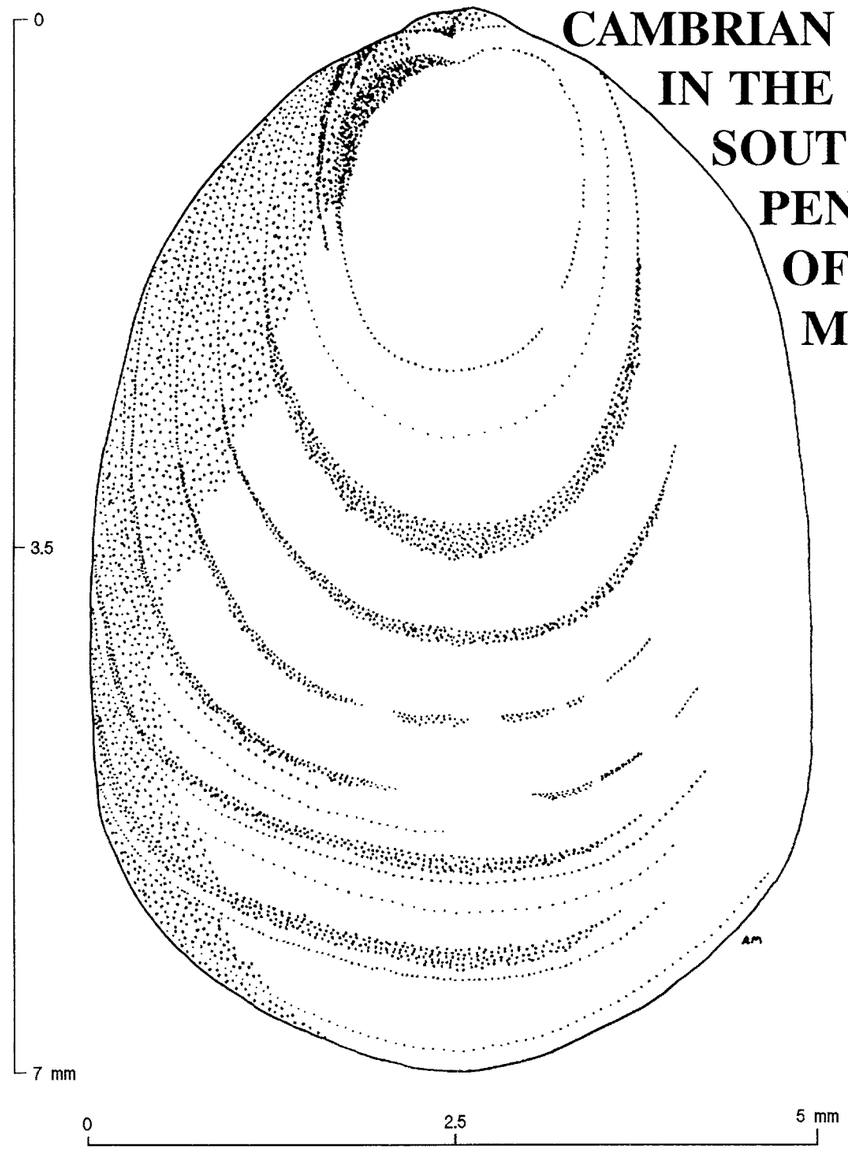
SUBSURFACE STRATIGRAPHY OF CAMBRIAN ROCKS IN THE SOUTHERN PENINSULA OF MICHIGAN



BULLETIN 7

by

RANDALL L. MILSTEIN
GEOLOGICAL SURVEY DIVISION
MICHIGAN DEPARTMENT OF NATURAL RESOURCES
LANSING, MICHIGAN 1989

DNR

Cover:

The drawing on the cover is of an inarticulate brachiopod *Lingulla* (Salter, 1866). It was noted in a core from the Upjohn #4 disposal well, Permit Number 327-794-829, Portage Township, Kalamazoo, Michigan. This *Lingulla* is one of several complete and partial brachiopods identified in the core from the Mt. Simon Sandstone interval at 5003.5 feet (1525 meters). The core is the property of the Geological Survey Division, Michigan Department of Natural Resources. Drawing by Randall L. Milstein.

GEOLOGICAL SURVEY DIVISION

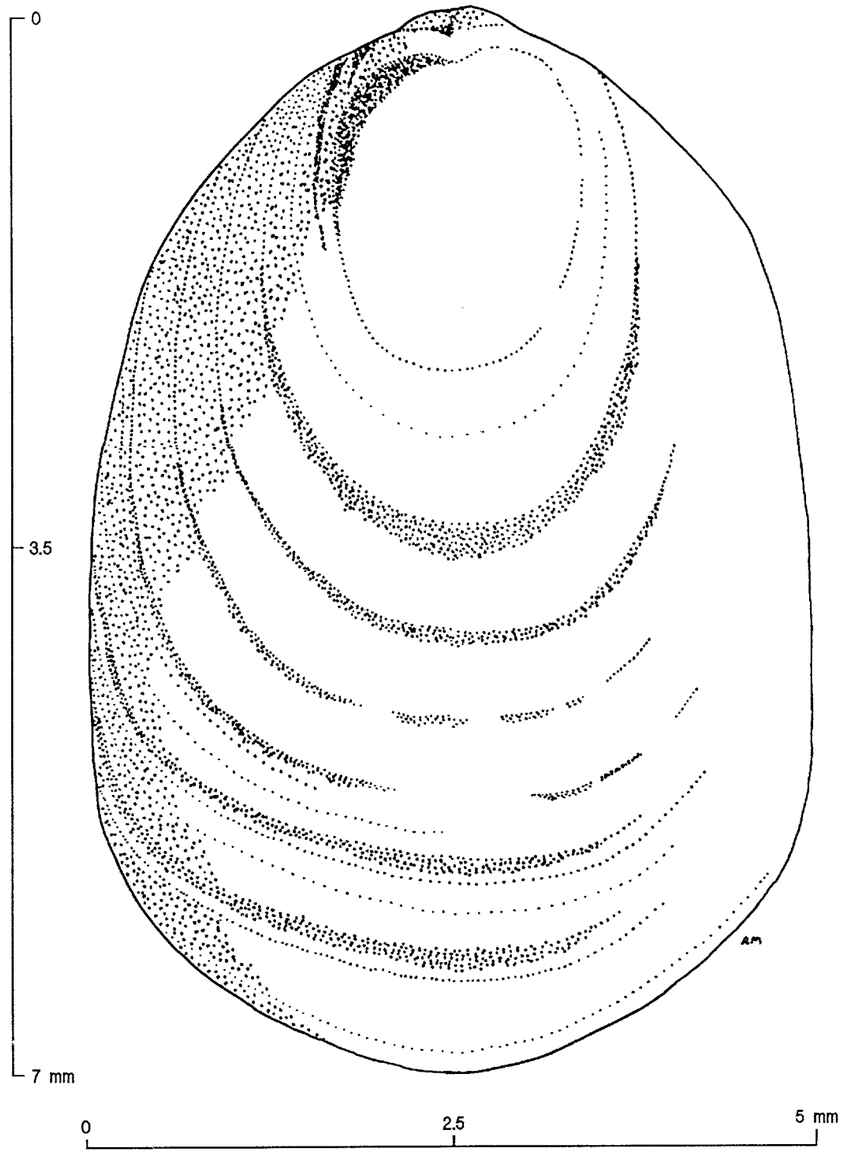
BULLETIN #7

SUBSURFACE STRATIGRAPHY OF CAMBRIAN ROCKS IN THE SOUTHERN PENINSULA OF MICHIGAN: MICHIGAN BASIN

by

RANDALL L. MILSTEIN
MICHIGAN DEPARTMENT OF NATURAL RESOURCES

LANSING, MICHIGAN 1989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ABSTRACT

Rocks believed to be Late Cambrian in age exist throughout the entire subsurface area of Michigan's Southern Peninsula. These Cambrian rocks represent the oldest Paleozoic sedimentary deposits in the Michigan Basin. Isopach and paleogeologic maps of these Cambrian rock units have been prepared with data derived from geophysical well logs, descriptive logs and well samples from 101 oil and gas test wells, mineral extraction wells and deep disposal wells

A generalized contour map of the Precambrian surface has also been prepared from this data.

The prepared maps indicate that the geologic structures known to be associated with the Precambrian surface are reflected upward into overlying Cambrian rock units. In many instances these features reflect upward through the entire Paleozoic section to form prominent bedrock structures.

Comparison between mapped Cambrian strata and structure contours of the Precambrian surface implies the presence of a unique relationship. The apparent distribution of Cambrian strata around the edges of the Michigan Basin, particularly along the Basin's eastern margin where the greater part of the data is available, indicates that successively younger beds overlap to lie directly on the Precambrian surface. This suggests that the regional configuration of the Precambrian surface, during Cambrian times, was similar to the present. In addition, the Mt. Simon Sandstone, the oldest Cambrian sedimentary deposit in the Michigan Basin, was apparently deposited directly on top of the Precambrian erosional surface. An isopach map of the Mt. Simon indicates Mt.Simon sediments were deposited in a nearly circular basin. This suggests that the Precambrian surface had attained a near circular configuration prior to the deposition of Cambrian sediments. Both observations suggest that an embryonic Michigan Basin, in a form similar to its present near circular morphology, existed as early as Middle Cambrian time.

INTRODUCTION

The Michigan Basin is a relatively shallow intracratonic basin encompassing all of Michigan's Southern Peninsula and the eastern portion of the Northern Peninsula (Figure 1). The Basin also includes parts of Wisconsin, Illinois, Indiana, Ohio and Ontario. The Michigan Basin is bounded on the north and northeast by the Canadian Shield, on the east and southeast by the Algonquin Arch in Ontario and the Findlay Arch in northern Ohio, and on the southwest by the Kankakee Arch in northern Indiana and northeastern Illinois, and on the west and northwest by the Wisconsin Arch and Wisconsin Dome. The Michigan Basin is roughly circular and has a slight northwest-southeast elongation.

The sedimentary rocks present in the Southern Peninsula of Michigan range in age from Precambrian, through Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, and Jurassic, with a known thickness greater than 15,800 feet (4816 meters). This study is concerned only with that part of the Paleozoic section assigned to the Lake Superior Group. These rocks rest upon either the Precambrian crystalline surface, Precambrian sedimentary deposits, or erosional Precambrian remnants and are overlain by the Early Ordovician Prairie du Chien Group in Michigan's Southern Peninsula. The beds described in this study constitute roughly 14% of the total volume of Paleozoic rocks in the Southern Peninsula, and are believed to be Late Cambrian in age.

