basin and for the fault to be analogous to other features present in the basin.

Tectonic Applications

In the region between the Appalachian foreland basin and the interior cratonic basins, there are a number of basement faults that are the product of plate convergent processes (Late Precambrian Grenville and Granite-Rhyolite Province convergence or Late Proterozoic crustal extension of the eastern mid-continent) [fig. 15] (Root & Onasch, 1999). These faults, which generally involve the Precambrian basement but are first observed in basal Cambrian strata as normal faults associated with passive margin rifting, have an extended deformational history (Root & Onasch, 1999). The faults continued to be active throughout the Paleozoic as growth faults; however, the Alleghanian deformation in the Pennsylvanian-Permian time reactivated many of these faults as wrench faults (Root & Onasch, 1999).

Prouty (1988) discusses a wrenching model to account for the linear intrastructures of the Michigan basin. The post-Mississippian reshaping of the basin indicates that a shearing stress brought about the elongation of the basin and a westward shift in the basin center (Prouty, 1988). However, it is unclear as to whether these activities played a role on the Waukesha Fault since most of the inner basin, not basin rim, structures were formed at this time. The Michigan basin is commonly studied for purposes of oil and gas exploration. Thus far, all of the fields tend to be linear and narrow, suggesting faulting and fracturing (Prouty, 1988). The Howell Anticline, a prominent structure in lower central Michigan [fig.1], was formed by post-Mississippian events described above and therefore cannot be used as an analogy. The Albion-Scipio Trend is another feature located in lower central Michigan [fig. 1]. This trend consists of en echelon faults and cross faults originating from shear faulting (Prouty, 1988). Other en echelon systems, such as the West Branch field and the Kawkawlin field, were found in the Michigan basin, which helps provide support for a wrenching tectonic system theory. The possibility exists for the Waukesha Fault to be part of an en echelon fault system either locally or regionally with other faults located along the eastern edge of Wisconsin.

Computer Models

Beaumont et al. (1988) and Quinlan and Beaumont (1984) used computer generated models to constrain estimates of the orogenic loading, dominated by the influence of the Taconic, Acadian, Alleghanian, and Ouachita orogenies that occurred in the Eastern Interior of North America from Early Ordovician through the end of the Permian time. The computer models followed the deposition and erosion of sedimentary packages through a number of model time steps in order to calculate a synthetic stratigraphy for the given study area (Beaumont *et al*., 1988). The result is an outline of the lithosphere flexing under orogenic loads and then relaxing during quiescence. With only minor exceptions near the Ordovician-Silurian boundary, flexurally raising and lowering the surface of the lithosphere against a background of constant sea level can explain the major features of the stratigraphy in the study area (Beaumont *et al*., 1988). It is not being suggested that no changes in sea level occurred but only that sea level changes are not necessary to explain the bulk of the stratigraphic record, according to the models produced. Using a viscoelastic plate with a temperature dependent viscosity structure (Quinlan & Beaumont, 1984), the computer-generated models ultimately help to explain the amount of lithospheric flexure necessary to allow for the subsidence of the Michigan basin.

Stress Studies

Using hydrofracturing tests in deep wells, Haimson (1978) found the state of stress in the upper crust of the Michigan basin to be indicative of a stable interior. However, the stress regime of the basin is one that could theoretically facilitate the three major types of faulting (Haimson, 1978). Strike-slip and normal faults are possible due to the vertical and maximum horizontal stresses being close in magnitude, and other testing showed the vertical stress is only slightly larger than the minimum horizontal stress, making thrust and strike-slip possible (Haimson, 1978). The overwhelming regional direction of maximum horizontal stress in the Midwest-Ontario region seems to be N60E-N70E [fig. 16], which Haimson suggests can be applied to the Michigan basin (Haimson, 1978).

Joints and Fractures in Michigan

In a study by Holst and Foote (1981) and again by Holst (1982), joint orientation was measured at a total of 142 locations in the Devonian rocks located in the northern portion of the Michigan basin [fig. 17]. The 1981 study by Holst and Foote found four major vertical joint sets at 052°, 134°, 091°, and 001° in the carbonate rocks [fig. 18]. The joints do not appear to be simply related to the formation of the Michigan Basin because the orientation of the various sets is independent of the regional strike around the basin, which varies from 054° to 114° in the study area (Holst & Foote, 1981). The joints also do not appear to be strongly related to basement structural trends, large folds and faults having an orientation of 120° to 150° [fig. 19] (Holst, 1982). No folds were observed in the Cambrian, Ordovician, or Silurian rocks; however, there was a fold found in the Devonian rocks at one of the localities of the study that did show a good similarity to the northwest joint trend (Holst, 1982). The northeast-trending (052°) set of joints appears to be extension joints related to the present-day tectonic stresses in the region (Holst, 1982).

In a study by Berndt and Morgan (2000), vertical joint orientation was measured in Devonian and Pennsylvanian rock at several locations in Michigan. The result was a predominant orientation between 040° and 060°, with less prevalent joints striking NW or NNE (Berndt & Morgan, 2000). Similar joints, striking NE, were found on the Appalachian Plateau in New York State and were associated with Alleghanian stresses, and it is suggested that the Alleghanian stresses or possibly a modern day tectonic stress field is responsible for the joint orientation in Michigan (Berndt &Morgan, 2000).

Apotria *et al*. (1993, 1996) studied the fracture patterns and history of the Devonian Antrim Shale of the Michigan basin. Both studies state that the NW-striking fractures formed as a result of natural hydraulic fracturing (NHF) from compression at the end of the Alleghanian orogeny. Conversely, the NE-striking fractures formed as a result of cooling and unloading during basin uplift of nearly 4000 feet since the Permian, and the fractures are aligned with the modern day, NE-directed maximum horizontal stress found in the mid-continent region (Apotria *et al*., 1996).

The origin of the Devonian Antrim Shale fracture patterns of northern Michigan was studied by Ryder (1996). The regional and local tectonic events in the vicinity of the

Michigan basin were considered in evaluating the origin of the fractures. One or more of the following events is proposed as being likely to have made an impact on the nature and origin of the Antrim Shale fractures: 1) pre-Michigan basin Proterozoic tectonics may have left structures in basement rocks that became reactivated by later tectonic events; 2) the northwest-southeast oriented Paleozoic compressional stresses from the Alleghanian orogeny may have reactivated the basement structures and/or created new structural fabrics; 3) post-basin uplift and cooling of the crust in Mesozoic and post-Pleistocene times and modern intraplate compression may have accentuated pre-existing fracture patterns or created new fractures (Ryder, 1996).

Joints and Fractures in Wisconsin

Fracture patterns in Silurian dolomite in northeastern Wisconsin have been used to infer paleostress orientations, giving evidence of the tectonic history of the region (Underwood *et al*., 2003). Fracture orientations measured in Door County, Wisconsin, [fig. 20] were found to resemble those in other parts of the Michigan basin (Holst & Foote, 1981; Holst, 1982; Berndt & Morgan, 2000; Ryder, 1996). Fracture mapping at a quarry in Door County discovered dominant fracture orientations of 040° and 160°, which, through further investigation, were found to be joints (Underwood *et al*., 2003). The Door County fractures have been inferred to be a result of either the present day stress field (~050°) (Haimson, 1978) or past stress fields of the Appalachian and Ouachita orogenies (134° and 001° respectively) (Underwood *et al*., 2003 after Craddock & van der Pluijm, 1989).

GEOPHYSICAL TECHNIQUES

The Waukesha Fault is an important feature in southeastern Wisconsin; however it is not well understood due to its very limited exposure. The use of geophysical techniques can help to clarify the ambiguities of the virtually unseen fault.

Gravity Studies

There have been very few investigations of the Waukesha Fault using geophysical means. However, one method that has been used for a number of different studies has been gravity. In 1974, C. Patrick Ervin and Sigmund Hammer completed a Bouger Anomaly map of the state of Wisconsin, which was a compilation of previous gravity surveys (Brukardt, 1983). According to Brukardt, this map shows a contour line passing through Waukesha County, approximately lining up with the known exposure of the Waukesha Fault.

For her 1983 Master's thesis, Brukardt surveyed all of Waukesha County in a one-mile spaced grid, using a LaCoste and Romberg G158 gravimeter [Plate 1]. Her results showed a general trend in the Bouger anomaly [Plate 2] that agrees with the general bedrock trend for the region as well as the gravity trend found by Ervin and Hammer (Brukardt, 1983). The major anomaly, that changed by more than 8 milligals across the fault, has a predominantly linear trend, oriented at about 040° with an offset near the center of Waukesha County. The fault located by the gravity survey is continuous with the fault exposed at the Waukesha Lime & Stone quarry. Near the center of Waukesha County, the Bouger anomaly contours become more widely spaced. In the southwest portion of the map, the contours continue to spread out and also turn from their original orientation. There is a second linear trend, with a slightly smaller gravity anomaly than the main fault, shown on the Bouger map that is oriented toward the northwest at about 120° and does not conform to any of the topography of the area. The two trends meet in the area between T7N, R18E and T6N, R19E, which is where the gravity contours start to spread out. Brukardt hypothesizes that the difference could be due to a change in the fault's dip or increased displacement across the fault. She states that this second trend is possibly from a shallower dipping fault because the signal is not as strong, and the trend is probably younger because it does not affect the major anomaly.

Brukardt also constructed cross sections of Waukesha County using well logs. The cross sections support her findings from the gravity survey. She notes that some of the gravity differences can be attributed to the increased thicknesses of the sedimentary beds on the southwest side of the fault, which are easily seen in cross sections. Although there is offset seen in the Waukesha Lime & Stone quarry, it is not clear if the Silurian and Ordovician formations are all penetrated by the fault throughout the region since the offset of the Precambrian is enough to account for the changes in the gravity values.

Brukardt used a computer modeling program to produce a viable gravity model of Waukesha County that would satisfy her data. With standard gravity values given for the known lithologies, the only aspect left to specify was the dip angle for the fault. Using the exposure at the Waukesha Lime & Stone quarry as a base, the fault was modeled as being nearly vertical. However, the resulting model did not provide a good fit to the actual gravity data. Brukardt found that a fault angle of 70° produced the best model, and the angle corresponded well with the geology of the area while accounting for the changes in the Precambrian basement as it crosses the fault.

From her survey, Brukardt concluded several important pieces of information. 1) The Silurian formations in the fault's area have 30 to 50 feet of displacement while the Precambrian is displaced about 1000 feet. 2) This difference in displacement, a result of more than one episode of major activity, is seen as an anomaly that changes more than 8 milligals across the fault. 3) The spreading out of gravity contours in the area around Waukesha is most likely the result of a change in the fault angle. Brukardt also acknowledges that the theory of a second fault in the county is not conclusive and could be explained instead by flexure in the beds or a very thick layer of glacial till (Brukardt, 1983).

In a report presented in 1997, Sverdrup *et al*. displayed their results of combined gravity surveys conducted in Waukesha County by Brukardt (1983) and in parts of Washington, Ozaukee, and Milwaukee Counties by Sharon Herb in 1985 [fig. 21]. The resulting gravity data showed a northeast-trending zone roughly 5 km wide of tightly spaced contours [fig. 22]. This trend is assumed to be the Waukesha Fault. The northwest side of the trend produced gravity values approximately 10 milligals greater than the region on the southeast side of the trend [fig. 23]. Sverdrup *et al*. were more specific as to the exact location of the trend zone, deduced from the contour lines:

> At the southwestern end, the gravity signature trends roughly N19E for 10 km from a point 3 km south of Eagle, Wisconsin on the Waukesha-Walworth County line to the town of North Prairie. At North Prairie it turns to N47E and continues for about 13 km to a point due west of Waukesha where it offset in a right-lateral sense 3 km to the western edge of the city of

> Waukesha. … From that point, it extends 23 km at N38E through Menomonee Falls to the Washington-Waukesha county line roughly 2.5 km west of the Ozaukee County line. It then continues for 6 km with a strike of N27E until, about 5 km southwest of Cedarburg, it changes strike to N36E and extends through Cedarburg and Grafton 22 km to Port Washington. The offset in the fault west of Waukesha was interpreted by Brukardt (1983) to be due to a second fault striking N60W.

The gravity data was modeled, taking into account the differential erosion of the Paleozoic sediments due to Pleistocene glacial activity. Also noted were the gently eastward dipping beds of the Precambrian and the variations in Cambrian to Silurian sediments. The model uses the density value of gabbro for the Precambrian beds due to the presence of magnetic and gravity highs found along the shore of Lake Michigan in Ozaukee County. The gravity models without gabbro required 2000 meters or more of displacement in the Precambrian, which is considerably more than was previously estimated.

The fault was initially modeled with a steeply dipping (80°) fault and properly offset Paleozoic beds. However, the results of this model yielded an unsatisfactory high RMS error value. The residual gravity curve suggested that the dip was too steep. Subsequent models were made with shallow dipping faults of 9° and 20°. Sverdrup *et al*. (1997) states that the shallow dip is not contradicted by well data, but that the vertical angle is taken from the exposure of the fault at the Waukesha Lime & Stone quarry. It is suggested, instead, that the fault may be listric, with a very steep dip near the surface and a decreasing angle of dip with increased depth (Sverdrup *et al*., 1997).

The results of this study show the Waukesha Fault to extend through Waukesha and Ozaukee Counties to Lake Michigan. It is not discounted that the fault could be high angle, but it is more accurately modeled as listric (Sverdrup *et al*., 1997). Further study is suggested.

The previous gravity surveys were followed up by a more complete gravity survey in Ozaukee County by Baxter *et al*. (2002) in hopes of further delineating the location and geometry of the Waukesha Fault in this area. A very specific survey, mainly surrounding Highland Road, indicated a significant change in fault geometry over a relatively short distance (Baxter *et al*., 2002). The gravity data was collected at ~1000 foot intervals and then reduced to Bouger anomalies that ranged from a change of ~8 milligals to ~14 milligals across the fault. This survey reinforced the previous findings that showed the northeast-striking, southeast dipping normal fault penetrating and displacing the Paleozoic strata but not the overlying Quaternary till (Baxter *et al*., 2002).

<u>Magnetic Studies</u>

A magnetic survey in southeastern Wisconsin was conducted in 1986 to help supplement the findings of the gravity surveys previous conducted in the area (Moll, 1987). The magnetic survey used a one-mile spaced grid covering 630 square miles over portions of Waukesha, Milwaukee, Ozaukee, and Washington Counties [fig. 24]. The data, collected with total field proton magnetometers, was appropriately corrected, plotted, and contoured to produce a total magnetic intensity map [Plate 3].

Moll cautions that previous research has shown that problems may result from trying to relate magnetic anomalies to specific basement lithologies when limited geological information is available. He states that Patenaude (1966) and Dutton and

Bradley (1970) found positive magnetic anomalies in areas where rocks normally associated with negative anomalies were located. Magnetic minima were correlated with granite and quartzite, which are the most commonly encountered basement rocks in the area, and the magnetic maxima were interpreted as being mafic igneous rocks (Moll, 1987). The Pleistocene deposits, Paleozoic sediments, and Precambrian quartzites were considered to be magnetically insignificant due to their small susceptibilities and low magnetic contrasts (Moll, 1987 after Kean, 1987).

Moll found that his total magnetic intensity map suggests a more complex lithologic and structural pattern for the basement than is indicated by the limited well data. The map is characterized by a discontinuous linear band 37 miles long and 2.5 to 8.5 miles wide of positive anomalies striking about N40E. There is also a semicircular-shaped, intensely positive anomaly located in the southwest corner of the survey. There are other anomalies as well that display greater amplitudes than the surrounding data points. The variation in intensities is probably due to different source depths. These anomalies indicate that mafic rocks should be more prevalent than the well data shows, and this theory is supported by the comparison of the gravity anomaly map and the magnetic anomaly map (Moll, 1987). In the models produced by Moll, the Precambrian surface is found to be approximately 2200 to 3200 feet below sea level on the downthrown side of the fault.

Moll states that the significance of the northeasterly striking band of positive magnetic anomalies is, at best, speculative in relation to the Waukesha Fault. He notes that the crests of the anomalies lie one to two miles west of and parallel to the closely spaced gravity contours, which were previous assumed to indicate the location of the Waukesha Fault. Perhaps the mafic material associated with the magnetic anomalies was intruded into fractures or areas of structural weakness related to the Waukesha Fault, possibly smaller faults in the Precambrian basement (Moll, 1987).

Jansen and Taylor (2000) conducted a time domain electromagnetic (TEM) induction survey in eastern Waukesha County to reveal the location and depth of high total dissolved solids levels in the sandstone aquifer. The aquifer supplies most of the water to Waukesha County and has been heavily exploited over the last century, causing a regional 500 foot deep cone of depression (Jansen & Taylor, 2000). The TEM data displayed different results depending on the location of the survey relative to the Waukesha Fault. The soundings on the northwest (upthrown) side of the fault showed a trend toward rising resistivity with depth, thus indicating high resistivity basement rock while the southeast (downthrown) side of the fault revealed a highly conductive electrical half space at depth, indicating high salinity groundwater (Jansen & Taylor, 2000). The survey reveals more information regarding the TDS levels in the groundwater than information about the geology of the area. However, it is suggested that the Precambrian beds in western Waukesha County may have isolated mounds on their surface and that the Waukesha Fault may be more complex than originally anticipated (Jansen & Taylor, 2000).

CONCLUSIONS

The Waukesha Fault is a more complex structure that was originally thought. Many studies have revealed pieces of crucial information but have not given a complete picture of the Waukesha Fault.

Most reports show the Waukesha Fault as a high-angle normal fault while Sverdrup *et al*. (1997) suggests the Waukesha Fault to be listric. Brukardt (1983) found a possible second, younger fault to accompany the high angle Waukesha Fault. Haxby *et al*. (1976) feel the basin formed as a result of lithospheric compensation under a diapiric load. However, Howell and van der Pluijm (1999) feel there is no single mechanism the fully explains the origin and subsequent evolution of the Michigan basin, but rather, they present a plausible theory of changing subsidence styles that require several mechanisms throughout the Paleozoic time. Since the Waukesha Fault penetrates all the Paleozoic sediments but not the overlying glacial till, the idea of glacial rebound acting as a mechanism for faulting is discredited. Root and Onasch (1999) discuss the reactivation of Precambrian basement faults as normal faults. Could the Waukesha Fault, which appears to follow basement structural trends [fig. 11], be a reactivated basement fault?

More research and geophysical studies need to be undertaken to further constrain important details regarding the Waukesha Fault.

SUGGESTIONS FOR FURTHER STUDY

Gravity and magnetic surveys have been conducted throughout southeastern Wisconsin, but a more complete investigation needs to take place. A seismic survey should be carried out over the region, focusing mainly on the Waukesha Fault. More research needs to be conducted regarding the possibly analogous features in the Michigan basin. Relevant features need to be sorted out from non-pertinent features.