The purpose of this study is to present updated, generalized isopach maps of the subsurface Cambrian rocks in the Michigan Basin. The maps were prepared with data derived from geophysical well logs, descriptive logs and well samples from 101 oil and gas test wells, mineral extraction wells and deep disposal wells. Each of these wells has fully penetrated at least one Cambrian rock unit.

Figure 2 illustrates areas of the Great Lakes Region in which rocks of Cambrian Age are believed to be present in the subsurface. These rocks exist throughout the Southern Peninsula of Michigan and are covered by Paleozoic strata.

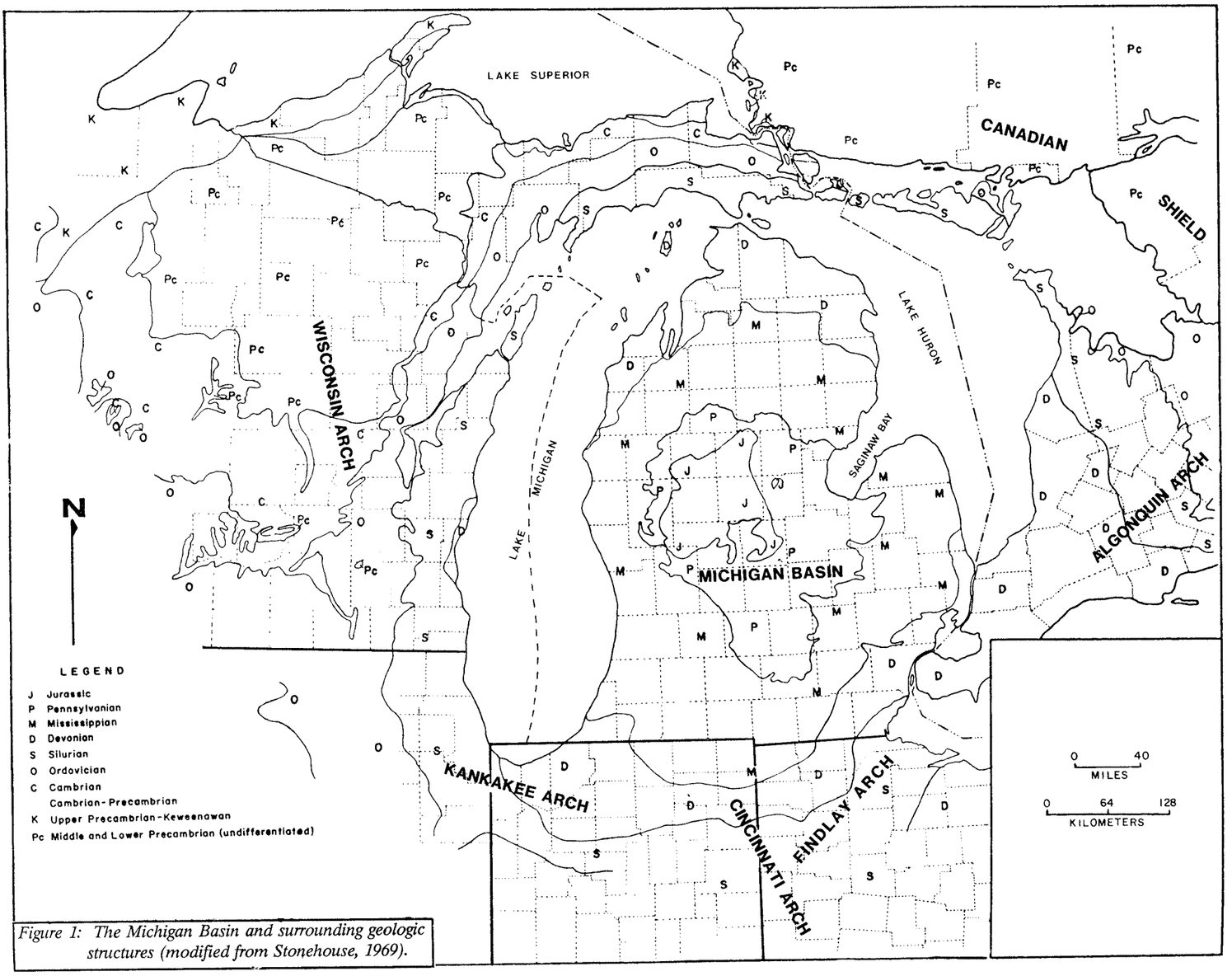


Figure 1: The Michigan Basin and surrounding geologic structures (modified from Stonehouse, 1969).

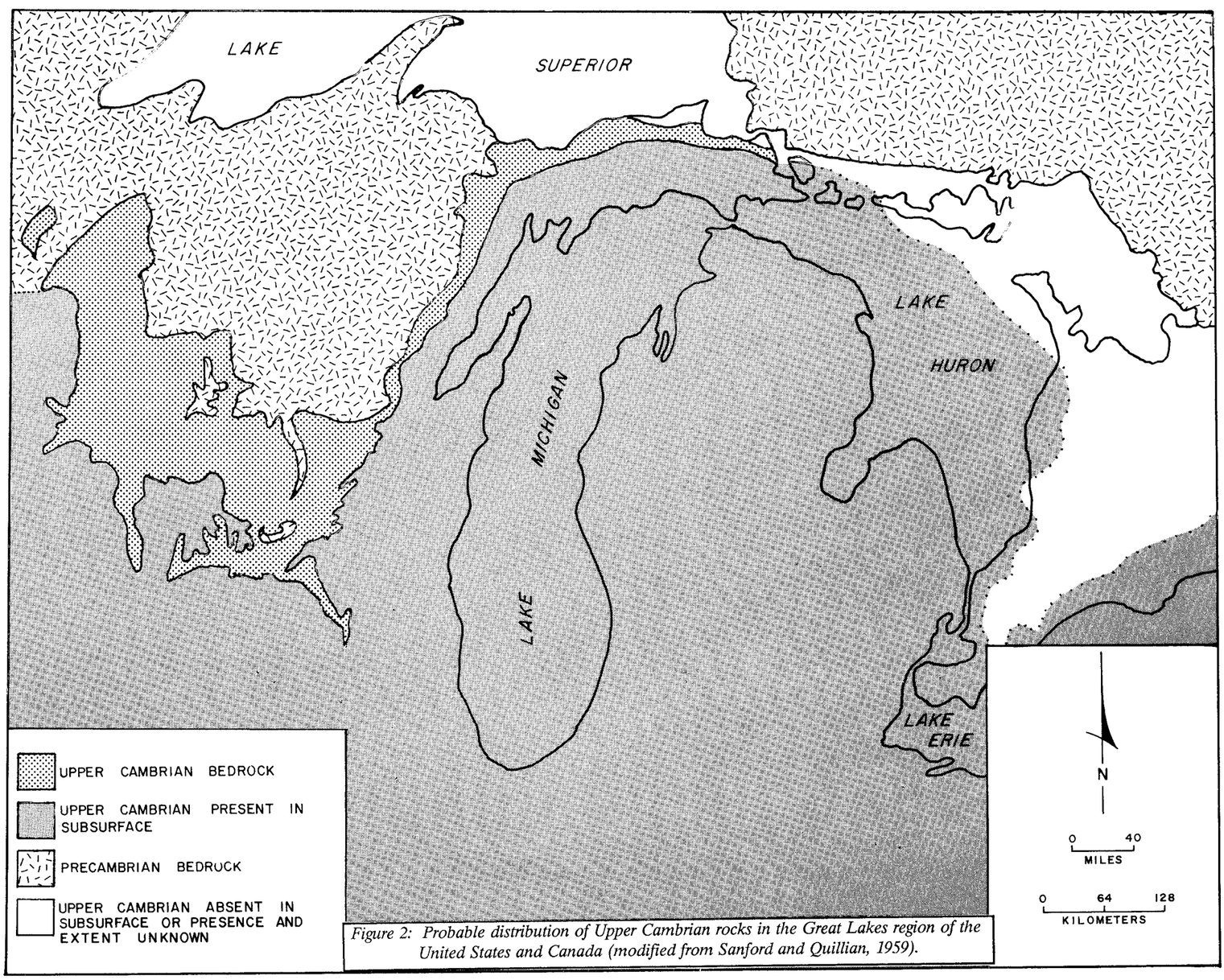


Figure 2: Probable distribution of Upper Cambrian rocks in the Great Lakes region of the United States and Canada (modified from Sanford and Quillian, 1959).

Dr. Douglass Houghton (1841), however, was the first geologist to undertake a serious and systematic study of these outcrops.

Houghton (1837–1845, ed., Fuller, 1928) first applied the term "Lake Superior Sandstones" to the lowest Paleozoic rocks in Northern Michigan which rest upon the Precambrian complex.

Foster and Whitney (1851, Part II, pages 110-139) presented the first detailed descriptions of Houghton's "Lake Superior Sandstones." They considered the sandstones to be equivalent to the Potsdam Formation of New York. Further work by Rominger (1873) supported this conclusion. Wadsworth (1892) and Lane (1892) assigned Houghton's "Lake Superior Sandstones" to the Cambrian.

Thwaites (1934) concluded that the Mazomanie and Dresbach formations of Wisconsin were correlative to the Munising sandstones in Northern Michigan. He also proposed the existence of a disconformity between the Jacobsville and Munising. Based on Thwaites 1934 publication, Martin (1936) reclassified the "Lake Superior Sandstones" as the Munising Formation. Martin considered the Munising Formation equivalent to the Dresbach, Mazomanie, Trempealeau, and Jacobsville formations. The Jacobsville at that time was assigned to the Cambrian.

Thwaites (1943), contrary to the conclusions in his 1934 paper, found no division in the Munising and at that time concluded the Munising was equivalent to the Franconia of Wisconsin.

In 1945, Cohee published the United States Geological Survey Oil and Gas Investigation Preliminary Chart Number Nine. Based on subsurface stratigraphic work, Cohee concluded the Hermansville as assigned by Martin (1936) to be equivalent to the Jordan, Trempealeau and Prairie du Chien and the Munising Formation to be equivalent to the Eau Claire, Dresbach and Franconia.

Sorensen and others (1964), in developing the stratigraphic succession chart of the Michigan Basin for the Michigan Geological Survey, divided the Late Cambrian Lake Superior Group into the Trempealeau and Munising formations. The Trempealeau was divided into three members within the subsurface; the Jordan, the Lodi and the St. Lawrence. The Munising was divided into four subsurface members; the Franconia, the Dresbach, the Eau Claire and the Mt. Simon. Sorensen assigns a Middle and Early Cambrian age to the Jacobsville Sandstone.

Shaver and others (1985), in compiling the "Midwestern Basin and Arches Region" of the Correlation of Stratigraphic Units of North America Project (COSUNA), express the present opinion of many researchers on the nomenclature of the Late Cambrian rocks in the Michigan Basin. Following the correlations of Sorensen and others (1964), they divide the Late Cambrian Lake Superior Group into the Trempealeau and Munising formations. They do not divide the Trempealeau Formation or assign it subsurface members. Shaver and others (1985) divide the Munising Formation into the Franconia, Galesville and Eau Claire members. In their study the Mt. Simon Sandstone has formation status and the Jacobsville Sandstone has been assigned to the Precambrian. This nomenclature is now in use by many researchers studying Cambrian rocks in the subsurface of the Michigan Basin. The name Galesville is not widely used or recognized and many researchers still refer to the Dresbach in subsurface studies.

In order to standardize information for future research, the nomenclature used in this report is that employed by the Michigan Geological Survey. This nomenclature is a modification of the work of Sorensen and others (1964) and Shaver and others (1985). The terms have proven themselves effective and reliable in daily usage.

Figure 3 shows the general development of Cambrian nomenclature in the Michigan Basin. A more detailed presentation, in chart form, is found in Martin and Straight (1956).

Correlating these sediments from their Northern Peninsula outcrop locations into the subsurface of the Southern Peninsula has always proved a difficult and controversial task mainly because they are buried beneath thousands of feet of younger strata, and only a limited number of wells have completely penetrated them. Further, the information available from these wells is limited to incomplete well cutting sets, geophysical well logs which are open to varying degrees of interpretation, and only occasionally to a non-proprietary cored interval.

Subsurface correlations used in the preparation of the maps in this study were based on the previous work of Cohee (1945), Hamblin (1958), Sanford and Quillian (1959), Ells and others (1964), Ells (1967), Yettaw (1967), Catacosinos (1972), Janssens (1973), Syrjamaki (1977), Lilienthal (1978), and Milstein (1983).

The author is aware of the present controversy involving Early Ordovician nomenclature within the Michigan Basin and how the resolution of this problem may affect the Basin's Cambrian nomenclature. The purpose of this study however is to describe and map rock units constituting the Late Cambrian in the subsurface of Michigan's Southern Peninsula and, in doing this, the author has adopted the terms and classifications presently used by the Michigan Geological Survey. Modifications in subsurface stratigraphic nomenclature are to be expected as additional stratigraphically deep wells are drilled and more detailed studies are made.

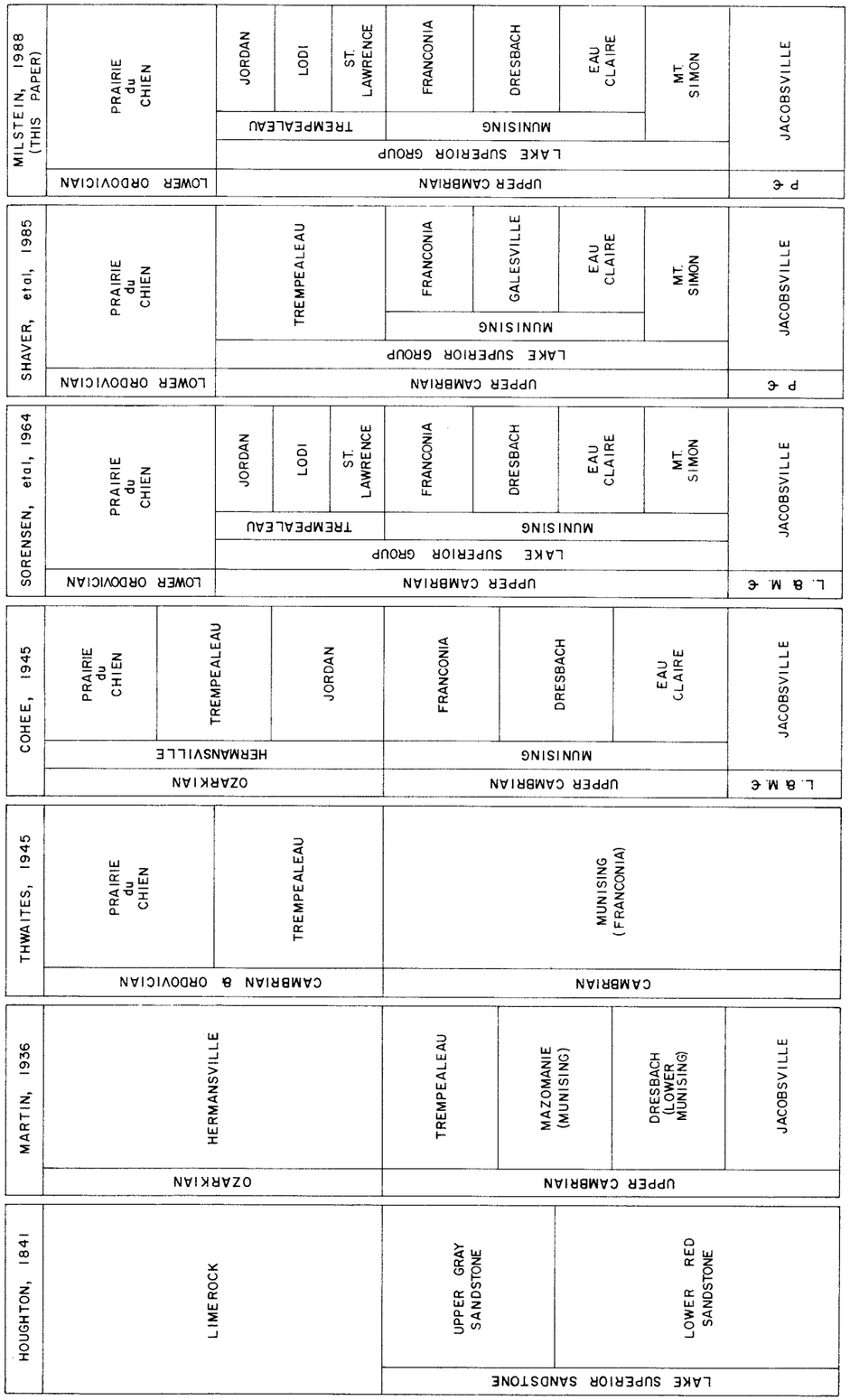


Figure 3: Evolution of Upper Cambrian nomenclature in the Michigan Basin.

STRATIGRAPHY

Rocks of Paleozoic age in the Michigan Basin dip from the contiguous areas toward the center of the Basin. Dips are not uniform everywhere, but most average between 25 to 60 feet/mile (5 to 11 meters/kilometer). During the Late Cambrian, the Michigan Basin was an area of major deposition. The units described here are represented mainly by clastic sediments deposited when early Paleozoic seas covered the region. The aerial extent of each rock unit has been illustrated on the accompanying maps. Thicknesses of Late Cambrian strata in the Southern Peninsula (Figure 4) range from 0 to 2190 feet (668 meters). The Cambrian sequence is predominately quartz sandstone and sandy dolomite interspersed with shale in the upper and lower units. Except for the Mt. Simon Sandstone, all units contain some glauconite.

The following lithologic descriptions are an overview of general characteristics noted for rock units presently identified as Late Cambrian in the subsurface of Michigan's Southern Peninsula. The descriptions are the result of combining major identifying characteristics from drill site sample descriptions, mud logs, electric and radioactive well logs, core inspection, microscopic analysis of well cuttings and petrographic thin sections.

Precambrian rocks, directly underlying the Cambrian sedimentary deposits in the Michigan Basin, appear in three general types. The Cambrian deposits may be found in direct contact with any one of the three types of Precambrian lithology described below. There is no pattern or special conditions that exist to predict the presence or absence of these three types in any portion of the Michigan Basin.

Numerous Precambrian test wells in the Southern Peninsula have encountered a grus after drilling through the Mt. Simon Sandstone. This grus is the fragmental by-product of in-situ granular disintegration of the granite or granite-like rocks lying below it. It is commonly identified in drilling records as a "meta-granite wash." Where identified, the grus is overlain by Cambrian deposits and it directly overlays the Precambrian rock surface.

A unit of red colored, sedimentary deposits, assigned a late Keweenawan age by some workers (Fowler and Kuenzi, 1978), underlays the Cambrian in isolated locations within the Michigan Basin. These strata have caused considerable debate as to their age, origin and stratigraphic position. The McClure Oil Company; Sparks, Eckelbarger and Whightsil #1-8 well in Gratiot County penetrated 5,000^{+} feet (1525^{+} meters) of these red beds. The only other wells in the Southern Peninsula reported to have encountered similar red beds, at depth and in significant quantities, are the McClure Oil Company, State Beaver Island #1 and #2 on Beaver Island, Charlevoix County. It is possible that these deposits may be stratigraphically and genetically related. In this report they have been assigned to the Precambrian.

Through August 1988, only 51 Precambrian test wells have been drilled in the Southern Peninsula of Michigan (Figure 5). The lack of direct geologic data about the Precambrian rocks in the subsurface has encouraged the use of geophysical methods. Hinze and Merritt (1969), through the use of gravity and magnetic surveys, suggest that mafic rocks are widespread throughout the basement of the Michigan Basin. Despite their conclusion, most Precambrian drill holes have encountered granitic rocks after drilling through the Cambrian..

LAKE SUPERIOR GROUP

Mt. Simon Sandstone

The Mt. Simon Sandstone is a medium to coarse grained, silica-cemented sandstone, with subangular to rounded grains and moderate sorting. The Mt. Simon's upper portion is white to gray and includes small amounts of shale and sandy dolomite. The basal segment is light pink owing to its slightly arkosic composition and the presence of hematite.

In the southwestern portion of the Basin the arkosic nature of the lower Mt. Simon is very evident. The presence of feldspar in this lower section may have resulted from the reworking of the Precambrian grus which underlies the base of the Mt. Simon in many areas of the Basin. The Mt. Simon reaches a thickness of more than 1200 feet (365 meters) in the central Basin, while rapidly thinning in southeastern Michigan (Figure 6).

The type locality of the Mt. Simon is near Eau Claire, Wisconsin, where it is regarded as a basal member of the Dresbach Formation (Bell and others, 1956). In the Michigan Basin the Mt. Simon is recognized as a distinct rock unit and is given formation status.