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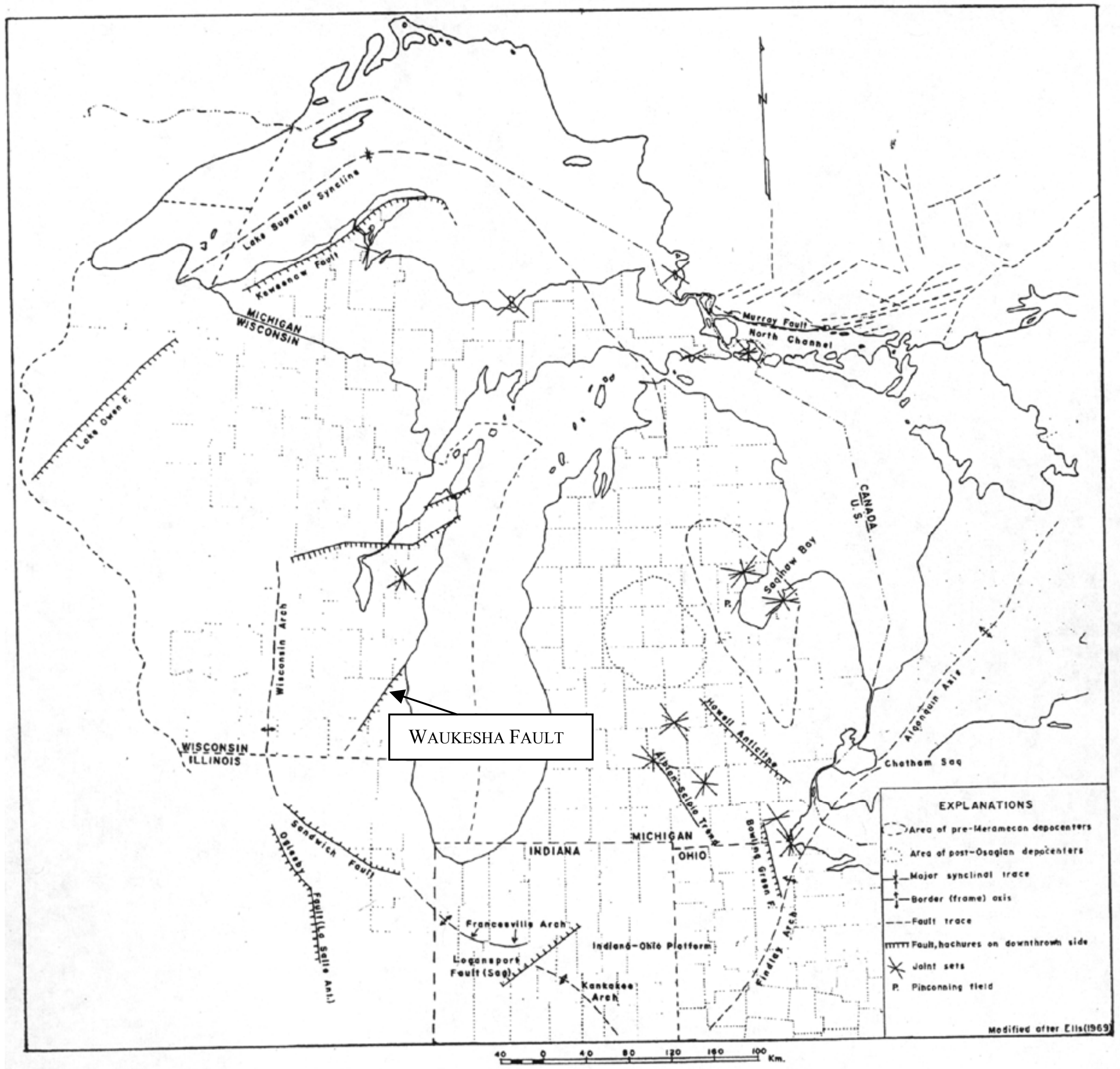


Figure 1- The location of the Waukesha Fault in southeastern Wisconsin. (Prouty, 1988)

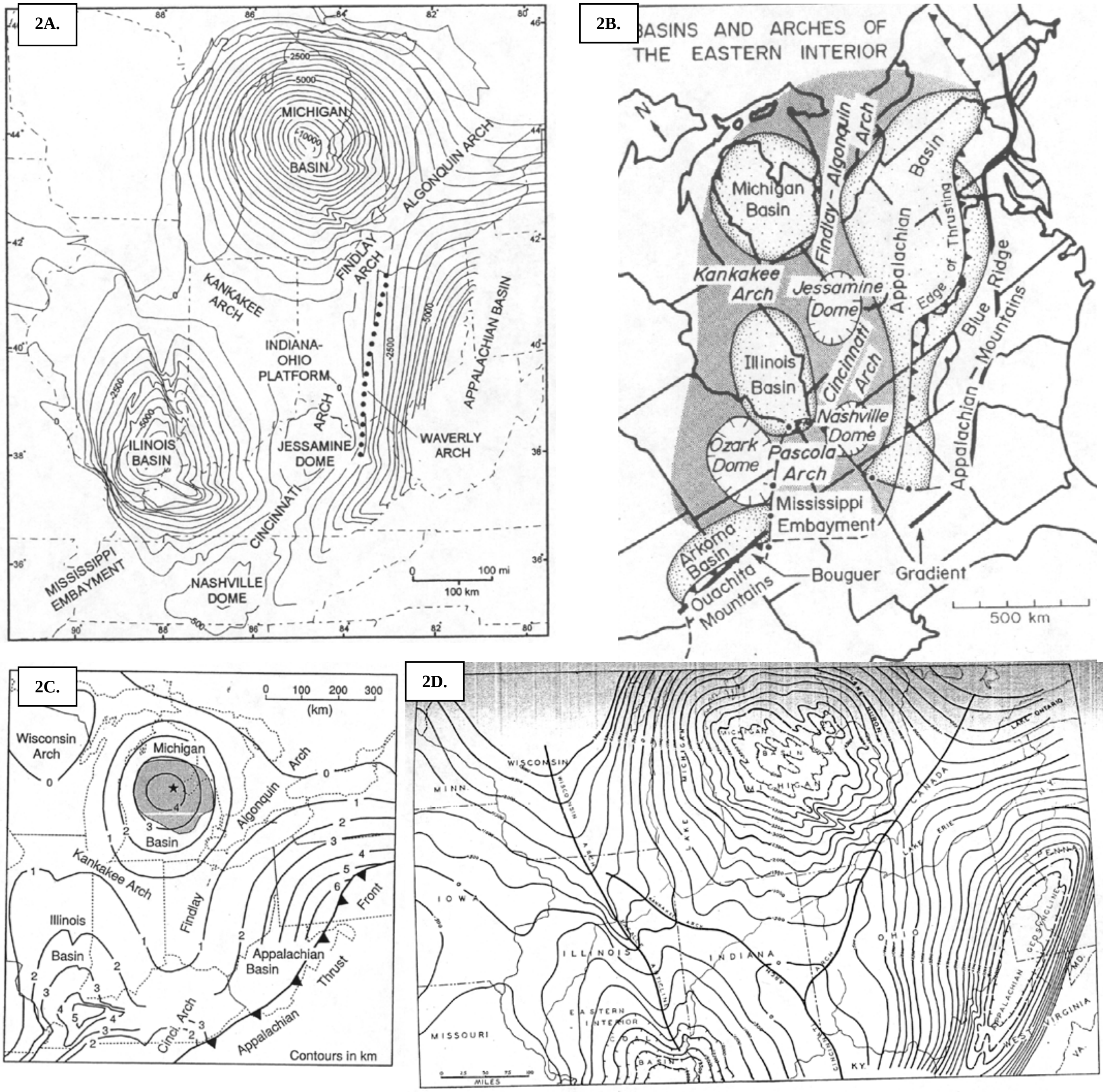


Figure 2- A) Structure contour map of the Upper Ordovician Trenton Limestone showing the location of the Michigan basin in relation to surrounding features including the Wisconsin, Kankakee, and Cincinnati arches (Root & Onasch, 1999). B) Base map of the eastern United States with prominent features indicated (Beaumont *et al*., 1988). C) Contours indicate total thickness of Phanerozoic sedimentary rocks and highlight the basic shape of the Michigan basin (Howell & van der Pluijm, 1990). D) Contours of the Trenton Limestone show the regional structure of the Michigan basin and adjacent areas (Pirtle, 1932).

3A.

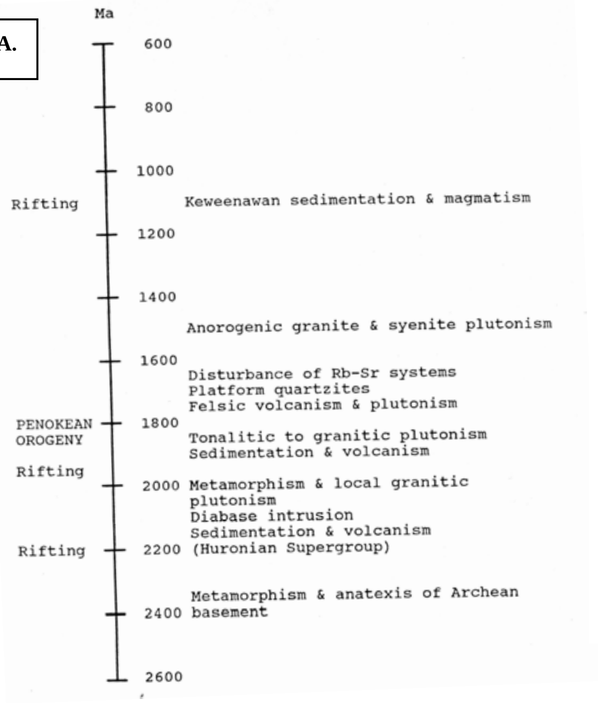


Figure 3-
A) Chronology of Precambrian events in the Great Lakes region. (Moll, 1987)
B) Stratigraphy of the Milwaukee-Waukesha area. (Foley, 1953)
C) Summary of Paleozoic History. (Paull & Paull, 1977)
D) Stratigraphic column of southeastern Wisconsin. (Brukardt, 1983)
E) Geologic column for bedrock and glacial deposits in southeastern Wisconsin. (Brown & Eaton, 2002)
F) Stratigraphic column for the Michigan Basin. (Coakley *et al*., 1994)
G) Intervals of stratigraphy and orogenies. (Beaumont et al., 1988)

3B.

System	Group	Formation	Thickness (feet)	Character	Water-bearing characteristics
Quaternary.		Recent alluvium.	Generally a few feet.	Alluvium, beach sand, peat, muck, marl.	Insignificant; will yield water from sand in places.
		Pleistocene deposits.	0-450	Boulder clay, sand, and gravel.	Yields water from sand and gravel. Important in buried valleys.
		Unconformity			
Carboniferous (Mississippian).			55	Black carbonaceous shale.	Not water yielding.
Devonian.		Milwaukee formation.	110	Gray shale, dolomite, and some limestone.	Yields some water to domestic wells from crevices.
		Thiensville formation.	50	Light- to dark-brown dolomite; some beds bituminous.	Yields some water to domestic wells from crevices.
Silurian.	Cayuga.	Waubakee dolomite.	477	White to gray dolomite; some coral reefs, mostly massive. Crevices and solution channels abundant but inconsistent.	Important aquifer but variable. Yields water from crevices and solution channels. Yields 5 to 600 gpm.
		Niagara dolomite.			
Ordovician.	Richmond.	Maquoketa shale.	90-225	Blue-gray dolomitic shale. Dolomite beds as thick as 40 feet.	Not water yielding. Usually cased off in wells.
		Galena dolomite. Platteville limestone	215-305	Light-gray to blue-gray dolomite; massive; sandy at base.	Yields some water from crevices.
		St. Peter sandstone.	80-357	Sandstone, fine- to medium-grained, white to light-gray, dolomitic in some places. Lower part may represent Dresbach sandstone (Cambrian).	Water yielding. Capacity as aquifer varies with permeability.
		Unconformity			
Cambrian.		Eau Claire sandstone.	105-390	Sandstone, fine- to medium-grained, light-gray to light-pink, dolomitic; some shale beds.	Water yielding but permeability low. Never developed as sole aquifer.
		Mount Simon sandstone.	145+	Sandstone, white to light-gray, fine to coarse, mostly medium; some beds dolomitic.	Water yielding. Generally best of deep aquifers.
Pre-Cambrian.				Crystalline basement rocks.	Not water yielding.

3C.

Stratigraphic Position	Depositional Situation and Cycle No.	Formation and Thickness in Ft.	
LOWER MISSISSIPPIAN	No record, but possible deposition of shales and limestones followed by uplift and erosion in Late Mississippian time		
MIDDLE AND UPPER DEVONIAN	Transgression and carbonate deposition	Devonian dolomite and limestone, 230'±	
	Regression	Unconformity	
SILURIAN	Transgression and carbonate deposition	Silurian dolomites, 400'-600'	
	Regression	Unconformity	
UPPER ORDOVICIAN	Transgression and carbonate deposition? or Regression	Neda Formation, 0-55'	
	Regression?	Unconformity?	
	Offshore; orogenic muds	Maquoketa Shale, 100'-350'	
	Regression	Unconformity	
MIDDLE ORDOVICIAN	Carbonate deposition	Platteville-Decorah-Galena Fms., 200'-350'	
	Offshore CYCLE V	Glenwood Formation, 20'±	
	Transgression	St. Peter Sandstone, 40'-350'	
	MAJOR REGRESSION	Unconformity	
LOWER ORDOVICIAN (Prairie du Chien Dolomite, 150'-350')	Carbonate deposition	Willow River Dolomite, 30'-60'	
	Transgression CYCLE IV	New Richmond Sandstone, 5'-50'	
	Regression	Unconformity	
	Carbonate deposition	Oneota Dolomite, 100'-200'	
	CYCLE III		
UPPER CAMBRIAN	Transgression	Jordan Sandstone, 20'-150'	
	Regression	Unconformity	Munising Fm. (U. Mich.)
	Carbonate deposition	St. Lawrence Formation, 50'-125'	
	Offshore CYCLE II	Franconia or Tunnel City Sandstone, 100'-200'	
	Transgression	Wonewoc Sandstone, 100'-400'	
	Regression	Unconformity	
	Offshore CYCLE I	Eau Claire Sandstone, 250'±	
	Transgression	Mt. Simon Sandstone, 300'-800'	
Angular Unconformity			
LOWER-MIDDLE CAMBRIAN(?)	Jacobsville Sandstone (Mich.) or Bayfield Group (Wisc.) Hinckley and Fond du Lac Sandstones (Minn.)		
UNCONFORMABLE WITH UNDERLYING PRECAMBRIAN			

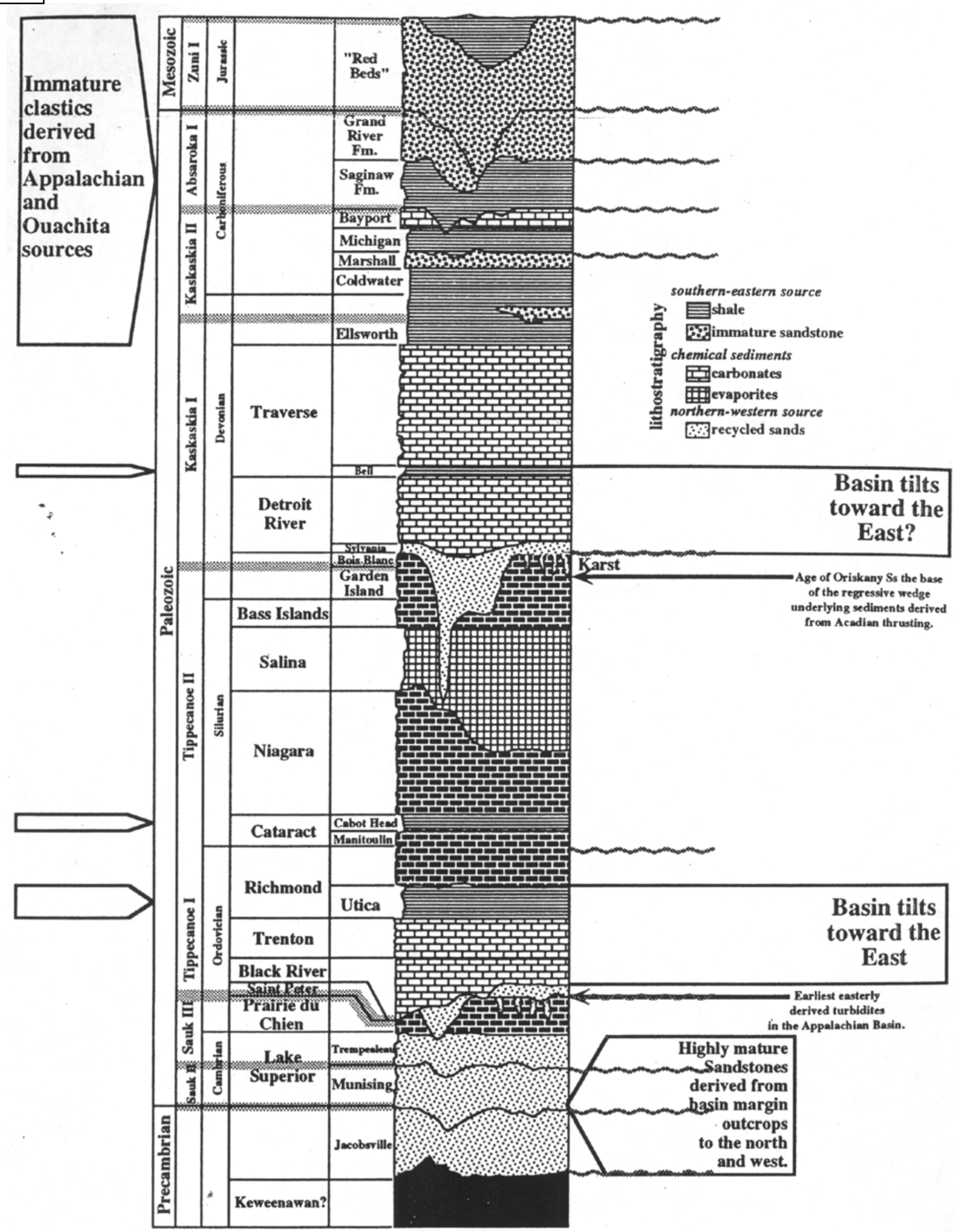
3D.

System			Thickness (ft)	Formation	Rock characteristics
QUATERNARY		Q_P	0- 470	Pleistocene deposits	Till, clay, silt, sand, and gravel.
SILURIAN		S_N	0- 325	Undifferentiated dolomite	Dolomite, white to gray; some coral reefs, mostly massive. Crevices and solution channels abundant but discontin- uous.
ORDOVICIAN		O_M	0- 210	Maquoketa Shale	Shale, dolomitic, blue-gray; contains dolomite beds as thick as 40 feet.
		O_{GP}	210- 290	Galena Dolomite, Decorah Formati and Platteville Formation undif- ferentiated	Dolomite, light-gray to blue-gray, massive; sandy at base.
		O_{SP}	75- 235	St. Peter Sandstone	Sandstone, fine- to medium-grained, white to light-gray; dolomitic in some places.
CAMBRIAN		€$_T$	150- 350	Trempealeau Formation	Sandstone, very fine- to medium-grained, dolomite, light-gray; interbedded with siltstone.
		€$_F$		Franconia Sandstone	Sandstone, very fine- to medium-grained; siltstone or dolomite in lower part.
		€$_D$		Galesville Sandstone	Sandstone, fine- to medium-grained, light gray.
		€$_{EC}$		Eau Claire Sandstone	Sandstone, fine- to medium-grained, light-gray to light-pink, dolomitic; some shale beds.
		€$_{MS}$	300-1,500	Mount Simon Sandstone	Sandstone, white to light-gray; fine- to coarse-grained, mostly medium; some beds dolomitic.
PRE CAMBRIAN		$_p$€	Unknown, but very great	Precambrian rocks undiffer- entiated	Crystalline basement rocks.

3E.

Geologic Time	Rock Unit		Lithologic Description
QUATERNARY			
Recent	Undifferentiated		Soil, muck, peat, alluvium, colluvium, beach sediment
Pleistocene *(all units include lake and stream sediment in addition to till)*	Kewaunee Formation		Brown to reddish-brown, silty and clayey till
	Horicon Formation		Coarser, brown, sandy till with associated sand and gravel
	Oak Creek Formation		Fine-textured, gray clayey till; lacustrine clay, silt, and sand
	New Berlin Formation		Upper: medium-textured. gravelly sandy till; Lower: outwash sand and gravel
	Zenda Formation		Medium-textured, pink, sandy till; limited distribution
PALEOZOIC			
Devonian	Antrim Formation		Gray, silty shale; thin; limited distribution
	Milwaukee Formation		Shaly dolomite and dolomitic siltstone
	Thiensville Formation		Dolomite and shaly dolomite
Upper Silurian	Waubakee Formation		Dense, thin-bedded, gray, slightly shaly dolomite
	Racine Formation		Finely crystalline dolomite; locally shaly beds and dolomite reefs
	Waukesha Formation		Cherty, white to buff, medium bedded, shaly dolomite
	Brandon Bridge beds		Pink to green shaly dolomite with shaly beds
	Lower Silurian beds (undifferentiated)		Dolomite and shaly dolomite
Ordovician	Neda Formation		Brown hematitic shale and oolite; occurs sporadically
	Maquoketa Formation		Green to gray dolomitic shale; locally layers of dolomite, fossiliferous
	Sinnipee Group	Galena Formation	Cherty dolomite with shaly dolomite at the base
		Decorah Formation	Shaly dolomite with fossils; thin or absent
		Platteville Formation	Dolomite and shaly dolomite
	Ancell Group	Glenwood Formation	Blue to green shale or sandy dolomite; thin or absent
		St. Peter Formation	Predominantly medium-grained quartz sandstone
	Prairie du Chien Group	Shakopee Formation	Light gray to tan dolomite or dolomitic sandstone; locally absent
		Oneota Formation	Massive, light gray to tan, cherty, sandy dolomite; locally absent
Cambrian	Trempealeau Group	Jordan Formation	Fine- to medium-grained quartz sandstone; locally absent
		St. Lawrence Formation	Tan to pink silty dolomite; locally absent
	Tunnel City Group		Fine- to medium-grained sandstone and dolomitic sandstone; locally absent
	Elk Mound Group	Wonewoc Formation	Medium- to coarse-grained, tan to white, quartz sandstone
		Eau Claire Formation	Fine- to medium-grained sandstone; local beds of green shale
		Mt. Simon Formation	Coarse- to medium-grained sandstone; lower beds very coarse and pebbly
PRECAMBRIAN	Undifferentiated		Granite or quartzite

3F.