MUNISING FORMATION

Eau Claire Member

The Eau Claire Member consists of thinly bedded units of dolomite, sandstone and shale. The dolomite often appears sandy or shaly, and has a variety of colors: gray to dark gray, pink, purple, red, green and

Figure 4

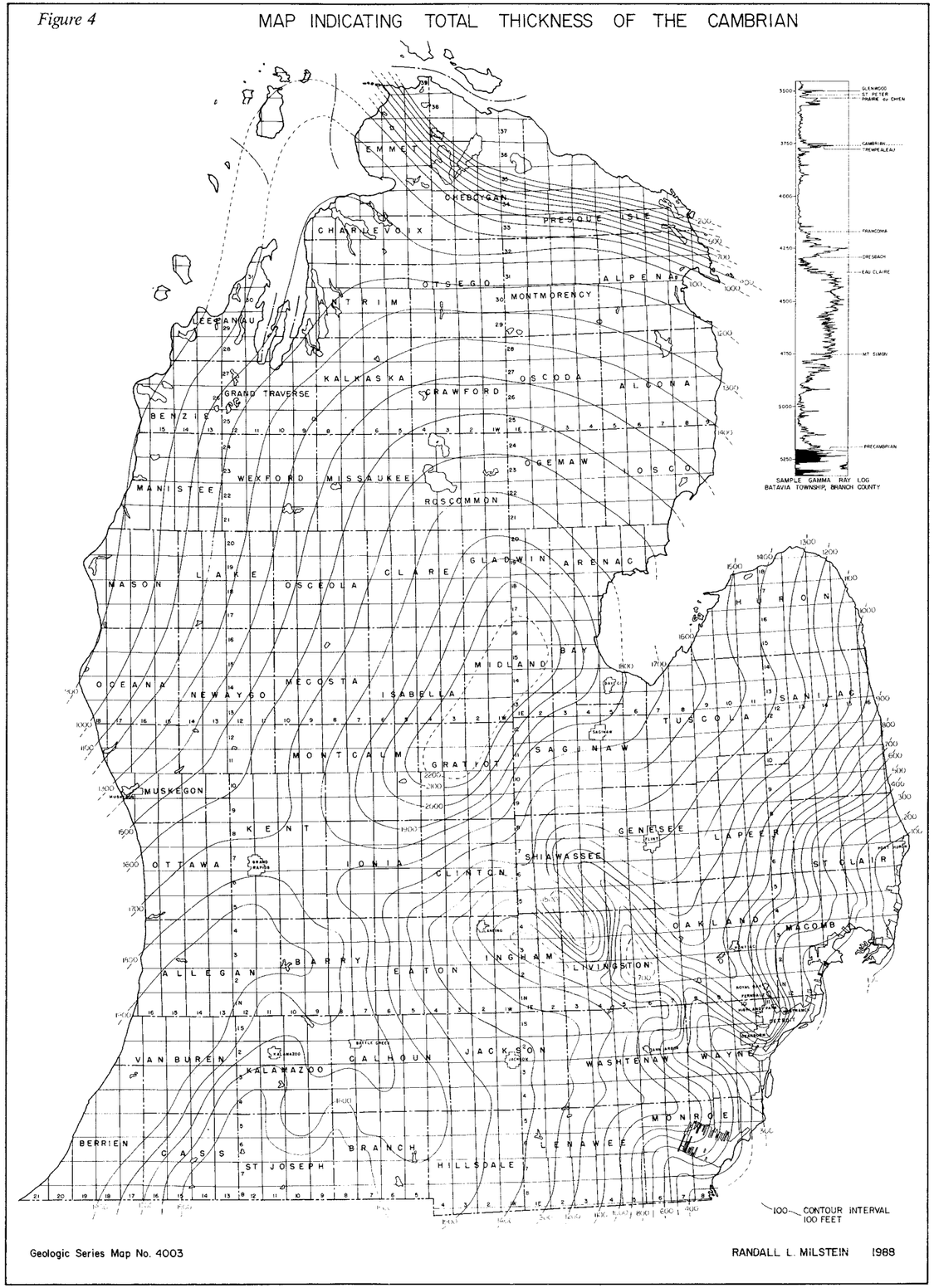
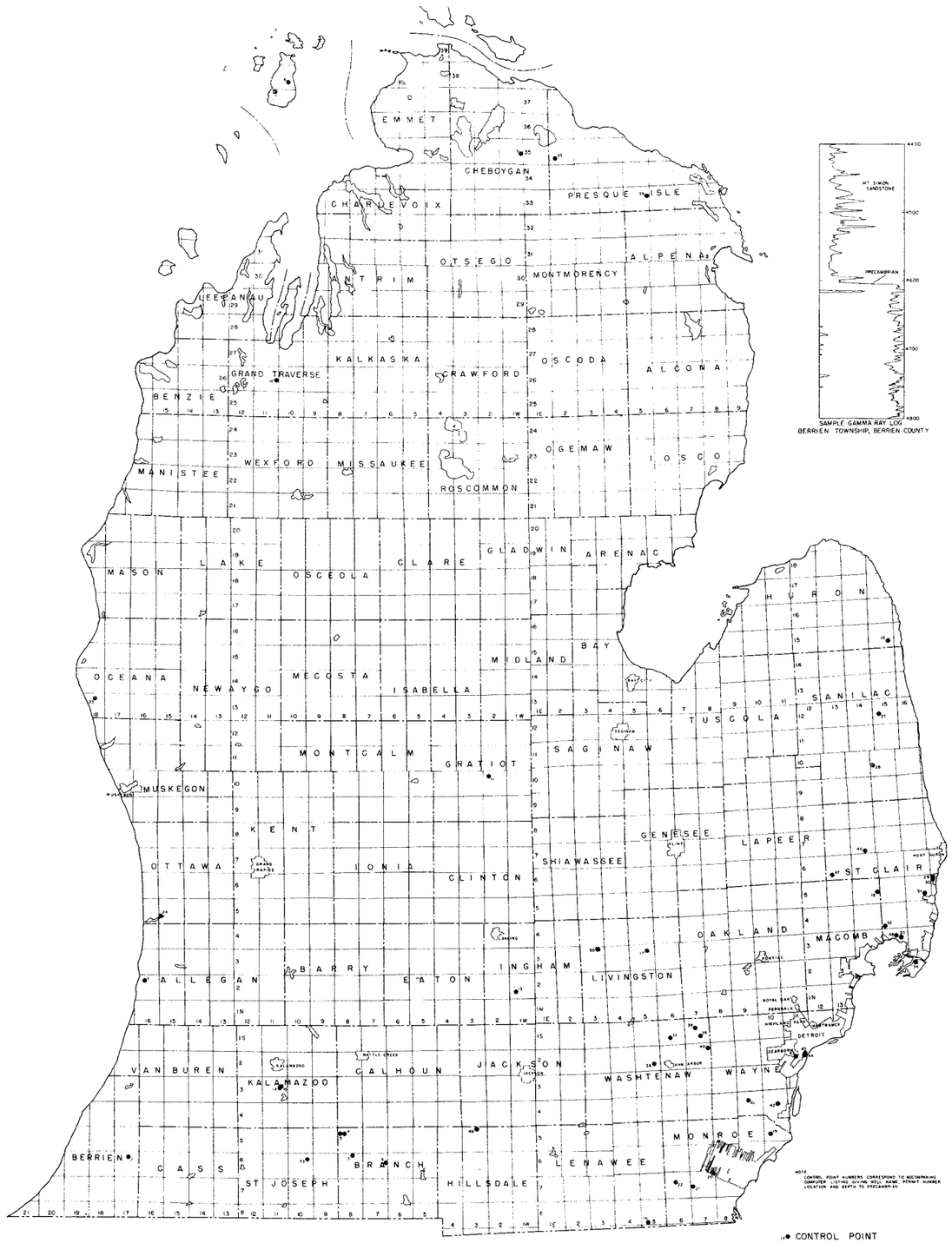


Figure 5

PRECAMBRIAN TEST WELLS – SOUTHERN PENINSULA OF MICHIGAN

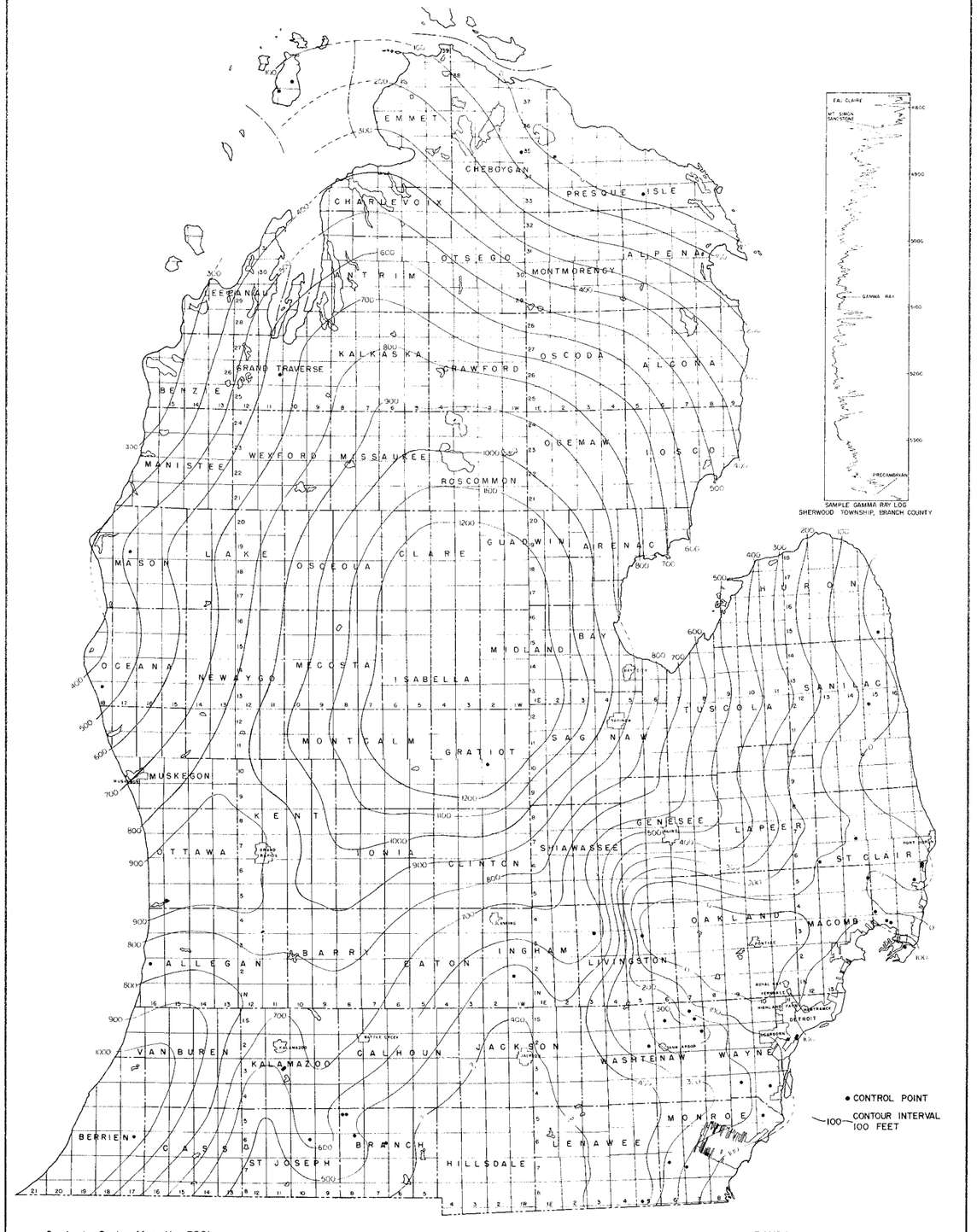


Geologic Series Map No 3976

RANDALL L MILSTEIN 1988

Figure 6

MAP INDICATING THICKNESS OF MT. SIMON SANDSTONE



Geologic Series Map No 3981

RANDALL L MILSTEIN 1988

brown. The sandstone is well sorted and held together with a light tan dolomitic cement. The shale exhibits the same range of colors as does the dolomite. Within the Eau Claire, fossil fragments, muscovite, and locally abundant glauconite are common. The Eau Claire Member has a maximum thickness of 830 feet (253 meters) in the central part of the Michigan Basin (Figure 7).

The Eau Claire overlies the Mt. Simon Sandstone stratigraphically, but in portions of southeastern Michigan where the Mt. Simon is absent, the Eau Claire lies directly on top of the Precambrian.

The Eau Claire Member is named for exposures in Eau Claire, Wisconsin. At the type locality these beds are considered to be a member of the Dresbach Formation (Bell and others, 1956). Within the Michigan Basin the Eau Claire is a distinct, mappable rock unit. The Eau Claire is marked on gamma ray logs by an increase in radioactivity, in sharp contrast to the low gamma ray response of the Dresbach Sandstone (Galesville) above it.

Dresbach (Galesville) Member

The Dresbach covers the entire Southern Peninsula of Michigan attaining a maximum thickness of 606 feet (185 meters) in the central part of the Basin (Figure 8). It is a sandstone and consists of subangular, medium-sized grains, and contains minor amounts of glauconite. The lower part is well sorted, coarse-grained quartz sandstone with well rounded, frosted and pitted grains. This sandstone commonly contains thin beds of white dolomite and minor amounts of gray-green shale.

The type locality of the Dresbach is at Dresbach, Winona County, Minnesota (Thwaites, 1923).

Franconia Member

The Franconia lies beneath an unconformity at the base of the overlying Trempealeau Formation, and is the uppermost member of the Munising Formation. It is a light pink to gray, fine-grained, angular quartz sandstone. Interbedded with the sandstone are beds of gray to tan dolomite, shaly dolomite, finely crystalline sandy dolomite, dolomitic siltstone, and green-gray shale. The Franconia contains pyrite and abundant glauconite.

The Franconia Member can be identified quite readily on a gamma ray log. It appears as an intensification of the gamma ray curve compared with the gamma ray curve's low reading throughout the Trempealeau Formation (see below). The exception is where the bottom of the Trempealeau is intercalated with shale and sand stringers. The Franconia has a maximum thickness of 828 feet (252 meters), with its depositional center situated east of the central part of the Michigan Basin (Figure 9). It is absent in the northern tip of the Southern Peninsula and locally in the southeastern part of the State (Figure 9).

The type locality for the Franconia Sandstone is at Franconia, Chisago County, Minnesota (Berkey, 1897).

While the author has chosen to present the Eau Claire, Franconia and Dresbach (Galesville) as members of the Munising Formation in this report, it is concluded that a reclassification of these rock units should be considered. These rock unit's mappable geographic extent, their consistent lithologic characteristics, consistent and distinct geophysical log signatures and their individual fossil assemblages warrant reassessment. This author believes that sufficient data exists to support this the reclassification of these members as distinct formations within the subsurface of the Michigan Basin in the near future.

TREMPEALEAU FORMATION

The Trempealeau consists of a mostly buff to light-brown dolomite, often exhibiting a pink mottling. The dolomite appears to be moderately sandy, and in certain regions, slightly cherty. Hematitic dolomite, dolomitic shale, shaly dolomite and glauconite are also common. The Trempealeau has a maximum thickness of 655 feet (200 meters), and this occurs in the east central part of the Basin (Figure 10). This formation is absent in the northern tip of the Southern Peninsula, in eastern Cheboygan and northern Presque Isle counties and locally in the southeastern part of the state in St. Clair, Macomb, Wayne and Monroe counties.

In both subsurface and outcrop nomenclature, the Trempealeau Formation has been divided into three members: The St. Lawrence, the Lodi and the Jordan Sandstone; although it is common practice among researchers involved in subsurface studies of the Michigan Basin to leave the Trempealeau Formation undivided.

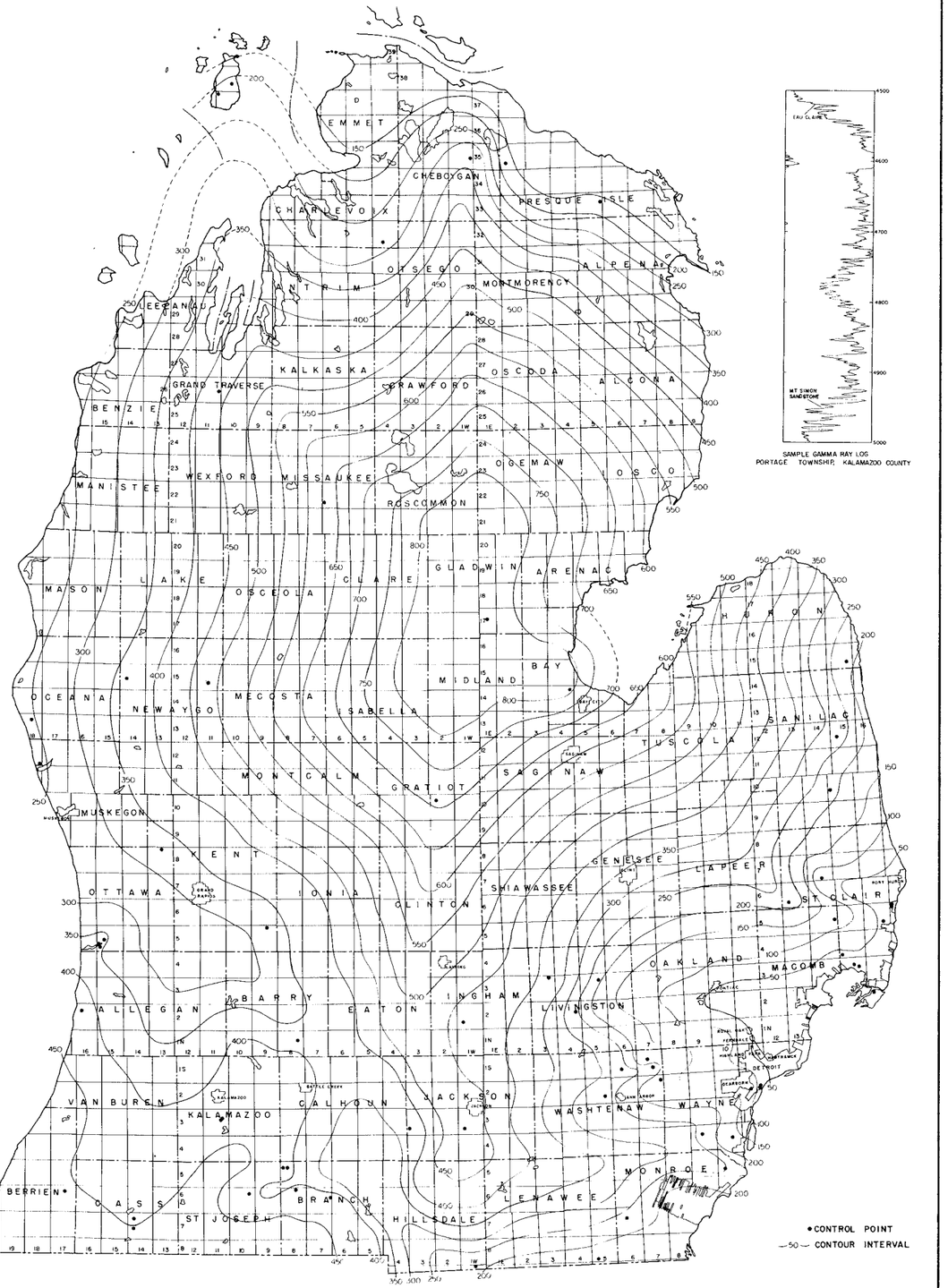
The Trempealeau Formation is named for exposures at Trempealeau, Wisconsin (Ulrich, 1924).