Immature clastics derived from Appalachian and Ouachita sources
Mesozoic
Paleozoic
Precambrian
Zuni I
Absaroka I
Kaskaskia II
Kaskaskia I
Tippecanoe II
Tippecanoe I
Sauk III
Sauk II
Jurassic
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
"Red Beds"
Grand River Fm.
Saginaw Fm.
Bayport
Michigan
Marshall
Coldwater
Ellsworth
Traverse
Bell
Detroit River
Sylvania
Bois Blanc
Garden Island
Bass Islands
Salina
Niagara
Cataract
Cabot Head
Manitoulin
Richmond
Utica
Trenton
Black River
Saint Peter
Prairie du Chien
Lake Superior
Trempealeau
Munising
Jacobsville
Keweenawan?
lithostratigraphy
southern-eastern source
shale
immature sandstone
chemical sediments
carbonates
evaporites
northern-western source
recycled sands
Basin tilts toward the East?
Karst
Age of Oriskany Ss the base of the regressive wedge underlying sediments derived from Acadian thrusting.
Basin tilts toward the East
Earliest easterly derived turbidites in the Appalachian Basin.
Highly mature Sandstones derived from basin margin outcrops to the north and west.

3G.

Model Time Step	Model Time, m.y.	Age, Ma	Stratigraphic Interval	Combinations of Stratigraphic Intervals Used in the Text		
	0	470				
1			Middle Ordovician (post-Beekmantown-Knox unconformity)	Middle Ordovician (Champlainian)	Taconian orogeny	
	1	469				
2			Middle Ordovician			
	12	458				
3			Ordovician (erosion)			
	20	450				
4			Upper Ordovician (Cincinnatian)			
	32	438				
5			Lower Silurian (Medinian and Clintonian)			
	37	433				
6			Silurian (erosion)			
	40	430				
7			Upper Silurian (Lockportian and Salinian)	Siluro-Devonian carbonate sequence		
	62	408				
8			Lower Devonian (Helderbergian and Deerparkian)			
	70	400				
9			Lower Devonian (erosion)			
	75	395				
10			Middle Devonian (post-Oriskany)		Acadian orogeny	
	96	374				
11			Upper Devonian and lowest Mississippian (Kinderhookian)			
	118	352				
12			Lower Mississippian (Osagean and Meramecian)			Ouachitan orogeny
	130	340				
13			Upper Mississippian (Chesterian)			
	150	320				
14			Lower Pennsylvanian (Morrowian and Des Moinesian)	Pennsylvanian	Alleghanian orogeny	
	175	295				
15			Upper Pennsylvanian (Missourian and Virgilian)			
	184	286				
16			Permian			
	220	250				
17			erosion step 1	post-Alleghanian erosion		
	235	235				
18			erosion step 2			
	310	160				
19			erosion step 3			
	470	0				

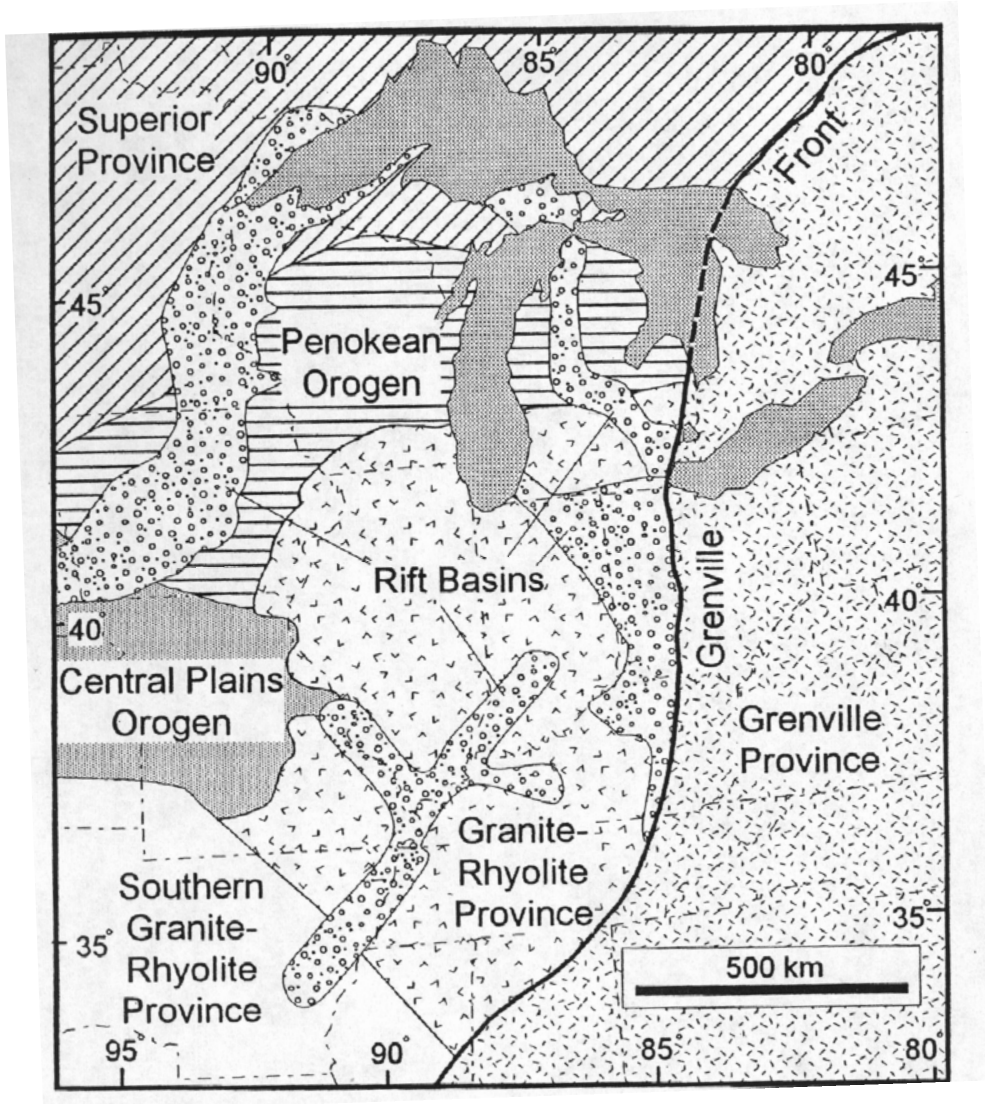


Figure 4- Precambrian provinces and major structural features in the basement of the eastern mid-continent, including the midcontinent rift basins. The contact between the Penokean Province and the Granite-Rhyolite Province can be seen in Wisconsin. (Root & Onasch, 1999)

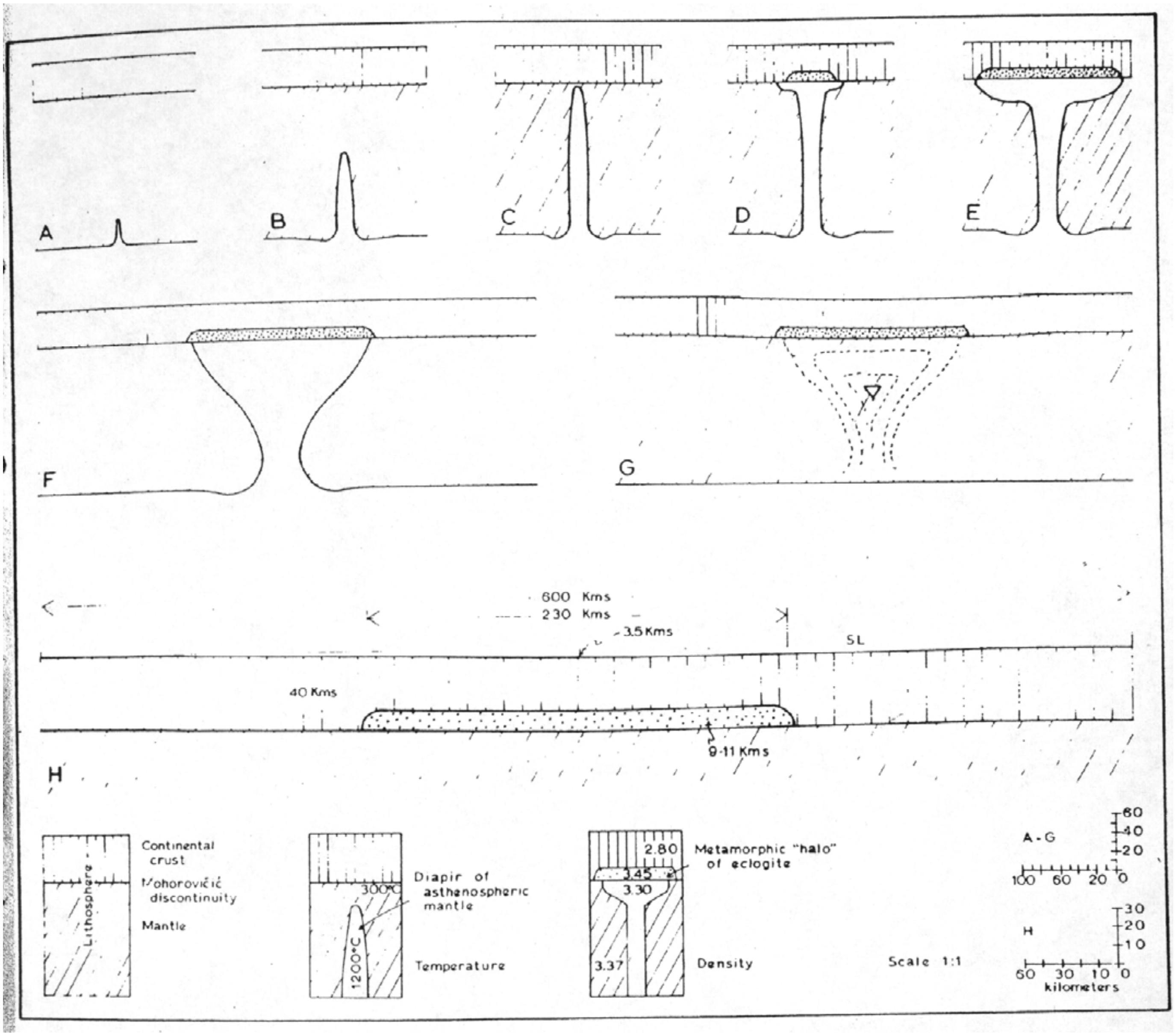


Figure 5- Model for the evolution of the Michigan basin. A-C) Diapiric penetration of the asthenospheric material into the lithosphere; D-F) impingement of hot asthenospheric rock on the base of the crust, and thermally activated transformation of lower crustal rocks from gabbro to eclogite; G) cooling of hot diapiric rock and subsidence of the basin due to the weight of eclogite; H) the Michigan basin today (Haxby *et al*., 1976).

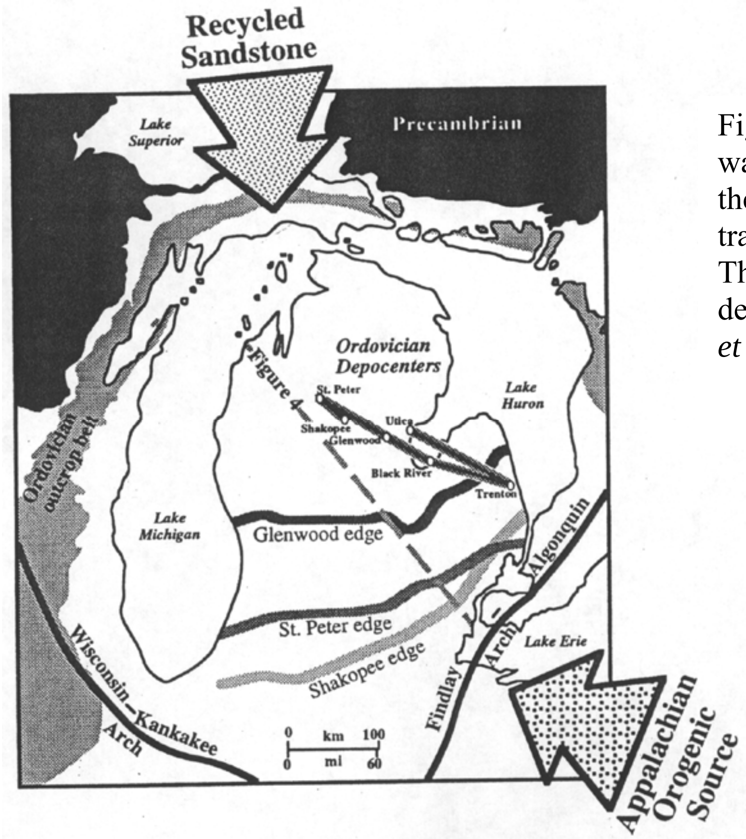
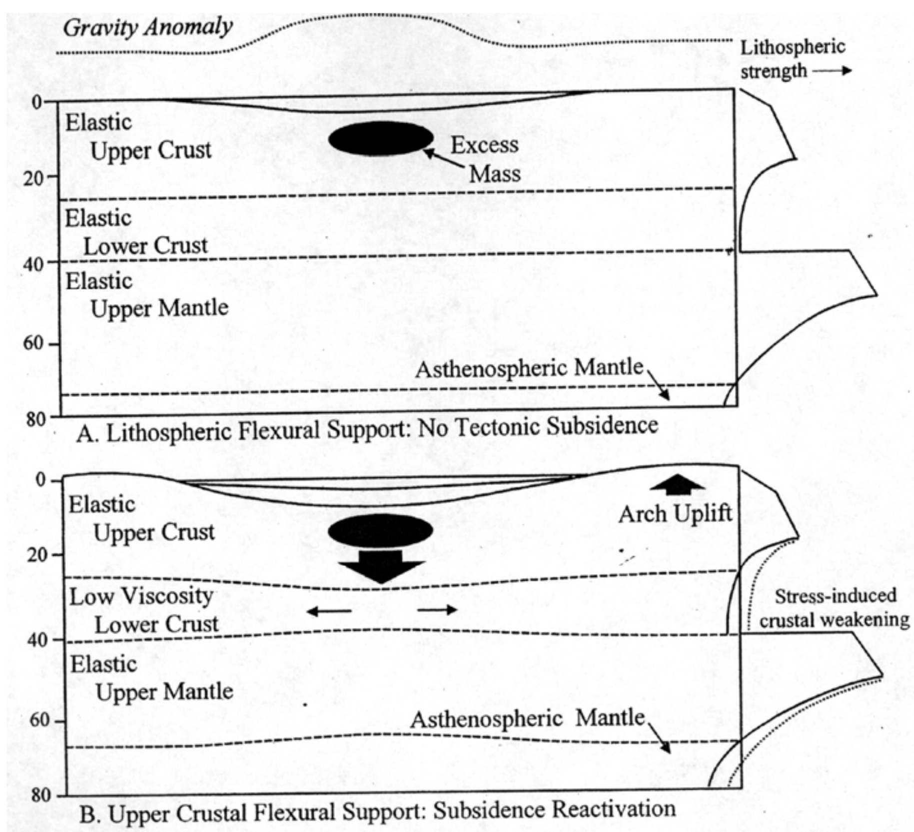


Figure 6- When the Findlay-Algonquin arch was a topographic low, the sediments from the Appalachian Orogenies could be transported into the Michigan basinal region. This map also shows the migration of the depocenters during the Ordovician. (Coakley *et al*., 1994)

Figure 7- Model for subsidence caused by stress-induced crustal weakening. Each panel shows the location of an excess mass in the upper crust and behavior of different lithospheric layers. A) Under low stress conditions, the excess mass is flexurally supported by the entire lithospheric thickness. B) High stress levels cause a weakening of the lithospheric portions where strength is controlled by crystal plasticity. Here the lower crust becomes sufficiently viscous to flow and the lithosphere-asthenosphere boundary is elevated. This allows the excess mass to be supported by the lower crust alone, resulting in narrow (low rigidity), basin-centered subsidence accompanied by lower crustal flow toward the basin margins, causing uplift of the surrounding arches. The total amount of flexure is exaggerated for clarity. (Howell & van der Pluijm, 1999)



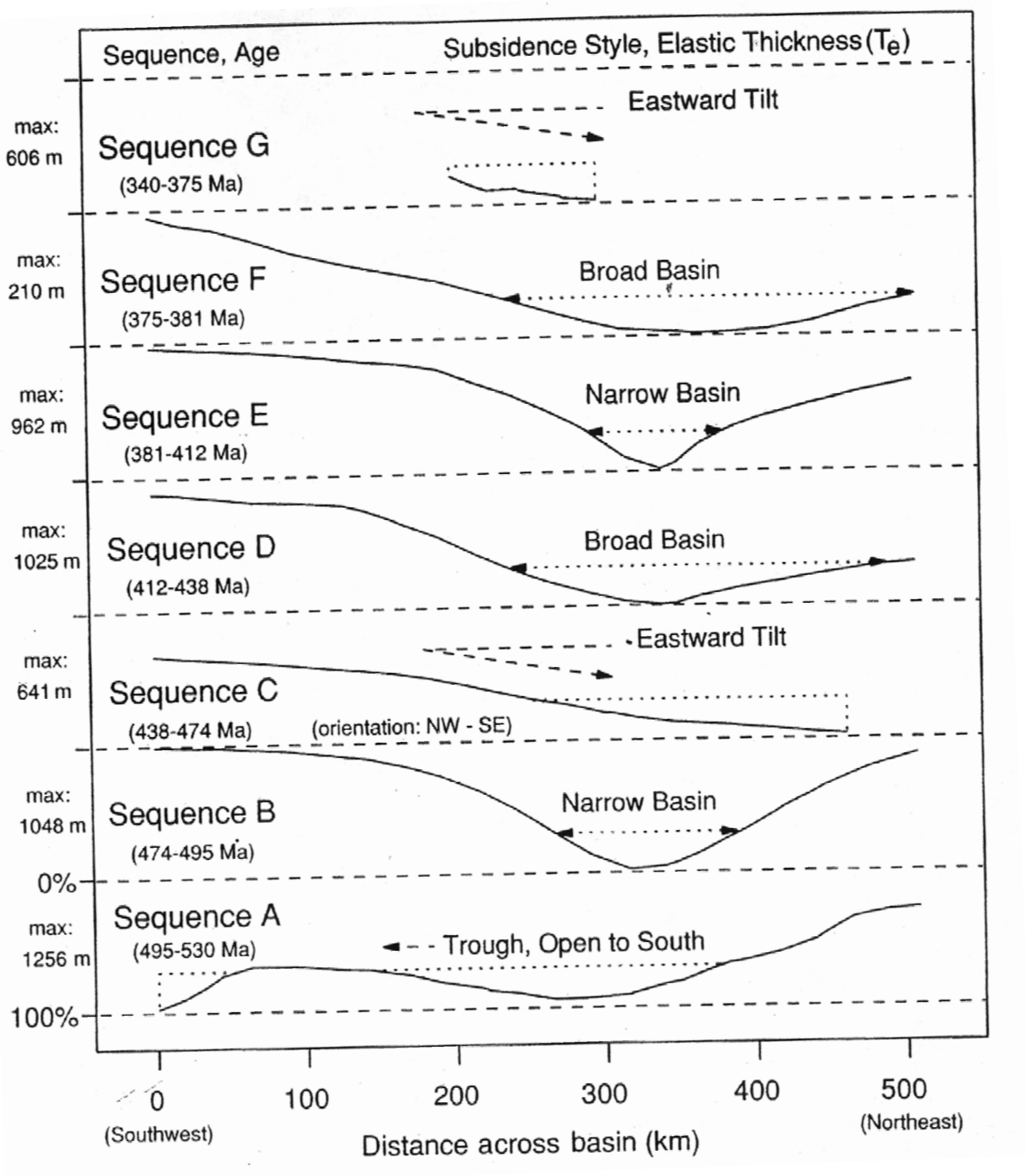


Figure 8- Summary of basin activities during Sequences A-G. The cross sections are oriented northeast-southwest, except as indicated. (Howell & van der Pluijm, 1999)

THWAITES (1931)	**84** MILES
THWAITES (1940)	**84** MILES
THWAITES (1957)	**81** MILES
USGS & AAPG (1962)	**38.5** MILES
AAPG & USGS (1967)	**88** MILES
USGS (1968)	**133** MILES
USGS (1969)	**97.5** MILES

Figure 9- This chart shows the variation in reported lengths of the Waukesha Fault since 1931. (modified from Kuntz & Perry, 1976)

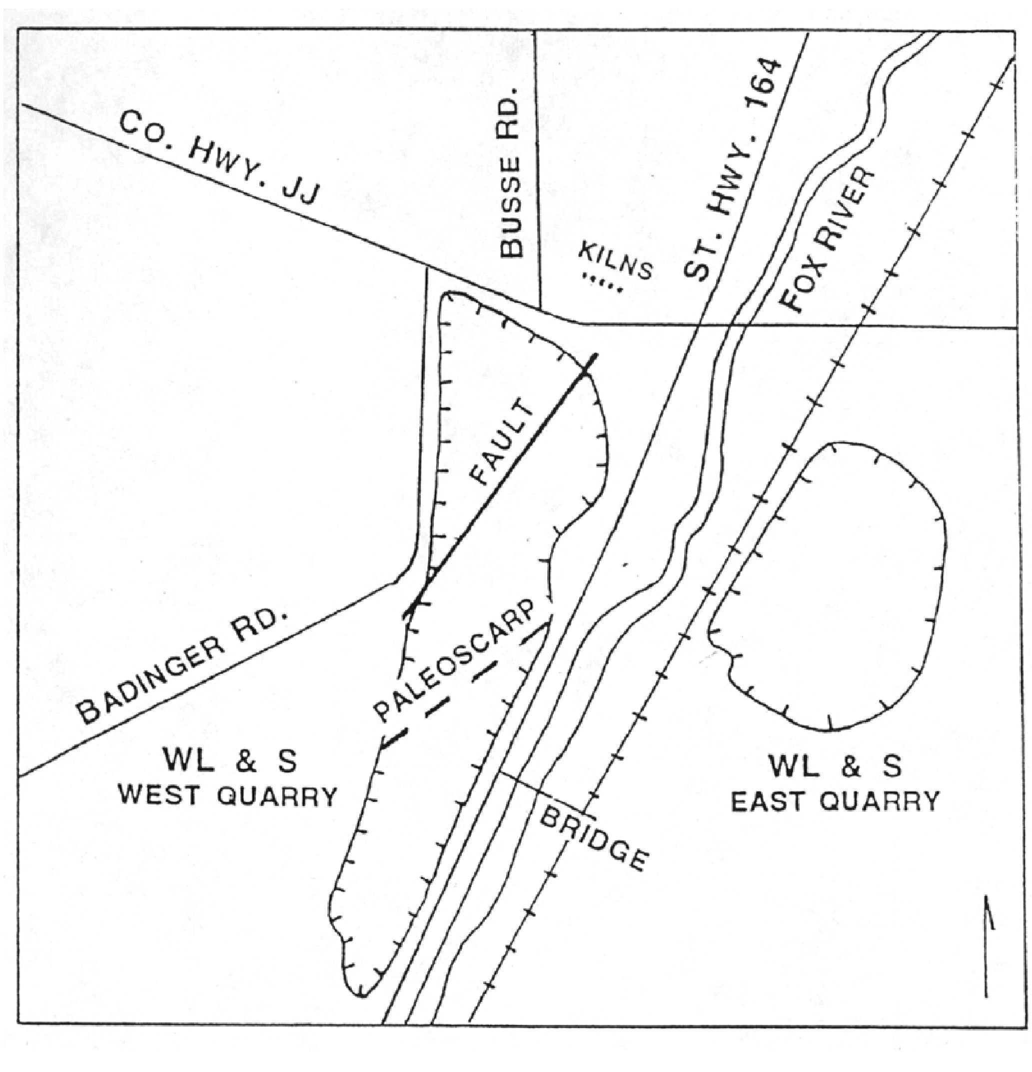
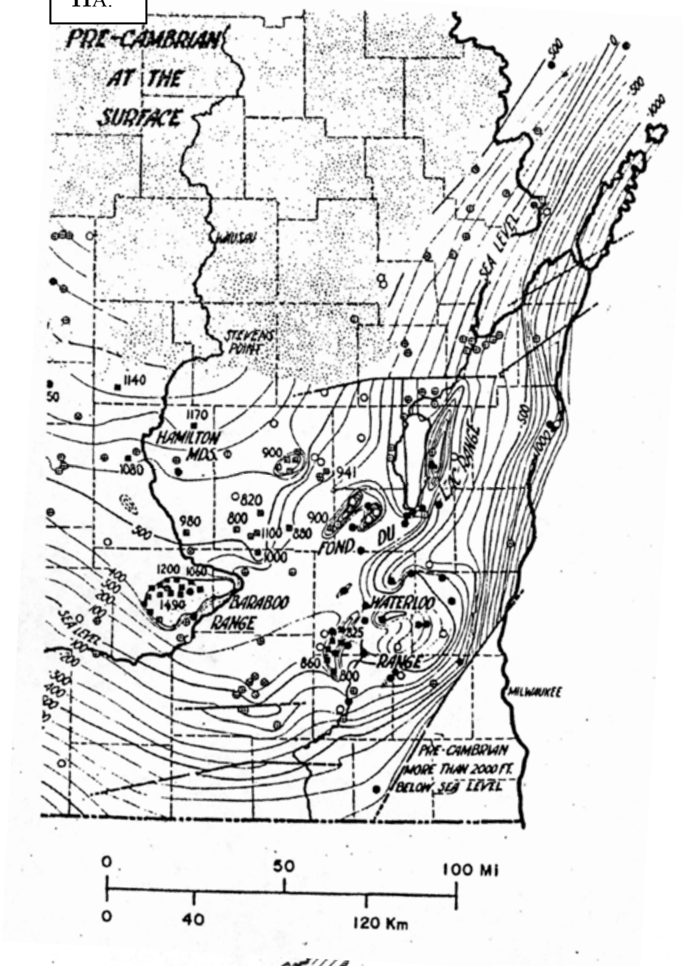


Figure 10- Location of the Waukesha Fault in the Waukesha Lime & Stone Company (west) quarry. The quarries are located in Waukesha County, Wisconsin. (Kluessendorf & Mikulic, 1994)

11A.



11B.

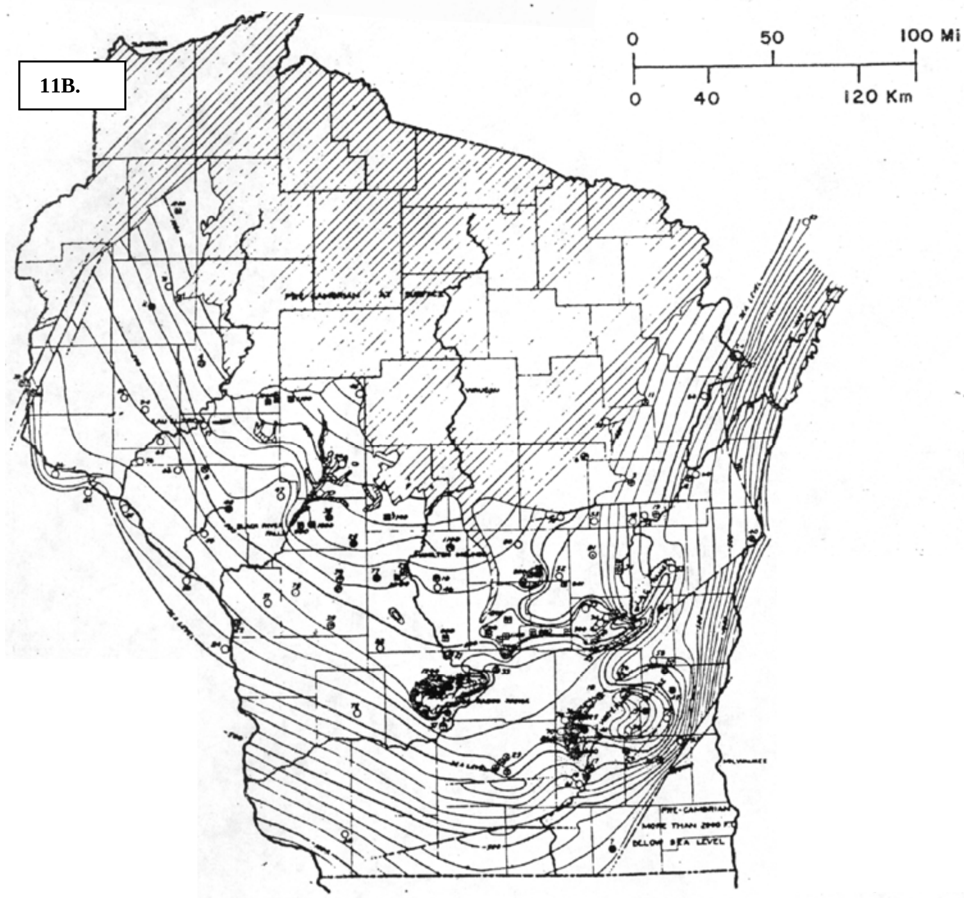


Figure 11- Two different interpretations of the Waukesha Fault by the same researcher.
A) Thwaites (1931): map of Precambrian basement in Wisconsin.
B) Thwaites (1957): map of Precambrian basement in southern and eastern Wisconsin. (Kuntz & Perry, 1976)

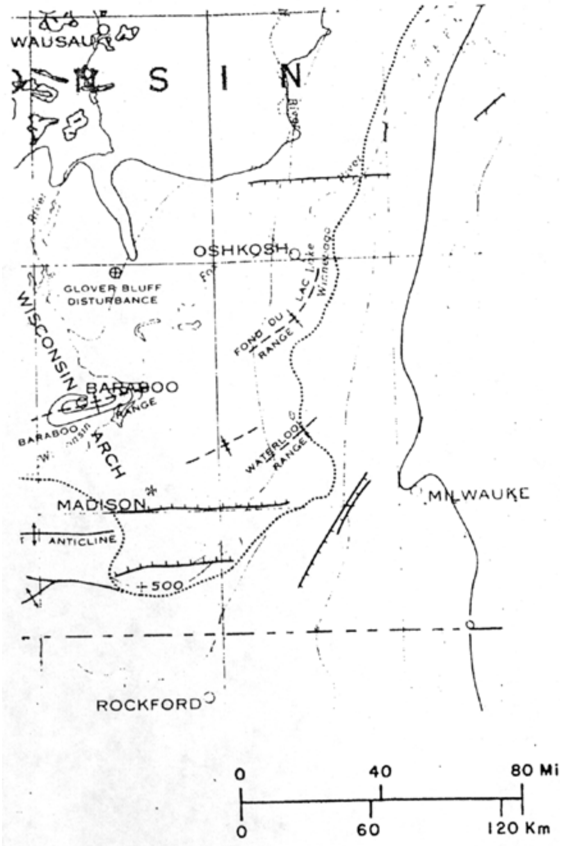
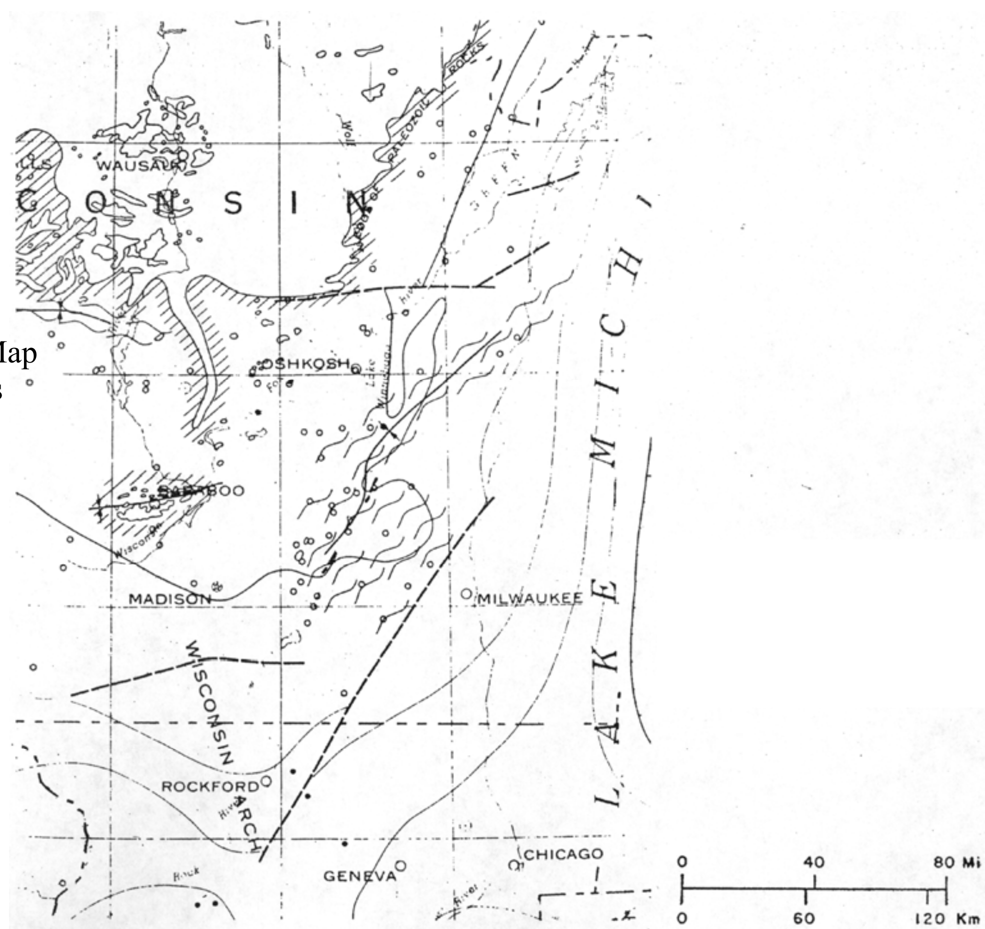
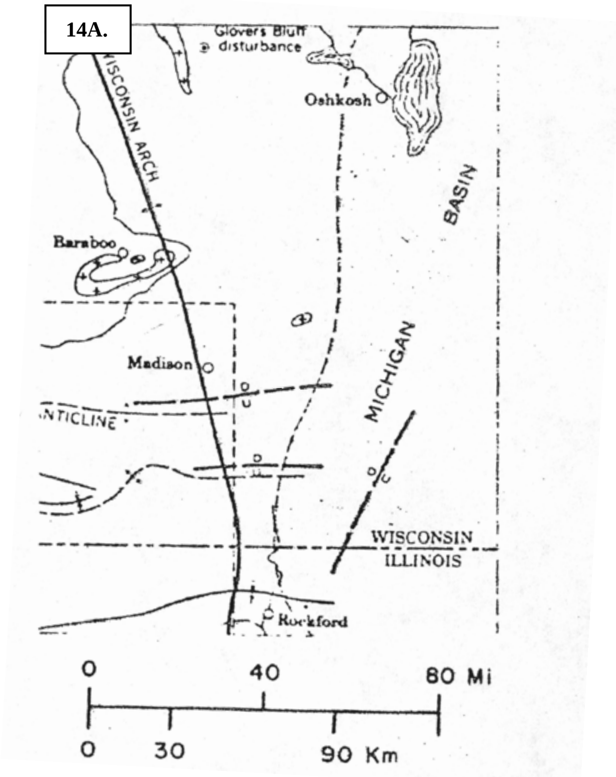


Figure 12- USGS & AAPG (1962): Map of the Waukesha Fault at its shortest length of 38.5 miles. (Kuntz & Perry, 1976)

*Note the presence of two Waukesha Faults, which is not discussed in the report.

Figure 13- USGS (1968): Map of the Waukesha Fault at its longest length of 133 miles. (Kuntz & Perry, 1976)





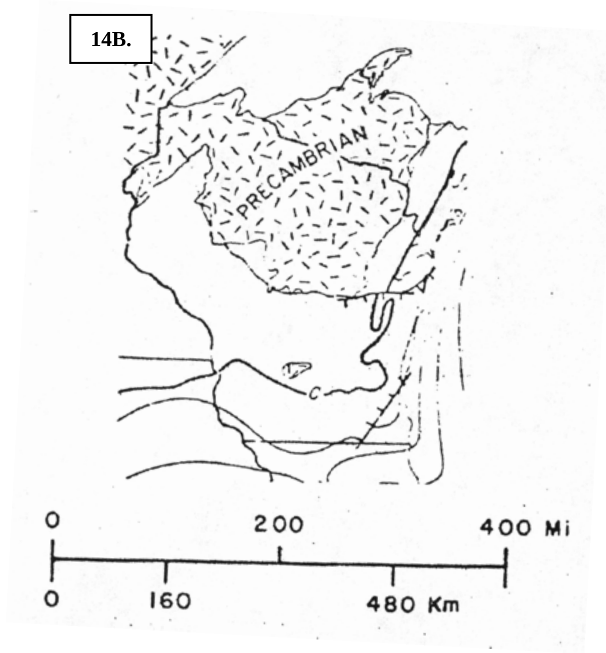
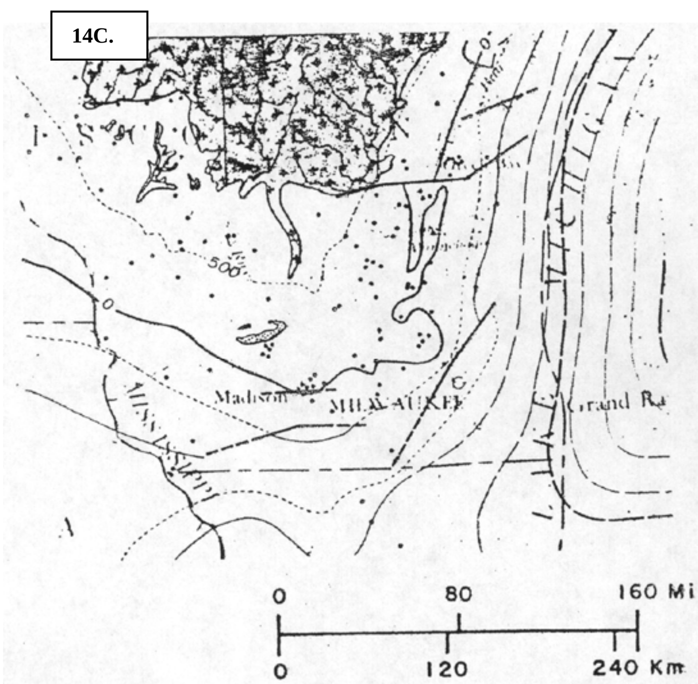
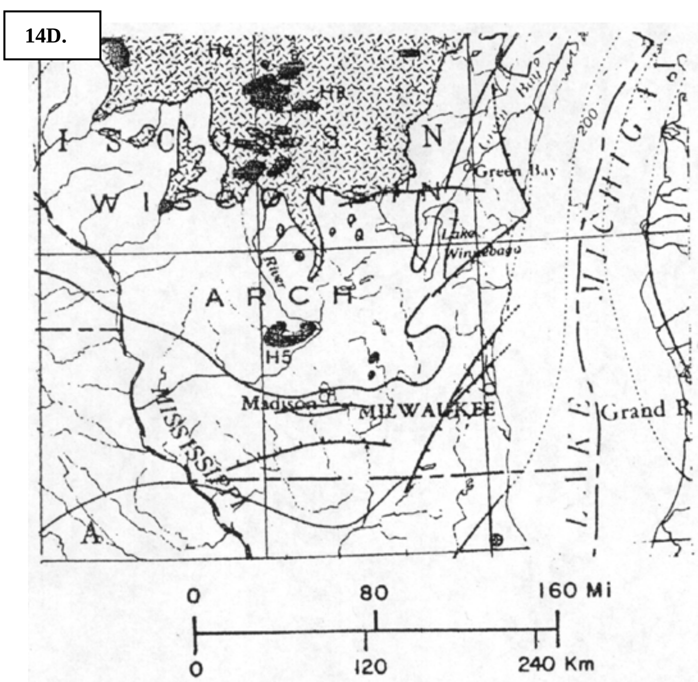