St. Lawrence Member

The St. Lawrence Member is a sandy, very glauconitic dolomite. Its color ranges from light to dark gray. Intermingled within the member are dark colored dolomites and dolomitic shales. These tend to range in color from dark green to dark gray. All these rocks are interbedded with anhydrite and a white to tan colored, fine-grained sandstone. Algal balls, often

Figure 7

MAP INDICATING THICKNESS OF EAU CLAIRE MEMBER

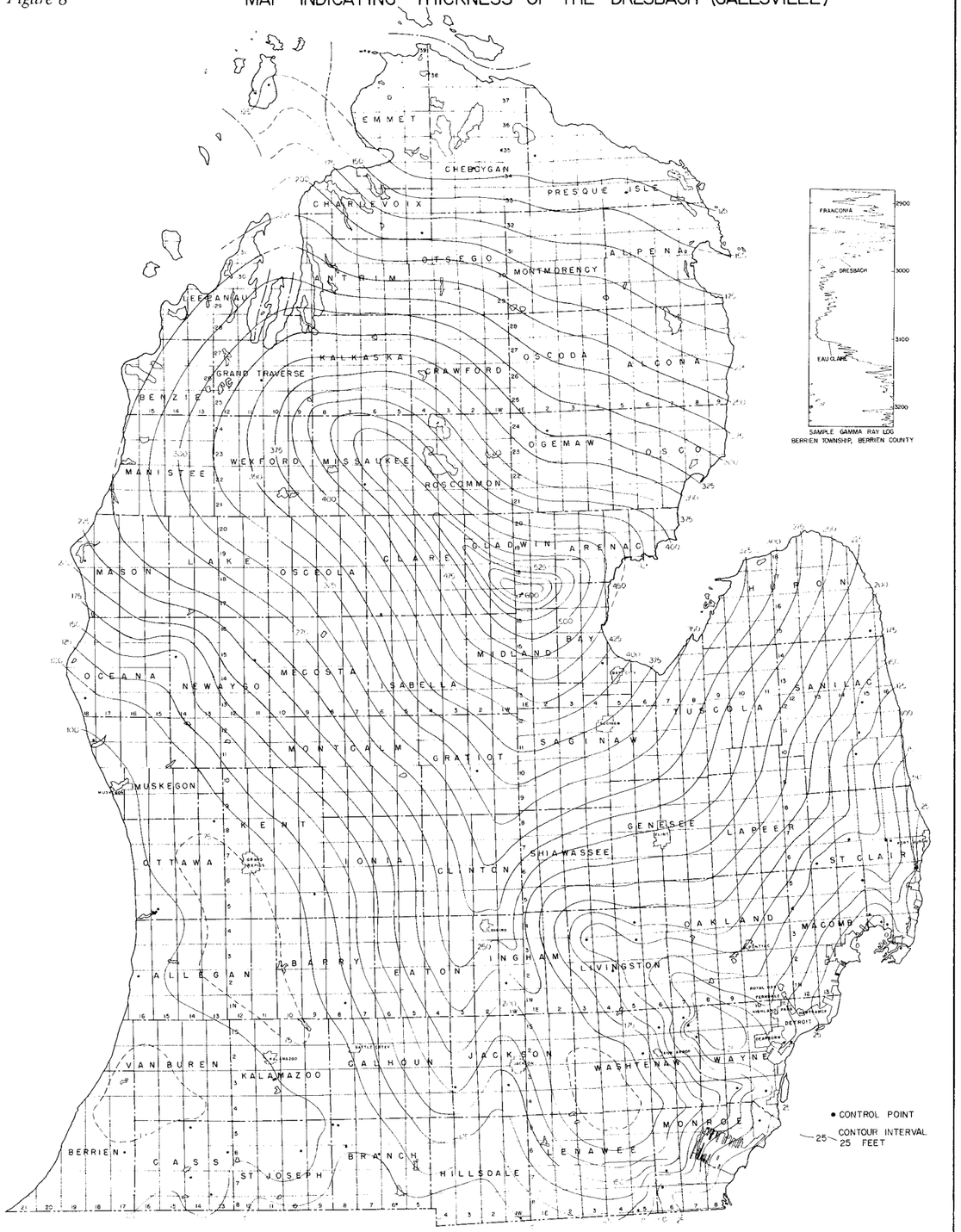


Geologic Series Map No. 3980

RANDALL L MILSTEIN 1988

Figure 8

MAP INDICATING THICKNESS OF THE DRESBACH (GALESVILLE)



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RANDALL L. MILSTEIN 1988

Figure 9

MAP INDICATING THICKNESS OF THE FRANCONIA

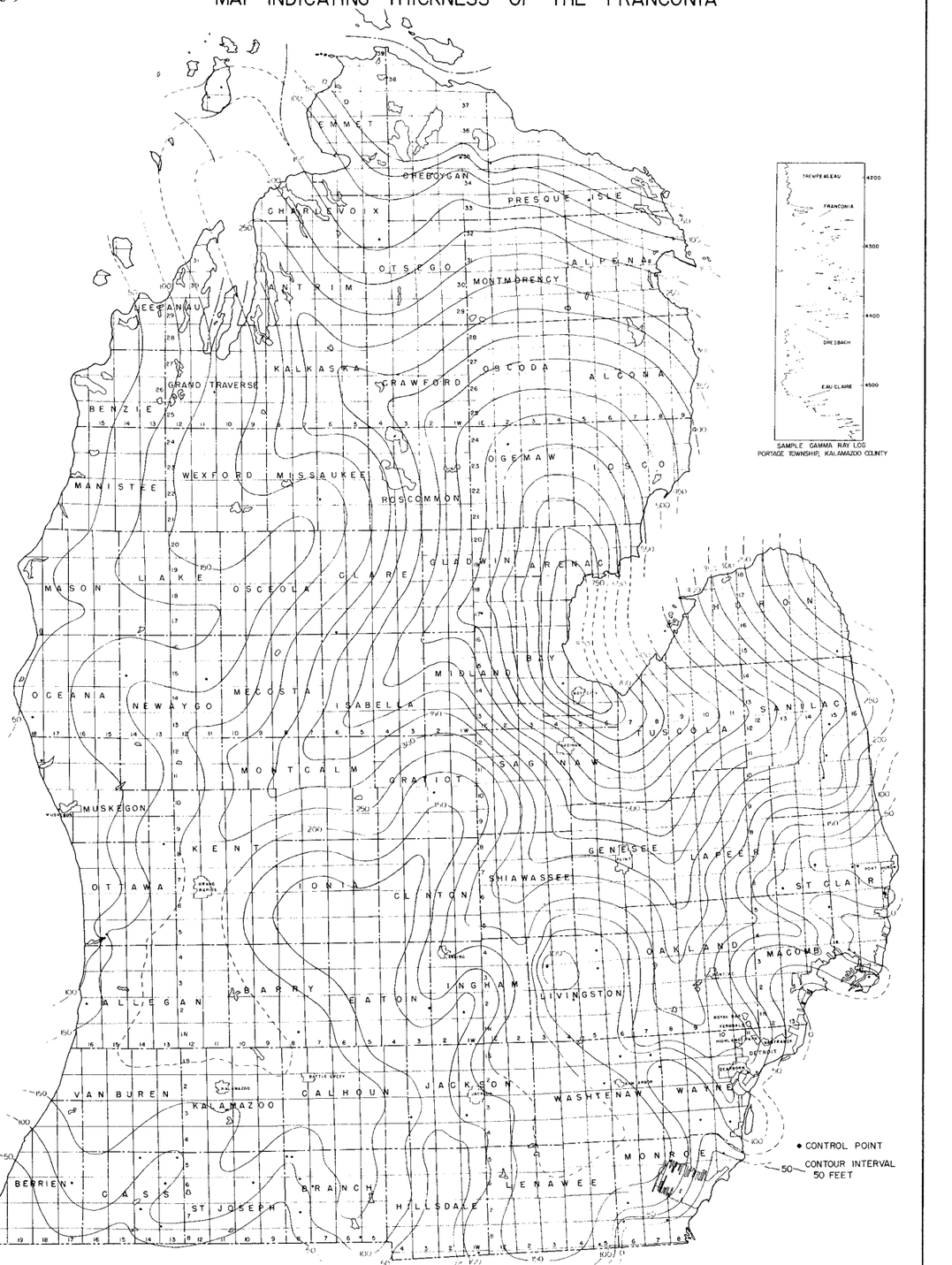

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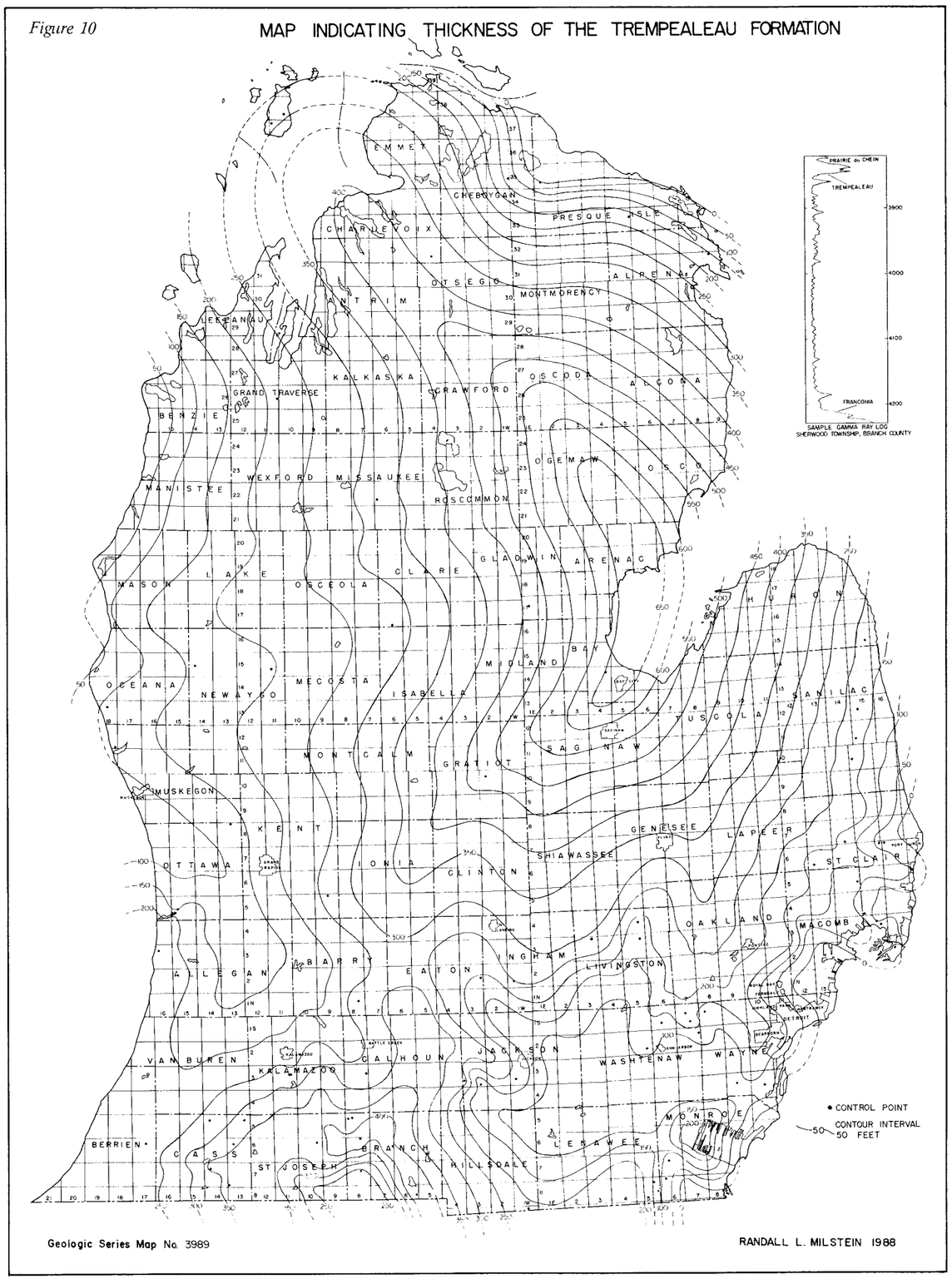
Figure 10



dolomitic, have been identified in the lower section of the St. Lawrence Member.