Figure 14- A and B show downward displacement on the northwest side of the Waukesha Fault, possibly the result of drafting errors. A) Heyl *et al*. (1959); B) Rudman *et al*. (1965)

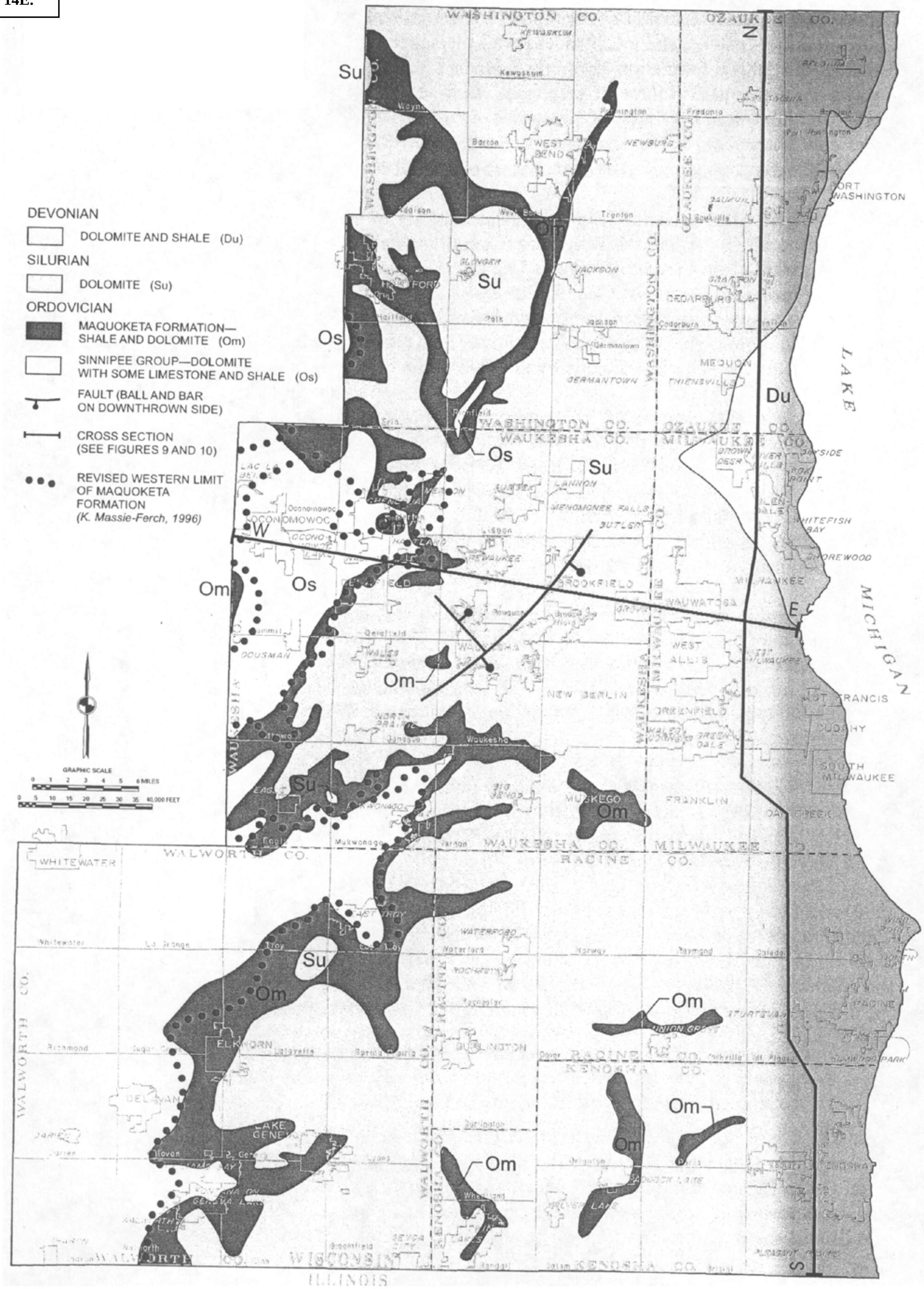
C, D, and E are more maps of versions of the Waukesha Fault. C) AAPG & USGS (1967); D) USGS (1969); E) Brown & Eaton (2002)

A-D: (Kuntz& Perry, 1976); E: (Brown & Eaton, 2002)





14E.


DEVONIAN
DOLOMITE AND SHALE (Du)
SILURIAN
DOLOMITE (Su)
ORDOVICIAN
MAQUOKETA FORMATION—SHALE AND DOLOMITE (Om)
SINNIPEE GROUP—DOLOMITE WITH SOME LIMESTONE AND SHALE (Os)
FAULT (BALL AND BAR ON DOWNTHROWN SIDE)
CROSS SECTION (SEE FIGURES 9 AND 10)
REVISED WESTERN LIMIT OF MAQUOKETA FORMATION (K. Massie-Ferch, 1996)
GRAPHIC SCALE
WASHINGTON CO.
OZAUKEE CO.
WAUKESHA CO.
MILWAUKEE CO.
WALWORTH CO.
RACINE CO.
KENOSHA CO.
WISCONSIN
ILLINOIS
LAKE MICHIGAN
Su
Os
Om
Du
N
S
W
E

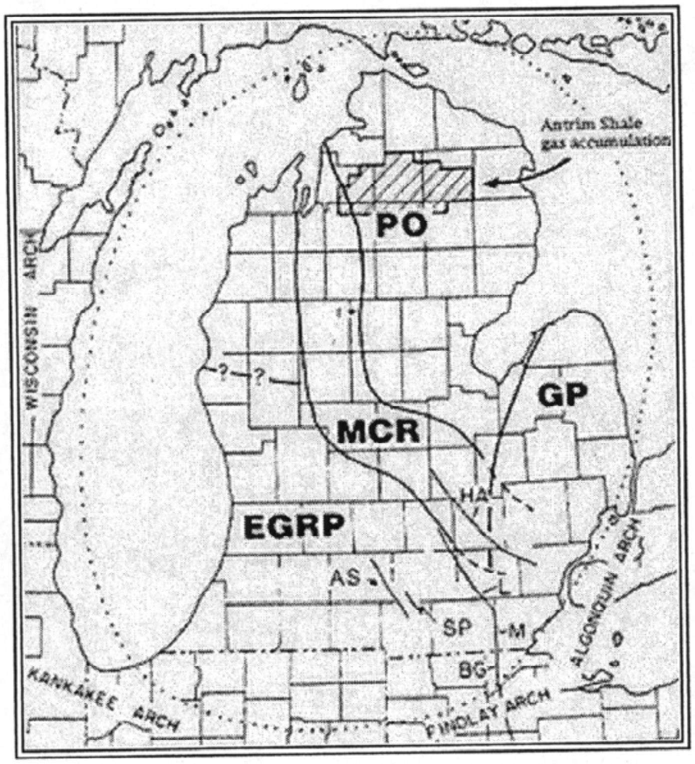


Figure 15- Basement provinces and faults of the Michigan basin.
PO: Penokean Orogen; EGRP: Eastern Granite-Rhyolite Province; MCR: Mid-Continent Rift System; GP: Grenville Province; HA: Howell anticline; L: Lucas fault; M: Monroe fault; BG: Bowling Green fault; AS: Albion-Scipio oil field; SP: Stoney Point oil field.
(Ryder, 1996)

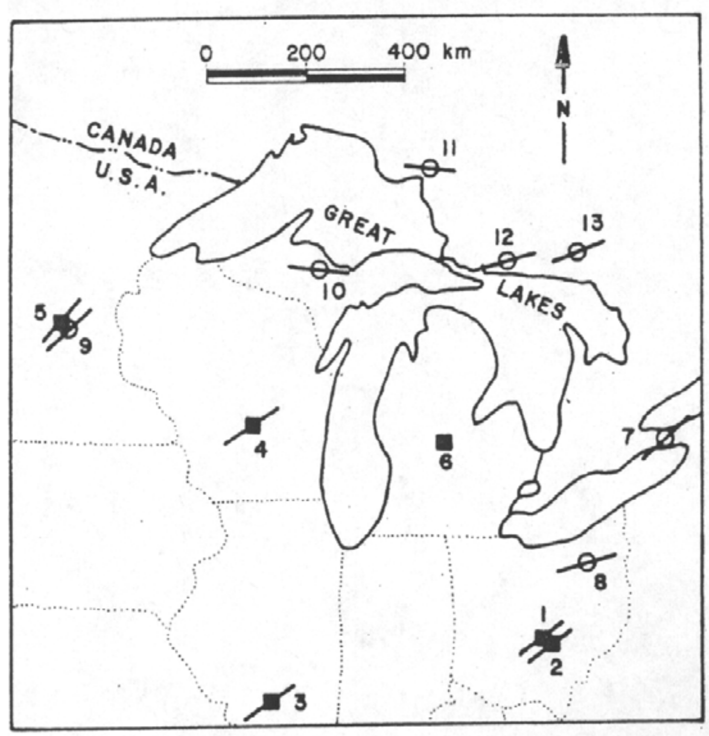


Figure 16- Map of the Midwest-Ontario region showing locations of known stress measurements (solid squares represent hydrofracturing and open circles represent overcoring) and directions of maximum horizontal compressive stresses (straight lines). Numbers indicate various test sites. (Haimson, 1978)

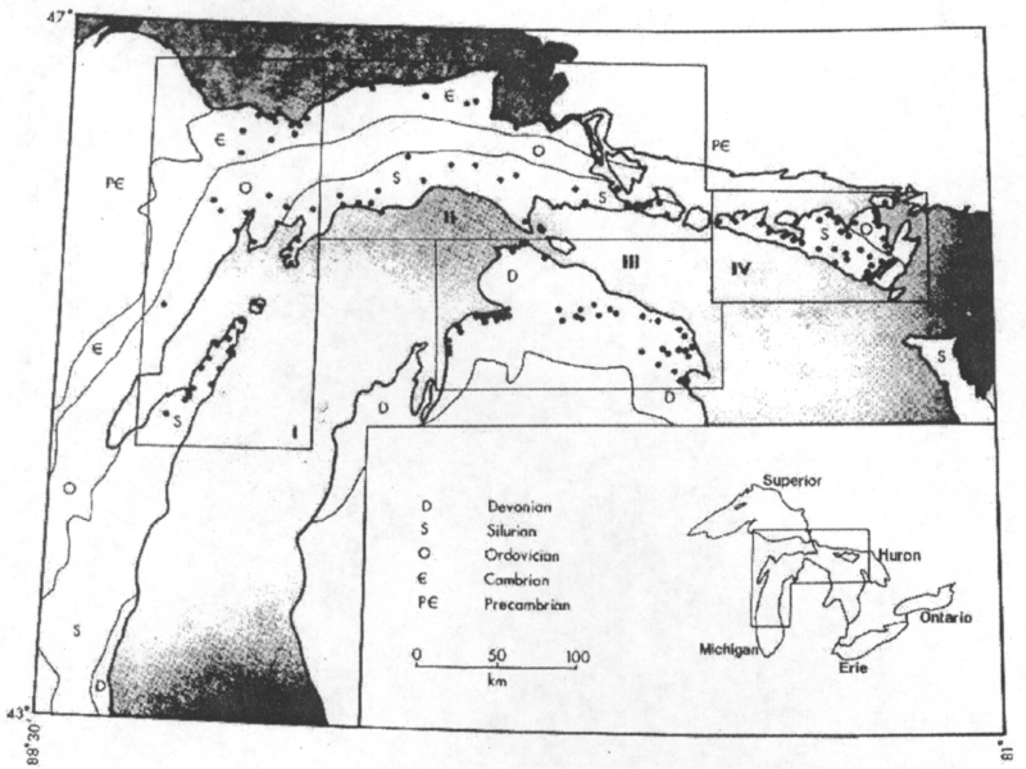
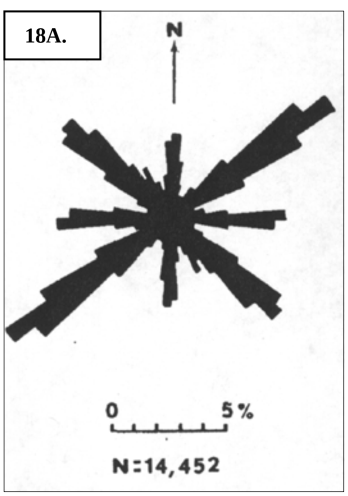


Figure 17- Map of study areas covered by Holst & Foote (1981) and Holst (1982) where joint orientations were measured. I: western Upper Peninsula, Michigan and Door County, Wisconsin; II: eastern Upper Peninsula, Michigan; III: Lower Peninsula, Michigan; IV: Manitoulin Island, Ontario. (Holst, 1982)



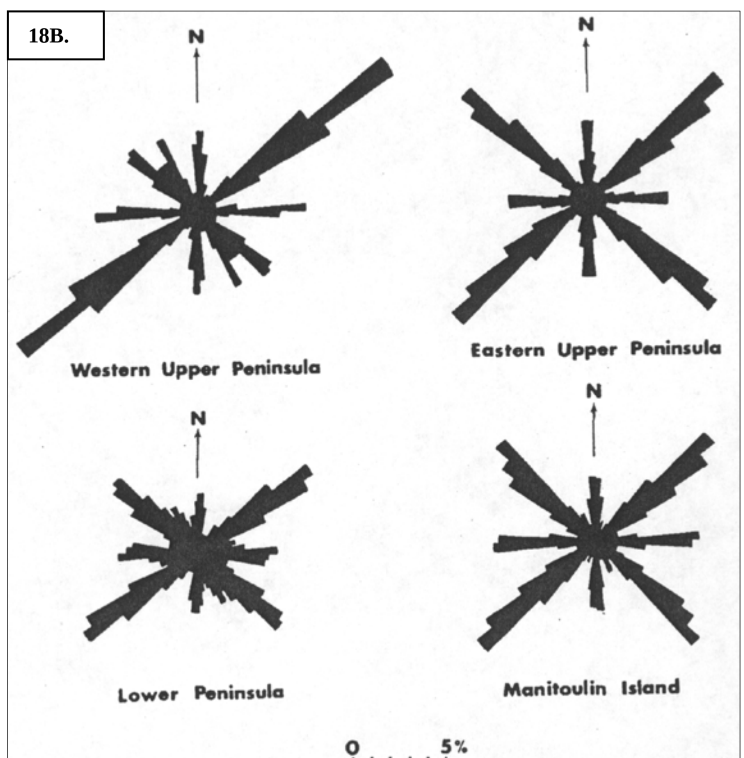


Figure 18- A) Rose diagram of total vertical joint data from northern Michigan basin- 14,452 joints. Scale is 0% to 5% of total data within each 6º sector. B) Rose diagrams of joint orientation in four large regions of northern Michigan basin. Scale is 0% to 5% of total data in each region per 5º sector. (Holst, 1982)

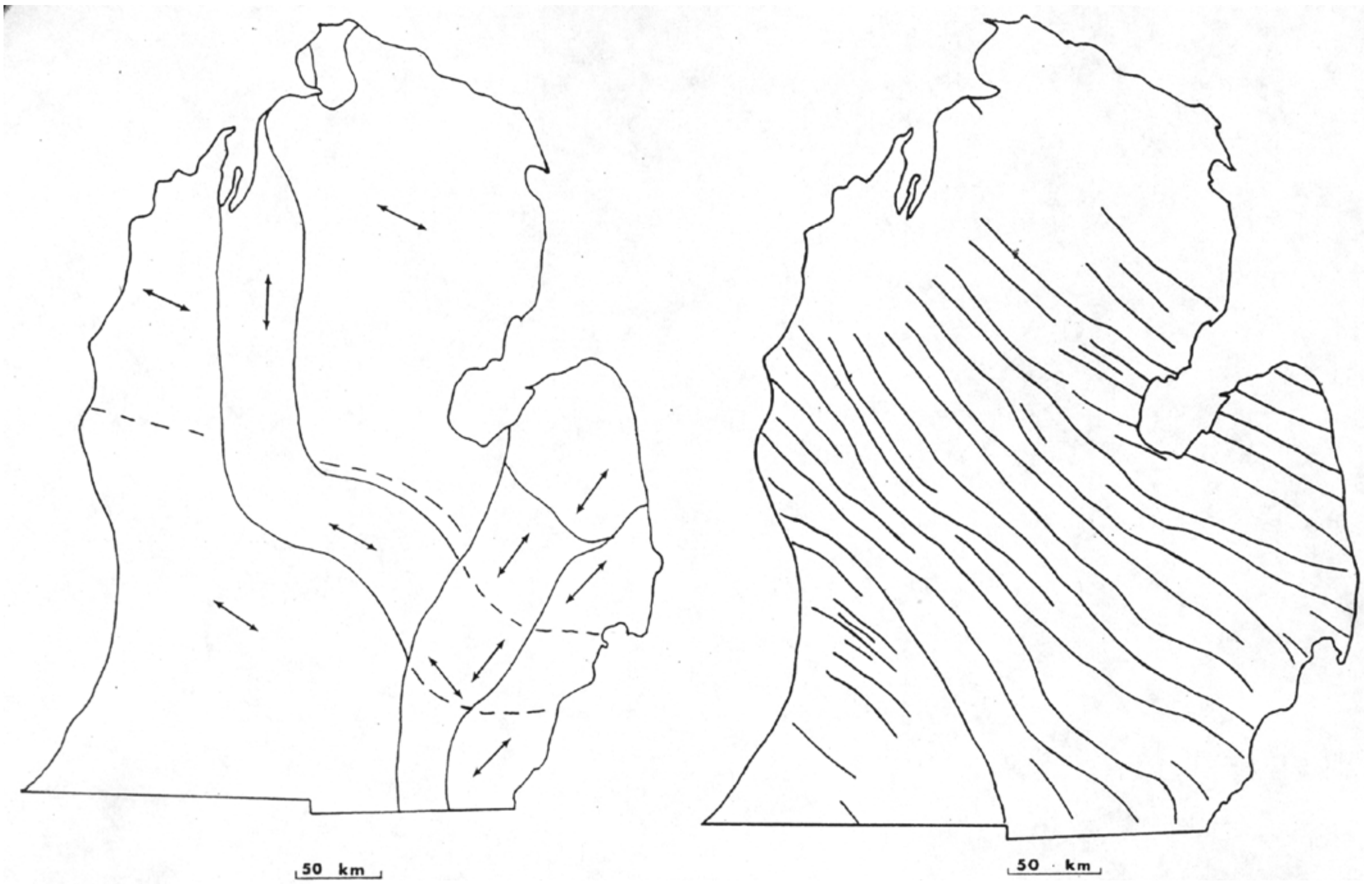


Figure 19- A) Postulated structural trends in the Precambrian basement beneath the Michigan basin, and the predominant structural trend within each province (from Hinze *et al*., 1975). B) Trends of axes of major anticlines within the Michigan Basin (after Newman, 1940). (Holst & Foote, 1981)

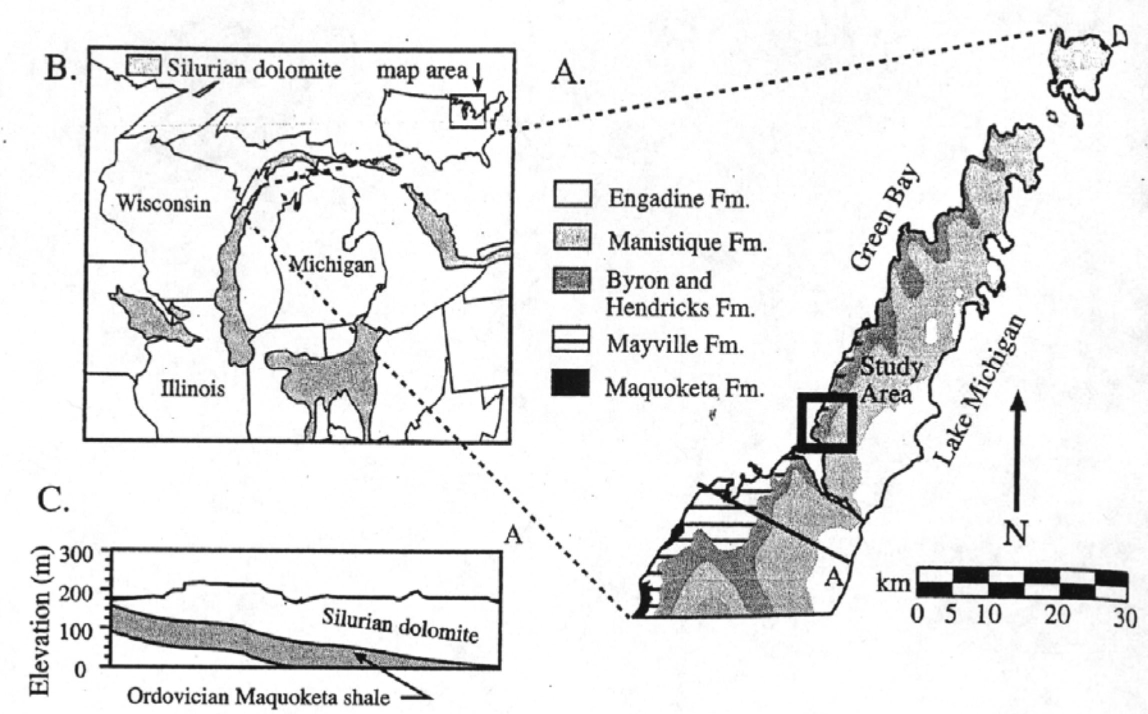


Figure 20- A) Location of Door County, Wisconsin (from Muldoon *et al*., 2001); B) Bedrock geology of Door County (from Roffers, 1996); C) Cross section through Door County (from Muldoon *et al*., 2001). (Underwood *et al*., 2003)

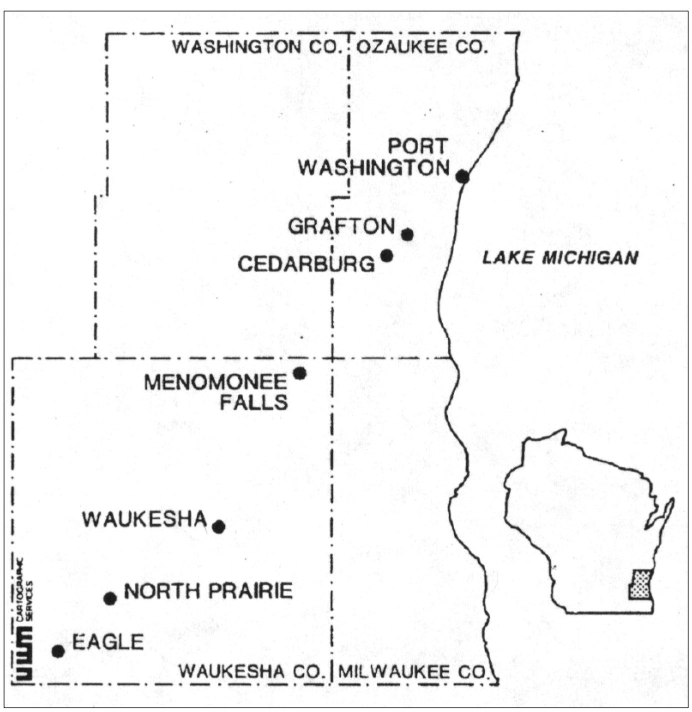


Figure 21- Location of gravity survey across southeastern Wisconsin. (Sverdrup *et al*., 1997)

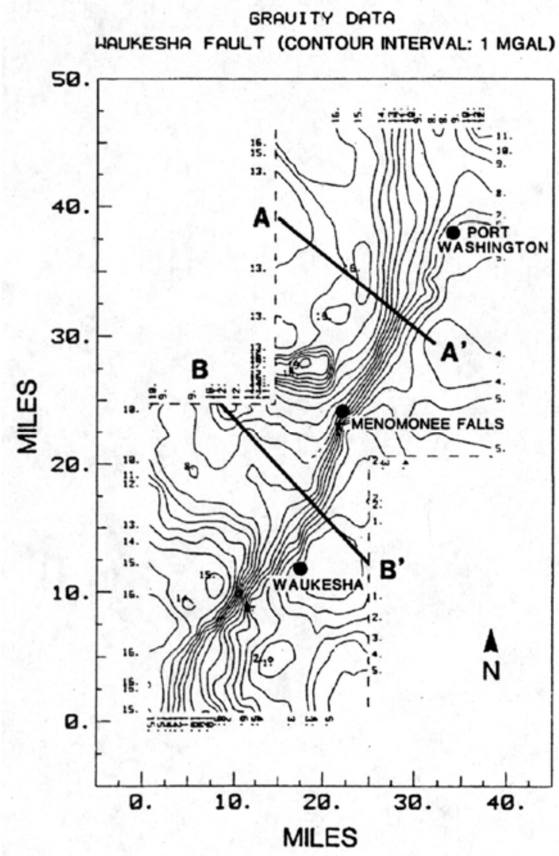
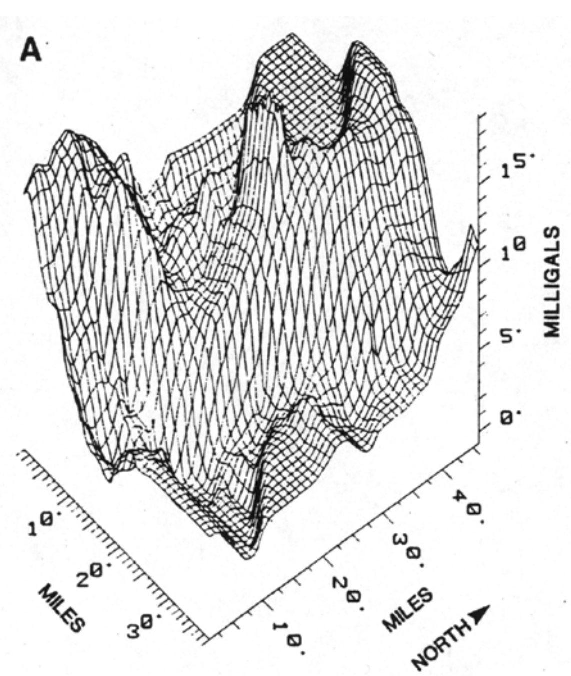
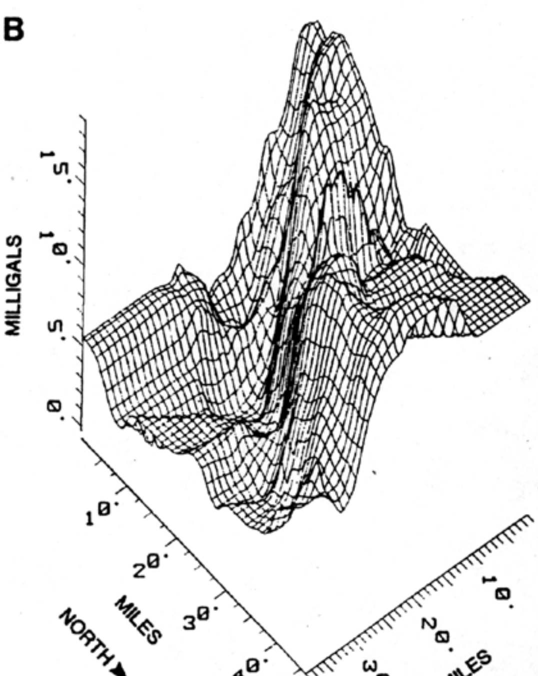


Figure 22- Contour plot of the gravity data across Washington, Ozaukee, Waukesha, and Milwaukee Counties. Contour interval is 1 milligal. Locations of profiles in figure 23 are indicated. (Sverdrup *et al.*, 1997)

Figure 23- 3-dimensional plot of the gravity signature of the Waukesha Fault: A) viewed from the southeast in a direction N50W; B) viewed from the northeast in a direction S40W. (Sverdrup *et al.*, 1997)





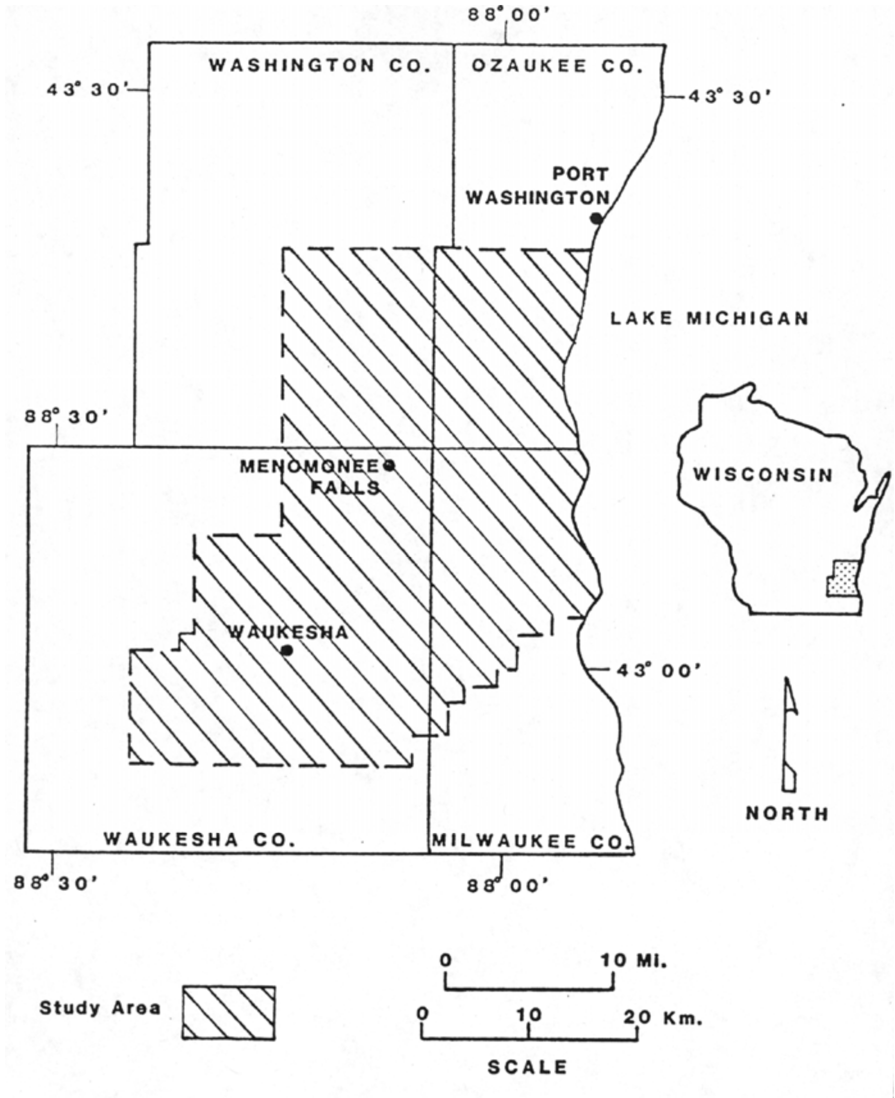


Figure 24- Location of the magnetic survey across Washington, Ozaukee, Waukesha, and Milwaukee Counties. (Moll, 1987)

Appendix: Research Notes

•Apotria, T., Kaiser, C.J., & Cain, B.A. (1996). Fracturing and stress history of the Devonian Shale, Michigan Basin *in Production from Fractured Shales. SPE Reprint Series, no.45*, 9-17.

The joint and fracture systems in sedimentary basins continue to be a problem for the exploration and production of oil and gas in low permeability reservoirs. It is noted that the NE-striking sets of fractures are extension fractures related to the contemporary stress field, while the NW striking set may be genetically related to the NW-trending folds in the Michigan Basin (Holst and Foote). "Versical (1991) noted that the NW-striking fractures are consistent in orientation with the principal shortening direction measured in deformed calcite twins from Paleozoic carbonates throughout the mid-continent (Craddock et al. 1993) and probably are related to the Alleghanian orogenic event." NE-striking fractures are found to be younger, shallower than the NW-striking fractures, which are older and deeper.

The older, near-vertical fractures in the basin are NW-striking and were formed as natural hydraulic fractures. This fracturing occurred during burial and was assisted by thermal maturation and hydrocarbon generation during the late Paleozoic, which is coincident with the Alleghanian Orogeny in the Appalachians, where the regional maximum horizontal stress direction had a NW orientation.

"NE- and EW-striking fractures formed during basin uplift and consequent unloading and cooling." The uplift marked the transition from NW-maximum horizontal stress (Alleghanian Orogeny) to the present ENE-directed maximum horizontal compression (contemporary stress field). "The precise depth above which NE- and EW-striking fractures form depends on lithology and elastic properties, and the extent to which other mechanisms contribute to fracturing during uplift. The fact that many of these fractures do not abut older fractures suggests the appreciable traction existed across NW-striking fractures when the NE-striking set formed. Such conditions would exist at greater depths than the near-surface. Uplift also provides a mechanism for the formation of a second generation of NW-striking cross fractures which are less systematic (younger than NE-striking fractures). As the NE-striking fracture sets forms, the local minimum effective horizontal stress is reduced to zero, and may become larger (less tensile) than the intermediate effective stress."

•Beaumont, C., Quinlan, G., & Hamilton, J. (1988). Orogeny and Stratigraphy: Numerical Models of the Paleozoic in the Eastern Interior of North America. *Tectonics, v.7, no.3*, 389-416.

Beaumont creates a computer model in which he can estimate lithospheric deformation caused by obduction and removal of loads within orogenic belts. "By following the deposition and erosion of sedimentary packages through a number of model time steps it is possible to calculate a synthetic stratigraphy fir a given study area." In the Eastern Interior region of North America, the lithospheric deformation is associated with the Appalachian and Ouachita orogens and the independent development of the Michigan and Illinois intracratonic basins. (He thinks that the MI and IL basins were not influenced much by the Appalachian and Ouachita orogens.) "The post-Early Ordovician stratigraphy of the Eastern Interior of North America is dominated by the influence of the Taconian, Acadian, Alleghanian, and Ouachita orogenies spanning the interval from the end of the Early Ordovician through the end of the Permian." These computer models illustrate the lithosphere flexing under the orogenic loads and then relaxing during quieter times.

Three different models were made where the lithosphere was treated differently in each one: as an elastic plate, as a Maxwell viscoelastic plate with uniform viscosity, and as a Maxwell viscoelastic plate in which viscosity increases exponentially with decreasing temperature. The models play around with the responses the earth would yield. It is noted that "orogenic unloading is therefore accompanied by the development of a widespread unconformity" and that the area that undergoes uplift shrinks with time. (Can this be applied to the Michigan basin and the Wisconsin arch?)

*There is a nice diagram of when different orogenies occurred in geologic time.

Different geologic times are gone through, describing the events that affected sedimentation. There are lots of isopach maps showing deposition.

"With only minor exceptions around the Ordovician-Silurian boundary, the major features of the observed stratigraphy can be explained by flexurally raising and lowering the surface of the lithosphere against a background of constant sea level. We are not suggesting that no changes in eustatic sea level occurred over this interval but only that such changes are not necessary to explain the bulk of the stratigraphic record. Sediment lithology in the foreland basin, over the intrabasinal arches and into the intracratonic Michigan and Illinois basins is related to both the magnitude of the overthrust loads and to the morphology of the inherited passive margins."

•Brukardt, S.A. (1983). "Gravity Survey of Waukesha County, Wisconsin" Masters Thesis, UW-Milwaukee.

This gravity survey was conducted in Waukesha County, using a LaCoste and Romberg G158, in a one-mile grid, and all appropriate corrections were made to the data to produce a Bouger anomaly map.

The glacial till is thinner over the fault than to the north and south of the fault. This is probably due to the Paleozoic topography. Overall, the beds seem to be gently dipping with quite an offset at the fault. At this time, the fault was still not completely constrained, and it was theorized that the fault might continue as far north as Lake Michigan. However, there was no work to confirm or deny this theory. She states that the fault can be observed at the Waukesha Lime & Stone Company Quarry, trending N40E, and appears to be nearly vertical.

"Gravity contours tend to be rather tightly spaced to the northeast and southwest of the exposure at the Waukesha quarry, yet at this center portion there occurs a bit of spreading of the contours, and to the southwest corner, contours not only a spread out, but also a turn from the original orientation." (p.34) The gravity values along the gravity profile decrease dramatically at the fault due to less glacial till and the variations in the bedrock (the appearance of the Maquoketa and Niagaran in the western portion). The thickness of the Mt. Simon sandstone changes dramatically over the fault; it is very thin or non-existent on the western side, but is very thick on the eastern side.

The computer modeling revealed the best fit for the angle of the fault was 70º. A vertical fault produced values that "fell off too fast" and a fault angle less than 60º shows too slow a decrease in gravity values. These models also took into account the great decrease in the Precambrian as it crosses the fault. The displacement of the lower Paleozoic and Precambrian formations is possibly as much as 1000 feet, while the upper formations have displacement as little as 30 to 50 feet. The gravity anomaly differs by 8 milligals across the fault.

Brukardt also found a second linear trend that has less displacement (no more than 50 feet) than the Waukesha fault. It is reported an event that occurred after at least one activity on the main Waukesha fault. She also states that there is strong evidence that more than one event that contributed to the formation of the fault. The evidence for the second fault is not as conclusive. "there is a definite linear trend oriented at N60W, with an accompanying decrease in values to the north of 5 milligals. However, the geological evidence for this is less certain. This could simply be a flexure in the beds, with a very thick layer of glacial till contributing to the lower gravity values." (p.74) Also noted is the change, spreading out, of contours near the city of Waukesha while other areas have very tight contours.

•Coakley, B.J., Nadon, G.C., & Wang, H.F. (1994). Spatial variations in tectonic subsidence during Tippecanoe I in the Michigan Basin. *Basin Research, v.6,* 131-140.

"Episodic subsidence in intracratonic basins remains an outstanding problem. On the North American continent intracratonic basins share similar tectonic settings and are filled by correlative sedimentary sequences of similar lithostratigraphy (Sloss, 1963)."

"Previous quantitative examinations of subsidence in the Michigan basin have used the changing basin shape over time to constrain the magnitude of an assumed increasing thermal contraction load and the strength of the underlying lithosphere. Isopach data have been interpreted in support of declining lithospheric strength over time (viscoelasticity) (Nunn, 1986), constant lithospheric strength (Sleep & Snell, 1976), and increasing lithospheric strength Haxby *et al*., 1976; Ahern & Dikeou, 1989). These previous studies have not considered the influence of the Appalachian orogeny on the Michigan basin, though Ahern & Dikeou (1989) recognized a tilt from isopachs of Ordovician sediments and suggested that it might be related to the Taconic orogeny."

This paper focuses on the response of the Michigan basin to the Taconic orogeny in order to understand the development of the basin. There is stratigraphic evidence and forward basin models that suggest possible linkage between the Michigan basin and the Appalachian foredeep, which was initiated in response to thrust loading of the lithosphere in the early Middle Ordovician. "The Ordovician section of the Michigan basin brackets the time of Taconic thrusting (Bradley & Kusky, 1986) and provides a record of episodic tectonic subsidence over this time interval."

They use a backstripping method to explain their ideas. "Isostatic principles require that the mass of basin fill displaces the viscous mantle. Because sediment densities are less than that of the mantle, a driving mechanism that makes subaqueous space available for sedimentation is necessary to explain any long-term accumulation of sediment." The backstripping method assumes that the sediment compaction is a function of burial depth, that isostatic compensation is local, and that sedimentation keeps the basin full.

"While lithospheric stretching may be important, it is difficult to apply to equidimensional features like the intracratonic basins of North America, which seem to require that all extensional deformation related to basin initiation occurred beneath the basin." The significance of a thermal mechanism is well established for passive margins where thinned continental crust is continuous with cooling oceanic lithosphere; however, intracratonic basins are still poorly understood.