Lodi Member

The Lodi Member is slightly sandy dolomite with a wide range of colors. It may appear white, buff, pink or purple. It is interbedded with stringers of very fine-grained, poorly sorted sand and shale. The Lodi also contains some minor anhydrite layers and traces of pyrite.

Jordan Member

The Jordan Member ranges from a very fine-grained quartz sandstone containing well rounded, frosted and pitted grains to a sandy dolomite which is white to buff to light brown in color and may be fairly calcareous.

STRUCTURE

When comparing the extent of Cambrian strata in the Michigan Basin (Figures 4 and 11) with contours drawn on the Precambrian surface (Figure 12), a unique relationship can be inferred. The apparent distribution of these beds around the edges of the Michigan Basin, particularly along the Basin's eastern margin where greater data is available (Figure 5), indicate successively younger beds overlap one another to lie directly on the Precambrian (Figure 13a). This suggests that the regional configuration of the Precambrian surface, during Cambrian times, was similar to its present shape.

Subsurface control is too limited to provide much useful information regarding local structures. One could postulate that irregularities on the Precambrian surface could be reflected upward into the overlying Cambrian formations. The accompanying maps suggest the presence of several such Precambrian topographic features. Prominent Precambrian features such as the Washtenaw Anticlinorium in southeastern Michigan, and the Bowling Green Fault, located along the Lenawee and Monroe County boundary, are both reflected in the Cambrian sediments (Figure 4). The Washtenaw Anticlinorium is defined by the thinning and draping of sediments above and around the structure (Figures 4, 6 and 8), while the Bowling Green Fault is characterized by the almost right angle turn taken by isopachs in its vicinity (Figures 4, 9 and 10). These features also reflect through the entire Paleozoic section to form prominent bedrock structural features (Milstein, 1987).

The Precambrian surface of the Michigan Basin during Cambrian time was similar to its present near circular, bowl shaped morphology (Figure 12). The Mt. Simon Sandstone is the oldest Cambrian sedimentary deposit in the Michigan Basin. The Mt. Simon was apparently deposited directly on top of the erosional surface of Precambrian rock units. The Mt. Simon isopach map (Figure 6) indicates Mt. Simon sediments were deposited in a nearly circular basin. This would suggest that the Precambrian surface was predisposed to a near circular configuration before the deposition of Cambrian sediments.

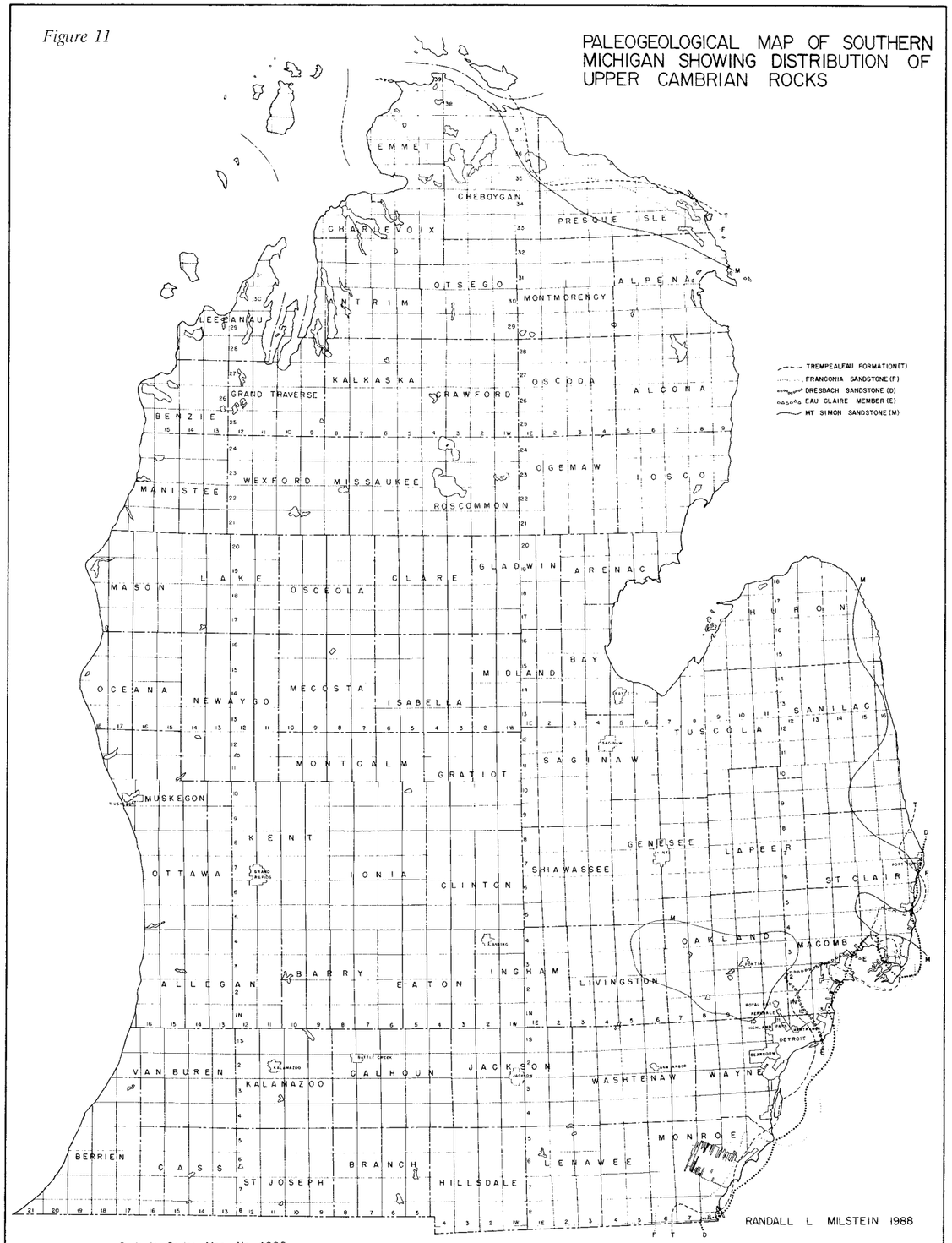
Theories suggesting mechanisms for the formation of the embryonic Michigan Basin include a failed Precambrian rift zone (Hinze and Merritt, 1969), a large, evolved, 2.5 billion-year-old impact structure (Hartung and Laney, 1979; Hartung, 1980), mantle diapirs (Haxby, et al. 1976), thermal contraction (Nunn and Sleep, 1984) and thermal subsidence (Nunn, et al., 1984).

OIL AND NATURAL GAS

To date, there has been no commercial quantities of oil or gas produced from Michigan's Cambrian sediments. Despite the possibility of favorable reservoir characteristics existing in the Cambrian sands and carbonates, the only recorded occurrence of hydrocarbons, from such stratigraphically deep rocks in the Southern Peninsula, has come from Precambrian erosional sediments (grus) found between the base of the Mt. Simon Sandstone and the Precambrian rock surface. There was a natural gas show in the grus encountered in the Martin Properties, Howard Hunt Unit #1 wildcat well which was drilled in Section 9, T2N, R16W, Ganges Township, Allegan County. This well was plugged and abandoned.