Next, they describe the various different subsidence configurations which occurred during the basin's history and are consistent with Howell and van der Pluijm's subsidence models. They also go into detail about different depositional sequences.

The Michigan basin was influenced by the Taconic orogeny, which is proven based on the basin's stratigraphic package composition and source. There are three sediment types that make up the bulk of the fill of the Michigan basin: mature quartz sandstone recycled from northern and western basin flanks, chemical sediments (carbonates and evaporites), and immature clastics derived from the Appalachian-Ouachitan orogeny (deltaic sandstones and shales). "The stratigraphic response to the Taconic orogeny begins with recycled sandstones from the basin flanks (St. Peter), continues with carbonate deposition while the basin is isolated from clastic input (Black river-Trenton), and is culminated by the arrival of easterly derived shale (Utica). A similar package can be correlated across the [Findlay-Algonquin] arch to the products of the Acadian Orogeny, beginning with the Sylvania Sandstone and culminating with the Bell Shale. … While the similarity of the lithostratigraphic package suggests a common cause, we have not been able to isolate any indication of a distinctive tilting event during this interval. The youngest preserved sediments in the Michigan basin show the late dominance of the orogenic source."

Howell and van der Pluijm are cited as having similar observations about the Michigan basin. "They found that the periods of basin-centered subsidence correlated with the Taconic and Acadian orogenies and suggested that these were caused by tectonic weakening of the lower crust, which would permit short-wavelength compensation of pre-existing crustal loads." It is suggested also that the basin-centered subsidence could have been activated by the initiation of subduction and an increase in plate stresses. The regional tilting is surmised to have been a long-term effect of the orogeny, perhaps penetration of a subducted slab beneath Eastern North America.

•Cohee, G.V. (1948). Cambrian and Ordovician Rocks in Michigan Basin and Adjoining Areas. *AAPG Bulletin, v.32, no.8*, 1417-1448.

Cohee systematically goes through the Precambrian to Upper Ordovician rocks in detail for the Michigan basin and applicable areas in Illinois, Wisconsin, and Ontario. (I'm focusing on applicable Wisconsin information.)

Precambrian rocks: mostly granite and metamorphic rocks

Cambrian rocks:

Mt. Simon sandstone: (Upper Cambrian- time equivalent to Jacobsville sandstone in northern Michigan), medium to coarse grained sandstone with subangular to rounded grains, a few thin beds of dolomite and sandy dolomite occur in the upper parts of the sandstone

Eau Claire sandstone: consists of sandstone, shale, and dolomite that is shaly and sandy, may be gray to dark gray, pink, purple, and red to brown in color, the shale is also variously colored, glauconite is locally abundant west of the Findlay arch, much more sandy in eastern Wisconsin than in eastern Michigan

Dresbach sandstone: coarse sandstone with well rounded grains, thin beds of dolomite are sometimes present

Franconia sandstone: fine, angular quartz grains, thin beds of sandy dolomite occur in places, generally very glauconitic, red and pink and sometimes as thick as 140 feet in Wisconsin, basal part consists of reworked Dresbach

Trempealeau formation: predominantly dolomite, can be somewhat sandy, also includes shaly dolomite and dolomitic shale at the base, may contain small amounts of chert, there are subunits of the Trempealeau

Hermansville limestone: includes dolomite and sandstone of both Lower Ordovician and Upper Cambrian age that can be traced all the way into northeastern Wisconsin, includes equivalents of the Tremplealeau and Prairie du Chien formations

Lower Ordovician rocks:

Oneota dolomite: buff to brown dolomite, contains small amounts of green shale in places, very cherty and sandy in parts and oolitic chert is common

New Richmond sandstone: thin sandstone unit

Shakopee dolomite: buff, brown and gray dolomite, thin beds of shale, small amount of chert, may also be sandy in parts

St. Peter sandstone: unconformably overlies Lower Ordovician and Cambrian strata in parts of Wisconsin

Middle Ordovician rocks:

Glenwood formation: fine-grained sandstone and shaly dolomite, ranges from 10 to more than 100 feet thick

Trenton and Black River: brown and gray crystalline limestone and dolomite (entirely dolomite in eastern Wisconsin), oil and gas are commonly produced from these beds

Upper Ordovician rocks: mainly gray and dark gray shale with minor amounts of dolomite and limestone

Structure: "The Michigan basin is bounded on the west by the Wisconsin arch extending northwest and southeast from central Wisconsin into northern Illinois, and on the southwest by the Kankakee arch which extends from northeastern Illinois to eastern Indiana where it joins the Cincinnati arch." The major movement of the Wisconsin arch occurred in post-Cambrian time with less movement occurring during Cambrian time.

The Kankakee arch's first major movement was after Shakopee time but before St. Peter time.

The Michigan basin has trends of folding which developed during several periods of deformation. There is a strong northwest-southeast structural trend in the central basin area. "In southwestern Michigan, the structural alignment is also northwest-southeast, but some of the anticlines are aligned northeast-southwest and north-south." The Howell anticline is noteworthy. Faulting occurs on the west flank of the anticline, and 75 feet of Devonian rocks are absent.

Oil and gas production are mentioned, but seem inconsequential.

•Foley, F.C., Walton, W.C., & Drescher, W.J. (1953). "Ground-Water Conditions in the Milwaukee-Waukesha Area, Wisconsin." Geological Survey Water-Supply Paper 1229.

This report states that there are three aquifers located under the Milwaukee-Waukesha area: sandstones of Cambrian and Ordovician ages, Niagara dolomite of Silurian age, and sand and gravel deposits of Pleistocene age. The Maquoketa shale acts as an aquitard between the Niagara dolomite and the sandstone aquifer below. The Paleozoic strata dip gently at 25 to 30 feet per mile. "There is no evidence that any of the faults and folds known or surmised to be present acts as a barrier to the movement of groundwater" (p.1). Static water levels of the sandstone aquifer have declined as much as 350 feet in the Milwaukee area during the period from 1880-1950. Most of the recharge to the shallow aquifers occurs locally from precipitation. However, groundwater recharge to the sandstone aquifer has occurred in some areas due to leakage from the Niagara dolomite by means of deep, uncased wells. Other reason for the decrease in groundwater level is due to increased pumpage linked to population growth in the area.

*There is a table of stratigraphy and water-bearing characteristics (p.8-9).

Precambrian rocks have only been found in three wells in the Waukesha-Milwaukee area (as of 1953): Wk27-dark green and red slate at a depth of 1315 feet, Wk28-granite at 1190 feet, and Wk4-pink quartzite at 770 feet. The Precambrian rocks are crystalline rocks which do not yield water. The surface of the Precambrian drops about 550 feet between Oconomowoc and Pewaukee and continues to drop rapidly eastward past Pewaukee. The estimated depth to the basement is thought to be at least 2500 feet at Milwaukee.

The rest of the formations are described all the way up to the Pleistocene deposits (*good descriptions).

Foley describes the principal geologic structure of the Milwaukee-Waukesha area as being a monocline. He uses the St. Peter sandstone as the datum and states that other horizons would yield the same pattern. It is noted that the eastward dip of the beds is slightly steeper in the northern part than in the southern part. "Significant details of the structure in the area are the faults shown in and near Waukesha and the apparent fold that extends southwestward from the Lake Michigan shore at Shorewood to the vicinity of West Allis in the northeastern part of T6N, R21E" (p.17-18).

The dominant topographic feature of the area is the dramatic shoreline of Lake Michigan, where bluffs rise 60-120 feet above the lake. The surface of Lake Michigan is about 580 feet above sea level. The surface topography, from the crest of the lake shore bluff, is an undulating plain that rises gradually toward the west. "The plain consists of a series of generally north-trending ridges successively higher westward from Lake Michigan." The ridges become more irregular toward the northwestern part of the area. The western part of the area has an altitude of about 1150 feet at its maximum. In the north, the elevation is higher than that of the south, but the local relief is generally not more than 100 feet. The north-south ridges control the flow of drainage in the area by dictating the path of the rivers. These rivers tend to flow parallel to Lake Michigan before finally turning and flowing into it. The drumlins, kettle moraine, and Niagara escarpment (provides a drainage divide) also affect the area.

The bedrock surface topography contains buried valleys which have been filled with glacial sediments. The glacial drift is missing in a few areas, but can be as thick as 429 feet. The bedrock for most of the Milwaukee-Waukesha area is Niagara dolomite. The Maquoketa shale and some Devonian deposits (Milwaukee formation) are also present.

The last seas receded from the area probably during the Mesozoic era, about 200 million years ago. If there were seas still in the area, all of the sediments have since been eroded away completely. As it was, erosion carried away hundreds of feet of the Paleozoic sedimentary rocks. "The continental glaciers of the Pleistocene (epoch) moved over the mature land surface and, as they melted, covered it with a variety of unconsolidated materials. Erosion by the ice probably did not change the bedrock topography greatly. It did round off abrupt slopes and cliffs, and probably gouged depressions in the bottoms of some valleys, but it did not greatly change the drainage pattern" (p.21). The deepest aquifer, the sandstone (St. Peter, Eau Claire, and Mt. Simon), is under artesian pressure.

*There are several good cross sections of the Milwaukee-Waukesha area which might be useful.

The rest of the report is an in-depth analysis of the groundwater conditions for these two counties.

•Haimson, B.C. (1978). Crustal Stress in the Michigan Basin. *Journal of Geophysical Research, v.83, no.B12.*

This paper goes over hydrofracturing tests in a 5,325m deep well in Gratiot County, MI. Four successful tests were run, three tests in perforations in a cemented cased zone.

Haimson goes over the details of the testing and the equipment used and also the details of the data collected and the stress calculations.

The test results show that the stress state in the upper crust of the Michigan Basin indicate a stable interior. The shear stresses are not high in comparison to the mean stress. At a depth of 1,230m in other areas of the Upper Midwest and Ontario, it can be seen that high horizontal stress in the upper kilometer of the crust is a regional characteristic. Haimson states that these stresses could be related to the Canadian Shield, which displays similar stresses, but it is not certain if this is true.

The overall σHmax direction seems to be N60E to N70E based on the findings here and more Midwest-Ontario measurements. "By interpolation we suggest that this direction is also dominant in the Michigan Basin, since it seems to be related to the tectonics of the North American Plate and not to local perturbations."

Haimson felt confident with the testing results. "The high horizontal stress conditions in the shallowest test correspond with both basin flexure and regional trends."

•Haxby, W.F., Turcotte, D.L., & Bird, J.M. (1976). Thermal and Mechanical Evolution of the Michigan Basin. *Tectonophysics, v.36*, 57-75.

Haxby looked at the formation of the Michigan basin in terms of elastic flexure of the lithosphere, and "the shape of the flexure accurately determines the flexural rigidity of the lithosphere and the lateral extent of the load responsible for the flexure."

The mechanisms that control subsidence along the continental margins cannot be applied to the Michigan basin, which is a continental interior basin. "The Michigan Basin is of specific interest because of its near-circular geometry and the virtual absence of secondary structural deformation." The sediments that exhibit the basin shape (subsidence) are from the Middle and Late Ordovician age to the Pennsylvanian age. It is suggested that differential subsidence and erosion probably continued throughout the rest of the Paleozoic and perhaps later. Haxby suggests that "the size and nearly circular shape of the Michigan Basin are strong evidence that the basin resulted from a flexure of the lithosphere under a load which had small horizontal dimensions compared with the characteristic radius of flexure."

This great load must have occurred in the lower crustal area, which is a concept supported by the long-term stability of the basin. The basin subsided over a period of about 75 m.y. This time estimate is consistent with the conductive decay of a thermal anomaly in the lower crust or upper mantle.

"We hypothesize that the subsidence of the Michigan Basin is the result of the flexure of the elastic lithosphere under a load. However, the thickness of the elastic lithosphere has not been a constant during the evolution of the basin." The structural evolution of the basin is consistent with flexure of the elastic lithosphere, but the flexural parameter if the lithosphere has not been constant with time. Haxby found the early thickness of the lithosphere to be 32km, and at the later stages, the lithosphere was 60km thick.

"Because the Middle Ordovician Trenton Limestone is the deepest sedimentary horizon that can be associated with the basin structure, the flexure of these strata can be used to deduce the total load causing the basin subsidence."

*They go into gravity analysis next, but I don't think they attributed the gravity anomalies to the Mid-Continent Rift zone. They don't mention it at all.

The gravity data is corrected for the assumed flexure of the Moho, which was deduced from the flexure of the Middle Ordovician horizon. They found the anomaly to be roughly disc-shaped, with a higher amplitude to the east and south of the center of subsidence.

In the thermal model of the basin, it is hypothesized that the subsidence of the basin is due to a loss of heat: the cooling region is thermally contracting, increasing the load.

The model they come up with to explain all of the findings, this far, consists of three main points. "1) The lithosphere beneath the region to become the Michigan Basin was penetrated by a diapiric intrusion of asthenospheric mantle rock. The diaper ascended into the Mohorovicic discontinuity. 2) The lower crust was heated by the diaper, and converted into a 'metamorphic halo.' It is proposed that the halo is a layer of dense rock, formed by the thermal metamorphism of gabbroic lower crustal rocks into garnet eclogite. 3) During intrusion of the diaper and the generation of the halo, the upward buoyancy of the diaper rocks was nearly balanced by the downward buoyancy of the forming eclogite. As the diapiric rocks cooled, the upward buoyancy diminished and then vanished. The lithosphere then deflected downward with the consequent formation of the Michigan Basin, due to the remaining excess weight of the eclogite body that formed in the zone of the metamorphic halo."

•Holst, T. B. (1982). Regional Jointing in the Northern Michigan Basin. *Geology, v. 10*, 273-277.

*This paper follows up from the 1981 Holst paper.

More joints sets at 98 new stations, which covered Cambrian to Devonian age rocks from the Door Peninsula, WI to Manitoulin Island, ON. "Regional strike around the basin within the study area ranges from about 20° on the west, to east-west in the central part, to about 135º on the east." Holst found a preferred orientation of joints, and four major joint sets were found in the northern Michigan Basin. The most common joint set had an average trend of 052° and was present at 139 of 142 locations. Others: Set 134° at 131 locations, Set 091° at 125 locations, and Set 001° at 124 locations.

The orientation of the four major joint sets seems to be consistent for the entire northern region of the Michigan Basin, except for local, random fluctuations. This indicates "that there is not a simple relationship between joint formation and basin formation." The orientation of the joints is independent of the age of the rocks in which the joints occur.

The joint pattern does not appear to be related to structural trends (roughly 115°) in the Precambrian basement rocks (deduced from geophysical studies). However, a series of northwest-trending folds (with surface relief measuring tens to hundreds of meters) exists in the Paleozoic rocks of the basin. The age and origin of the folding is not well established. No folds were observed in the Cambrian, Ordovician, or Silurian rocks (assumed to mean in the studied area here) but there was folding at one of the Devonian localities.

The northwest-trending joint set (134°) is probably related to a series of major folds in the Paleozoic strata. The northeast-trending sets (052°) are probably extension joints related to present-day tectonic stresses in the region. Holst doesn't know about the other joints.

•Holst, T.B. & Foote G.R. (1981) Joint orientation in Devonian rocks in the northern portion of the lower peninsula of Michigan. *GSA Bulletin, v.92*, 85-93.

This study measured 4,787 joints at 43 locations between Charlevoix and Alpena, MI. They found most (95%) of the joints to be vertical (greater than 80º). The rest of the joints (5%) did not seem to represent the area properly. There were 4 significant joint orientations present at most locations: 002, 054, 092, 133. These measurements were all taken in Devonian carbonate rocks and shales, except for two locations in the Antrim Shale and one location in shale from the Gravel Point Formation. "The presence or absence of any of the sets at a given outcrop is also independent of lithology, age of rock, or location."

•Howell, P.D. & van der Pluijm, B.A. (1999). Structural sequences and styles of subsidence in the Michigan Basin. *GSA Bulletin, v.111, no.7*, 974-991.

“Subsidence in the Michigan Basin produced ~5km of sedimentation over a period of more than 200m.y. during Paleozoic time.” The basin itself has gone through seven different periods of subsidence styles (different geometries). “A history of episodic subsidence reactivations is interpreted as the result of a stress-induced, crustal-weakening mechanism for the narrow, basin-centered subsidence, whereas broad basin-centered subsidence is interpreted as thermal contraction related to lower crustal attenuation during narrow subsidence episodes.”

Sequences:

G- Eastward Tilting (Upper Devonian- Mississippian)
F- Basin-Centered (broad) (Uppermost Middle Devonian)
E- Basin-Centered (narrow basin) (Uppermost Silurian- Middle Devonian)
D- Basin-Centered (broad basin) (Lower Upper Silurian)
C- Eastward Tilting (Middle Upper Ordovician)
B- Basin-Centered (narrow basin) (Lower Middle Ordovician)
A- Trough-Shaped (open to the south) (Cambrian- Lower Ordovician)

Each sequence is described in great detail.

•Howell, P.D. & van der Pluijm, B.A. (1990). Early History of the Michigan basin: Subsidence and Appalachian tectonics. *Geology, v.18*, 1195-1198.

The Michigan basin, 250km in radius and nearly 5km deep, is a simple, essentially undeformed cratonic basin. No consensus has been reached about the origin of the structure, which could be thermal contraction, deep crustal metamorphism, or lithospheric stretching. "Using sequence stratigraphy and backstripping, we show that Cambrian through Silurian subsidence consists of a series of subsidence reactivations and cessations, a history that is incompatible with simple thermal contraction models. We also demonstrate a temporal correlation between Michigan basin subsidence reactivations and major orogenic events in the Appalachians. On the basis of these observations and rheologic models for continental lithosphere, we suggest an alternative subsidence mechanism, which links the subsidence of the Michigan basin to Appalachian orogenic activity and mechanical weakening of the lower crust."

They go over the sequences of deposition that is covered in their 1999 paper. They suggest a model of episodic subsidence which is supported by the changes in the rate of tectonic subsidence.

•Kluessendorf, J. & Mikulic, D.G. (1994). Stop 7A and 7B, Waukesha Lime & Stone Company Quarries, Waukesha, Wisconsin *in "Guidebook to the Problems Associated with Artesian Systems and Land-usage in Southeastern Wisconsin"* AAPG Annual Fall Geology Field Conference.

The Waukesha Lime & Stone Company quarries have the only exposure of a nearly complete section of Silurian rocks in Southeastern Wisconsin.

<u>Mayville Dolomite</u>: oldest Silurian unit in Waukesha; type section in Mayville, WI; 26m thick; dark gray, argillaceous dolomite or mudstone at base; correlates with Kankakee dolomite (Plaines Member)

<u>Byron Dolomite</u>: 2nd oldest Silurian unit; type section in Byron, WI; light gray, well-bedded dolomite; the Mayville and Byron lithologies oscillate, showing shallow subtidal to intertidal settings from sea level fluctuations

<u>Chert</u>: 3m thick; yellowish-gray, dense, even-textured, peloidal dolomite that becomes slightly rougher-textures upward; shallow quiet water deposition

<u>Schoolcraft Dolomite</u>: located only in the northern part of the quarry (missing in eastern and southern parts); equivalent to Chamberlain's Lower Coral Bed; this stratum varies significantly by location

*The disconformities involving the Brandon Bridge, Byron, and Schoolcraft and stratigraphically equivalent to others across the mid-continent (widespread event)

<u>Brandon Bridge</u>: equivalent to Brandon Bridge member of the Joliet Dolomite (NE IL); 1.4m-8m thick; absent north of Waukesha; light green to pale red, argillaceous to finely-crystalline dolomite

<u>Waukesha Dolomite</u>: equivalent to Markgraf Member of Joliet Dolomite (IL); type section was covered by a stadium at Carroll College; 6m-11m thick; laminated to burrow-mottled, slightly argillaceous dolomite at base, to porous, coarsely-crystalline dolomite, to dense, well-bedded, very finely-crystalline dolomite at top; chert is common in Waukesha but absent to the north; Wenlock in age

<u>Racine Dolomite</u>:

<u>Romeo beds</u>: equivalent to Romeo Member of Joliet Dolomite (NE IL); 7m thick, thins to north; light gray, thick-bedded, coarsely-crystalline dolomite with a grainstone-rudstone texture

<u>Lannon beds</u>: 10m thick; dense, thick-bedded, light olive gray, subargillaceous to very finely-crystalline dolomite; inter-reef

Individual Silurian units remain fairly uniform in character and thickness from Waukesha to the Chicago area. The Waukesha Fault is located in the west quarry and the best exposure of the fault.

•Kuntz, C.S. & Perry, A.O. (1976). History of reports on selected faults in southern and eastern Wisconsin. *Geology*, 241-246.

Kuntz and Perry reviewed several reports about faults located in southern and eastern WI and discussed the varied findings. The focus of the paper was on four major faults: Madison Fault, Waukesha Fault, Two Rivers Fault, and Peshtigo-Brussels Fault. There were many discrepancies between researchers such as: location, extent, and layout for each of the faults. Thwaites (1931) had the Waukesha Fault starting at the Illinois border and continuing NE upwards all the way to Lake Michigan. Thwaites later went on to modify the fault a couple more times (1940 and 1957). The USGS and AAPG also produced other findings (minimum distance: 38.5 miles, max: 133 miles).

Overall, this paper does a good job of outlining the previous work that was done on these faults.

•Moll, J.G. (1987). "Magnetic Investigation of the Waukesha Fault, Wisconsin" Masters Thesis, UW-Milwaukee.

The magnetic survey was conducted in 1986 using a proton-precession magnetometer. Readings were taken at one-mile intervals on a square mile grid and a base station was used for diurnal corrections.

It has been found that the magnetic and gravity signatures are closely related. They both trend N40E, but they have different locations. However, the magnetic survey does not give an accurate location of the fault since there are problems with "relating magnetic anomalies to specific basement lithologies when sparse basement geological data is available."

*(my ideas…) There are discrepancies with interpretations due to the different theories on fault placement and whether it is nearly vertical or listric, placement of igneous intrusions in the Precambrian basement rocks, and varying thicknesses of strata on either side of the fault. There also isn't enough data of actual basement rocks. There aren't enough deep wells, just a few municipal water wells. There is also a possibility that the magnetic and gravity surveys responded to different geological features.

The Precambrian basement, from geological evidence, on the upthrown side (northwest) of the fault is depicted as being peneplain. It was assumed that the peneplain surface was also present on the downthrown side.

The "positive magnetic relief observed over the survey area is primarily a function of the function of the large susceptibility contrasts between the Precambrian granite and mafic intrusives and to a much lesser degree structural relief on the Precambrian surface." The overlying sediments, quartzite, and glacial deposits are not thought to contribute to the magnetic signature of the survey area.

The geologic models produced from the magnetics data and the limited deep well data suggest a primarily granitic basement that has been penetrated by mafic intrusives that do not subcrop at the Precambrian surface. There is a suggested "direct relationship between the northeasterly striking band of positive anomalies and the Waukesha Fault. Mafic material may have intruded into fractures associated with the development of the fault. Basement faults may also be associated with the steeply dipping to vertical edges of the mafic intrusives n the models and some of the high magnetic gradients revealed by the survey."

Suggestions for further work: p.59

•Paull, R.K. & Paull, R.A. (1977). "Geology of Wisconsin and Upper Michigan – Including parts of Adjacent States." Kendall/ Hunt Publishing Company, Dubuque, Iowa.

<u>Paleozoic: The seas come and go</u> (starting on p.37)

"Depositional patterns of the Upper Cambrian and younger Paleozoic rocks in our area reflect the influence of the Wisconsin arch and adjacent basins." The Wisconsin dome provided sediments to the Paleozoic seas that surrounded it. The Michigan, Illinois, and Forest City basins all progressively subsided during the Paleozoic and accumulated more sediments than the surrounding areas. "During Late Cambrian and Early Ordovician deposition, a faint suggestion of a Wisconsin arch developed when an embayment formed in the area of western Wisconsin, eastern Iowa, and southeastern Minnesota."

When seas returned to the area in the Middle Ordovician, the Wisconsin arch and Illinois and Michigan basins were well defined. The basins were separated by the Kankakee arch. "Although the arches that separate basins of the Upper Midwest were formed by Late Ordovician time, they were no longer emergent features, and the Late Ordovician and Silurian seas covered them. However, the water depth over the Kankakee and Wisconsin arches was shallow enough to allow Silurian reefs to develop around the edges of the Michigan basin."

During the late Silurian and Devonian time, uplift occurred which exposed the arches and parts of adjacent areas, exposing them to erosion. Deposition continued into the Pennsylvanian. "By Permian time, the role of the arches and basins in the depositional history of this area was over, the entire region was uplifted and a long erosional interval began." The formation of the LaSalle anticline is thought to have caused the southside of the Sandwich Fault to move upward hundreds of feet. It is also thought that there were a lot of earthquakes during this time. (*Did this help with the formation of the Waukesha fault?)

The Wisconsin and Kankakee arches were not from a process that involved the uplift of positive features. These arches were merely less subsident areas along margins of the more rapidly subsiding basins. Most of the sedimentary rocks were deposited in shallow seas. (p.39)

Each stratigraphic unit is thoroughly described, one by one. All the information is then summarized in a table (p.43).

Glaciers covered the land during the Pleistocene and consisted of four major continental ice sheets. The glaciers reached a maximum thickness of 10,000 feet and caused a crustal depression that may have exceeded 3,000 feet. There is still crustal rebound going on in this area. Milwaukee is rising about ¼ inch per year. There were other glacial periods: Precambrian and end of Paleozoic into the Mesozoic. (p.52)

Lake Michigan was formed during the Pleistocene, with the help of the glaciers. "The preglacial Great Lake basins were probably occupied by river systems. As the continental ice fronts began their advances and retreats some two million years ago, these valleys were modified and soured by glacial deposition and erosion. The entire region was also depressed by the great mass of the ice tongues."(p.67) The water in the lakes was caught between the retreating ice margins and other previously deposited drift, and it accumulated until it reached the overflow rate.

<u>Eastern Ridges and Lowlands</u> (starting on p.139)

The Eastern Ridges and Lowlands area is underlain by Paleozoic rocks. These rocks, although modified by Pleistocene ice, influenced the shape of the land with their alternating resistant and nonresistant Paleozoic sedimentary rock units, which parallel the shoreline of Lake Michigan. "The Late Wisconsinan ice (Woodfordian and Valderan) planed off the bedrock highs and filled in the lows to create a youthful glacial landscape."

"Over lying the Platteville-Galena in this lowland area is the Upper Ordovician Maquoketa Shale. The greenish shale, with its thin interbeds of fossiliferous limestone, occurs in a narrow belt along the base of the resistant Silurian dolomite." (p.142) (An equivalent formation to the Maquoketa is the Richmond, found in Escanaba.) *Other formations are described in detail.

There are a few small exposures of Precambrian rocks in the Eastern Ridges and Lowlands. The largest exposure is ledges of Animikean Waterloo Quartzite in Dodge and Jefferson counties, and this quartzite has small pegmatite dikes cutting through it at this locality. There are also some exposures of rhyolite in Green Lake County.

There are lakes throughout this area, some of which are the Kettle Moraine Lakes of Waukesha and Washington Counties. These lakes are primarily kettle holes in till or in outwash areas within the morainal complex.

"By the Middle Silurian, seas spread throughout our region and covered the Kankakee and Wisconsin arches along the western and southern margins of the Michigan basin. The widespread extent of this sea served to isolate most of our area from sources of land-derived sediment on the Canadian shield and from an orogenic belt far to the east. The water over the arches was relatively shallow, clear, and warm, with sufficient wave and current agitation to provide ideal sites where communal, calcite secreting animals and plants such as algae, corals, and stromatoporoids (extinct relatives of the corals) formed reefs. Similar conditions existed on the other flanks of the Michigan basin at this time, so it was encircled with growing reefs." (p.169)

•Pirtle, G.W. (1932). Michigan structural basin and its relationship to surrounding areas. *AAPG Bulletin, v.16, no.2*, 145-152.

The main map Pirtle uses is based on the Trenton Limestone (M.Ord.) through deep-well records and other data published (by states and Canada). The map highlights other features, such as: Appalachian, Michigan, and Eastern Interior Coal Basins, Wisconsin arch, Kankakee arch, Cincinnati arch, and LaSalle Anticline.

Wisconsin Arch: broad fold with axis N20W, extends from central WI down to IL, it is stated that there was movement along the axis during all Paleozoic time which would (hopefully) explain all the major unconformities

Kankakee Arch: relatively small uplift trending N45W, it connects the Wisconsin and Cincinnati Arches

Pirtle also states that the origin of the extensive parallel folding (it sounds like speculation) has to do with the early history of the basin itself, mainly pertaining to the subsidence which helped to form the basin shape.

•Prouty, C.E. (1988). Trenton Exploration and Wrenching Tectonics- Michigan Basin and Environs *in "The Trenton Group (Upper Ordovician Series) of Eastern North America- Deposition, Diagenesis, and Petroleum"* AAPG Studies in Geology #29.

Prouty (1976) proposed a wrenching model to account for the linear intrastructures of the Michigan Basin. Fault patterns and outcrop fracture analysis provided support for this early assessment. The basin has been elongated (NNW), but there are many different theories about how the basin formed. Most of the appeal to study the basin is due to oil and gas exploration. The fields all tend to be linear and narrow, which suggests a faulting and fracturing (due to fracture porosity and vuggy dolomite porosity). Seismic techniques are relatively ineffective (1988) because of insufficient vertical offset "that is characteristic of the strike-slip movement of the faults in a wrenching model."

The fractures measured at the quarries and outcrops were all essentially vertical, with spacing of several inches to several feet, and could be mineralized tight (usually dolomite) or open. Occasional slickensides were found indicating strike-slip displacement. "The azimuth of several hundred of these master joints strongly suggested shearing action." Later, using LANDSAT images, more of the area was mapped, covering Precambrian to Pennsylvanian rocks. The lineaments showed "little or no directional change related to rock type, topography, or thrust-faulted structures." These lineaments varied from about 1 mile to over 135 miles. The azimuths of the lineaments tend to form clusters, which have regional consistencies. LANDSAT imaging depends on detecting moisture (or something) being emitted from and open, linear source.

To further prove the idea of a wrenching model, more observations were made. A structure map of the West Branch field shows that there are several short axes arranged in en echelon form. The Kawkawlin field shows similar en echelon shear faults. Other fields also back up this data. A Fourier analysis of the stress field and simple shear model and strain ellipsoid, along with other analyses all support the wrenching tectonic system theory.

•Quinlan, G.M. & Beaumont, C. (1984). Appalachian thrusting, and the Paleozoic stratigraphy of the Eastern Interior of North America. *Canadian Journal of Earth Science, v.21*, 973-996.

This paper discusses tectonic activities that influenced the Eastern Interior of North America, mainly focusing on the Michigan, Illinois, and Appalachian basins and the interactions between them. "The sediment record of this area is found preserved in three deep sedimentary basins, the Appalachian, Michigan, and Illinois basins, and across intervening arches and domes." The subsidence in the Appalachian basin was episodic with centers of maximum deposition shifts along the length of the basin between Mid-Ordovician and Late Pennsylvanian times, perhaps even into the Permian. Quinlan and Beaumont suggest that the primary forces responsible for the behaviors of the basin are the overthrust loads in the Appalachian Mountain system and the response to these loads by the flexural properties of the lithosphere.

They talk about the development of arches near basins, and how they might be thermally uplifted as a lithospheric plate passes over a mantle plume. However, due to the complex pattern required for the development of all the arches, this is probably not the sole mechanism responsible. They suggest instead that the arches can be explained by the flexural interaction between the basins and their driving loads.

•Root, S. & Onasch, C.M. (1999). Structure and Tectonic Evolution of the Transitional region between the Central Appalachian Foreland and the Interior Cratonic Basins. *Tectonophysics, v.305*, 205-223.

Root and Onasch break down the structures found in the region between the Appalachian foreland basin and the Illinois and Michigan Basins into first and second order structures. The first order structures are the primary product of plate convergent processes: the Waverly and Cincinnati arches, which are both considered to be forebulges. (Forebulges form at the margin of a continent as the deformational load accumulates, and the compensation for the extra load occurs in the lithosphere, producing subsidence.)

The second order structures, which come from plate convergent processes also, are basement faults that have extended deformational history. “These faults involve the Precambrian basement and are first observed in basal Cambrian strata as normal faults associated with passive margin rifting” (p. 207). These faults continued to be active as growth faults during much of the Paleozoic. From the Pennsylvanian to Permian, many of these faults were reactivated as wrench faults due to the Alleghanian deformation.

“The Kankakee arch is interpreted as a consequence of subsidence in adjacent Michigan and Illinois Basins with relative rates of subsidence and/ or locus of orogenic loading controlling the position and magnitude of the arch.”

•Ryder, R.T. (1996). Fracture patterns and their origin in the Upper Devonian Antrim Shale gas Reservoir of the Michigan Basin: A Review. USGS Open File Report 96-23.

In the Michigan Basin, the Upper Devonian Antrim Shale is a source and reservoir rock for oil and gas, in the black shale units. Natural fracturing in this unit is almost a necessary feature for production so much focus is put on finding fractured areas.

Ryder cites Holst and Foote's (1981) joint set study in reference to joint orientation, saying the dominant sets are northeast-southwest (~52°) and northwest-southeast (~314°).

Ryder states the pre-Michigan basin Proterozoic tectonics may have left diagnostic structures in basement rock that became reactivated by later tectonic events. *Really good break down of stresses in basement rock that became reactivated by later tectonic events.

The gray Antrim Shale units have less quartz (30-40%) and more carbonate minerals (15-30%) than the black shale units. The gray shales are also not as brittle as the black shales. *Frequency and aperture width of fractures in the shales show a direct relationship to TOC (total organic carbon content) and carbonate content and an inverse relationship to clay content.

•Secor Jr., D.T. (1965). Role of Fluid Pressure in Jointing. *American Journal of Science*, 633-646.

Secor starts out by defining terms.

<u>Extension fracture</u>: fractures that form from normal to the least principal stress direction

<u>Tension Fracture</u>: special kind of extension fracture that forms normal to a tensile least principal stress

<u>Shear Fracture</u>: they are inclined to the directions of principal stress, can occur in two conjugate sets, intersecting along the line of intermediate principal stress direction, with the acute angle of intersection bisected by the direction of greatest principal stress

<u>Joint</u>: applied to fractures that have little or no tangential displacement

<u>Fault</u>: applied to fractures that have obvious tangential displacement

Secor goes on to further point out the characteristics of these features. Joints often have plumose structures which indicate no significant lateral movement. He states that "the fundamental fracture pattern of a rock mass is established early in its history."

Next, he goes through several formulas and Mohr diagrams with failure envelopes. "Internal pore pressure is one of the most important variables affecting the strength of brittle solids." Geologists in the past were reluctant to assign a tensile origin to joints because they thought it was nearly impossible to have tensile stress at depth in the earth's crust. However, it is possible to have effective tension fracturing at depth, but it “requires fluid pressure overburden weight ratios no greater than those observed in deep oil wells.”

•Sverdrup, K.A., Kean, W.F., Herb, S., Brukardt, S.A., & Friedel, R.J. (1997). Gravity Signature of the Waukesha Fault, Southeastern Wisconsin. *Geoscience Wisconsin, v.16*, 47-54.

This paper covers gravity surveys that were done in Southeastern Wisconsin in 1983 and another in 1985. The data from these surveys was combined and interpreted. They found a northeast trending zone, 5km wide, with gravity values 10mgals greater on the northwest side than on the southeast side. The offset (possible fault line?) trends N19E for 10km from about Eagle to North Prairie. From North Prairie to (west of) Waukesha (13km), it trends N47E. From there, the trend continues for 23km more at N38E through Menominee Falls to the Washington-Waukesha county line. Then, it continues at N27E for 6km till (5km southwest of) Cedarburg, Grafton, and to Port Washington (22km). The offset of the fault west of Waukesha was interpreted by Brukardt (1983) to be due to a second fault striking N60W.

The bedrock in Southeastern Wisconsin dips gently to the east from the Wisconsin Dome into the Michigan Basin. The contact between the bedrock and glacial deposits is irregular due to differential erosion that occurred in the Pleistocene deposition.

The depth to the basement is fixed sufficiently on the northwest side, but no wells are deep enough on the southeast side. Thwaites (1940) states that the depth to the Precambrian on the southeast side is more than 800m below sea level. (<-need better proof, more info)

They made gravity models of what the units were originally thought to be laid out as with a steeply dipping fault (nearly vertical). This model had a high error value, and the residual gravity curve suggested that the dip was too steep. They made new models with shallow dipping (9° and 20°) faults and were well within the allowed error value. The exposure of the fault in the Waukesha Stone & Lime Company quarry is nearly vertical, so they surmised that the fault could be listric.

This study confirms that the fault extends through Waukesha and Ozaukee counties to Lake Michigan. They could not conclude as to whether the fault is high angle or listric. They suggest further work to be done.

•Underwood, C.A., Cooke, M.L., Simo, J.A., & Muldoon, M.A. (2003). Stratigraphic controls on vertical fracture patterns in Silurian dolomite, northeastern Wisconsin. *AAPG Bulletin, v.87, no.1*, 121-142.

Fracture patterns, exposed on horizontal and vertical surfaces have been used to infer paleostress orientations, giving evidence of the tectonic history of a region, but interpretations from vertical outcrop patterns of fractures requires consideration of both tectonic s and stratigraphy (which can produce variations in the fracture pattern). Interface properties control fracture termination. Mechanical unit thickness, or spacing of mechanical interfaces, controls fracture density; therefore, predicting fracture density requires knowledge of the distribution of mechanical interfaces. To predict subsurface opening mode fracture networks by available observations of sedimentary stratigraphy, accurate descriptions of the relations between sedimentary stratigraphy and mechanical stratigraphy must be made. This allows for prediction of subsurface fluid flow because there is better characterization of potential flow paths.

"Fracture orientations in the Door Peninsula resemble those in other parts of the Michigan Basin. These fracture orientations are likely controlled by the present-day stress field (~50°) or past stress fields associated with the Appalachian and Ouachita orogenies (134° and 001° respectively). Joint surface textures, mostly hackle marks and fringe joints, were observed along many of the fracture surfaces, which means the surfaces are joints that formed by open-mode failure of the rock."

The comparison of fractures on different oriented quarry walls reveals little difference in fracture density and termination characteristics, within the same strata. "The close correlation of fracture pattern between these two sets suggests that each fracture set developed similarly within each Stratigraphic level of the Silurian dolomite." "Fracture density is a function of mechanical unit thickness and rock stiffness."

They used two methods to locate the mechanical interfaces. One method is visual identification in the field, which could be influenced by visual bias at visually distinct horizons being overlooked. The second method: a stratigraphic horizon is considered as a mechanical interface if both 1) a small percentage of fractures propagate through the horizon and 2) a sufficient number of fractures terminate at the horizon.

In this study, "all fractures are vertical and perpendicular to bedding so that fracture length describes the vertical trace length observed on quarry walls." They found that fractures that are in the thinly bedded inner shelf facies association are generally evenly distributed, densely spaced, and confined to distinct layers. The organic horizons in this facies association appear weak and friable in outcrop, so these layers are weak and should stop vertically propagating fractures. Even though the mud horizons are not as weak and friable as the organic horizons, fractures generally stopped at these shallowing –upward cycle boundaries.

It seems that the sedimentary stratigraphy controls the fracture patterns. Stiffness measurements were also taken at several locations within each facies association, and the stiffness variation throughout the Silurian does not exceed the error of this testing method. Stiffness changes are minimal throughout the Silurian dolomite, so fracture termination is most likely not the result of the material property differences between mechanical units, such as grain-size differences or cementation variations. Instead, the termination of vertical fractures is likely controlled by the nature and distribution of stratigraphic horizons that act as weak mechanical interfaces.

The fracture density data indicates that mechanical units are generally unsaturated with respect to fracturing, which is expected because of the low-strain tectonic environment. "Fracture mapping and analysis indicates that the length (vertically) and density of fractures in the Silurian dolomite are primarily controlled by the distribution of mechanically weak interfaces. Determining the distribution of these [weak] interfaces is a requirement for predicting fracture patterns at depth."