Figure 11

PALEOGEOLOGICAL MAP OF SOUTHERN MICHIGAN SHOWING DISTRIBUTION OF UPPER CAMBRIAN ROCKS

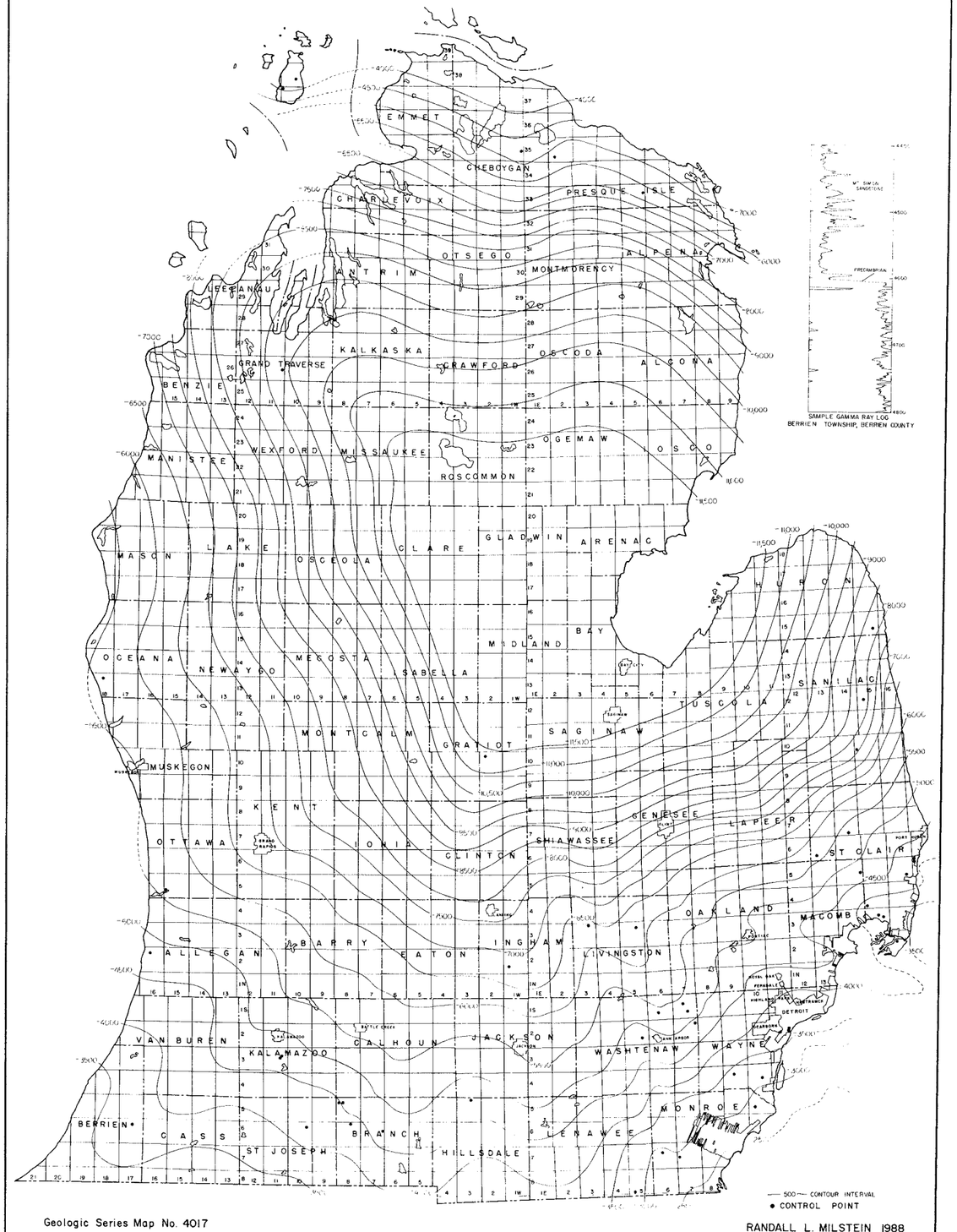


RANDALL L MILSTEIN 1988

Geologic Series Map No 4005

Figure 12

STRUCTURE CONTOUR MAP OF THE PRECAMBRIAN SURFACE



— 500 — CONTOUR INTERVAL
• CONTROL POINT

Geologic Series Map No. 4017

RANDALL L. MILSTEIN 1988

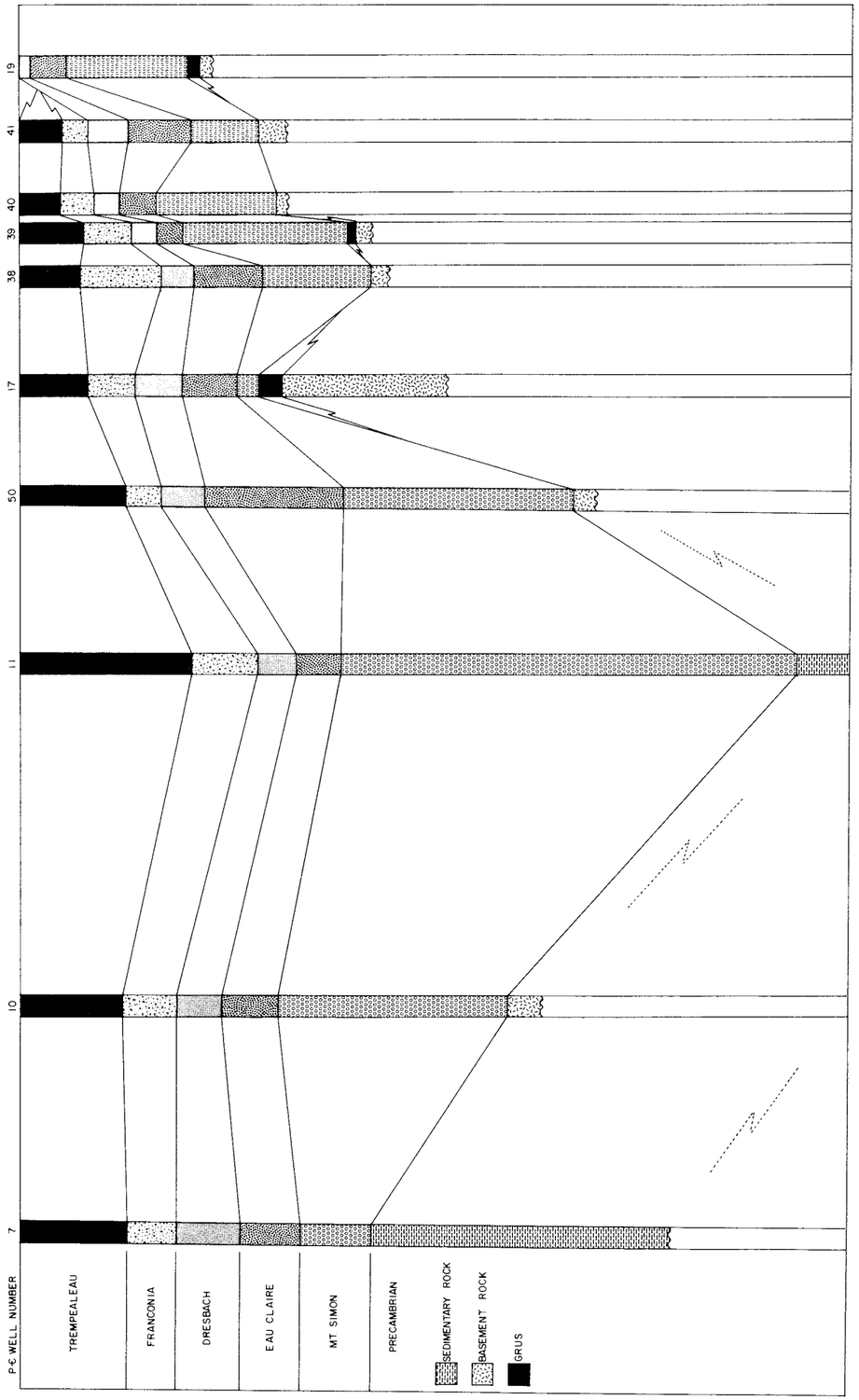


Figure 13a: Generalized cross-section of Late Cambrian sediments.

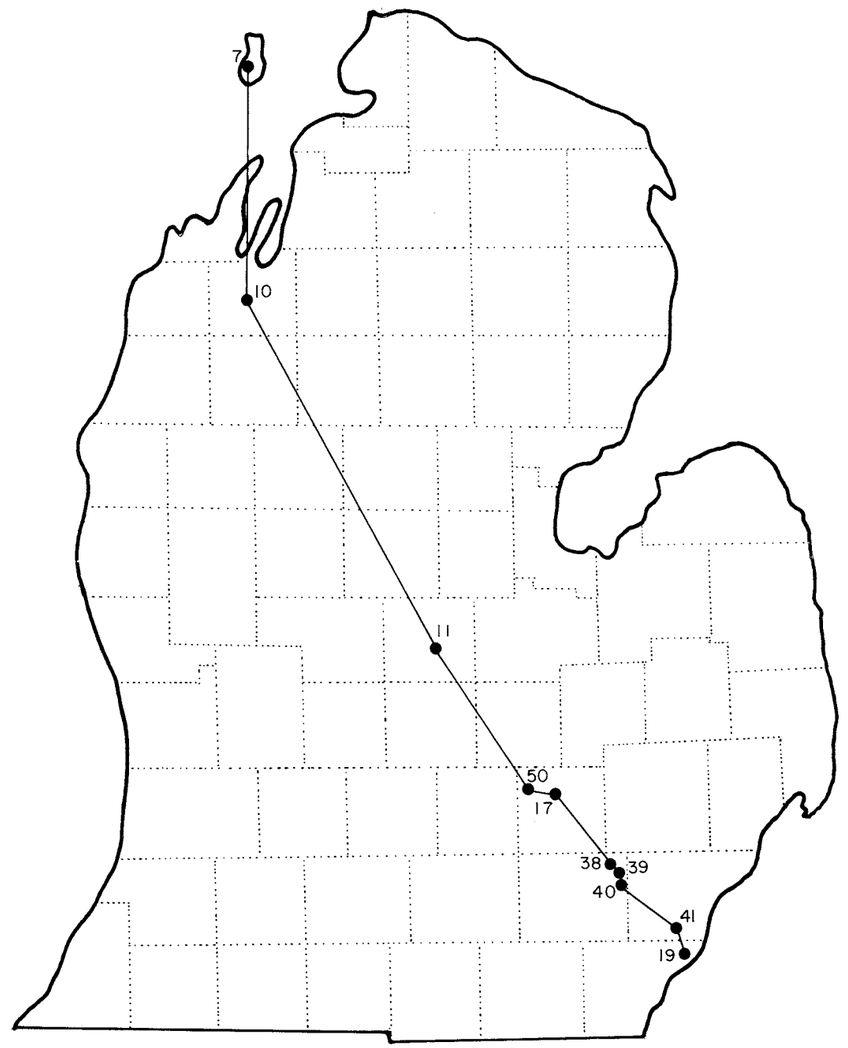


Figure 13b: Index map showing line of cross-section.

REFERENCES

Bell, W. C., and others, 1956, Croixan type area - Upper Mississippi Valley: International Geological Congress, Cambrian Symposium, part 2.

Berkey, C. P., 1897, Geology of the St. Croix Dalles: American Geology, volume. 20, pages 345-383.

Catacosinos, P. A., 1972, Cambrian stratigraphy of the Lower Peninsula of Michigan, Ph.D. Thesis, Michigan State University.

Cohee, G. V., 1945, Stratigraphy of Lower Ordovician and Cambrian rocks in the Michigan Basin: U.S. Geological Survey Oil and Gas Investigation, Preliminary Chart number 9.

Ells, G. D., 1967, Correlation of Cambro-Ordovician rocks in Michigan, in Correlation problems of the Cambrian and Ordovician outcrop areas, Northern Peninsula of Michigan, N. E. Ostrom and A. E. Slaughter, editors: Michigan Basin Geological Society, pages 42-57.

Ells, G. D. and others, 1964, Report on the geologic potential of atomic waste disposal in the Michigan Basin: Committee on Atomic Waste Disposal - Michigan Basin; Michigan Geological Survey.

Foster, J. W. and Whitney, J. D., 1851, Report on the geology of the Lake Superior land district: Part 2: U.S. 32nd Congress, Special Session Senate Executive, Document 4, pages 110-139.

Fowler, J. H. and W. D. Kuenzi, 1978, Keweenawan turbidites in Michigan (deep borehole redbeds): A foundered basin sequence developed during evolution of a protoceanic rift system: Journal of Geophysical Research, volume 83, pages 5833-5843.

Fuller, G. N., 1928, Geological Reports of Douglass Houghton: Michigan Historical Commission.

Hamblin, W. K., 1958, The Cambrian Sandstones of Northern Michigan: Publication 51; Michigan Geological Survey.

Hartung, J. B., 1980, A model for impact basin evolution, in Papers presented to the conference on multi-ring basins—formation and evolution, Houston, 1980, Lunar and Planetary Institute (LPI), LPI contribution 414, pages 33-35.

_____ and R. T. Laney, 1979, The Michigan Basin as an Evolved Impact Structure, II: The Huronian of Southern Ontario, Canada: EOS, volume 60, number 18, page 300.

Haxby, W. F. and others, 1976, Thermal and mechanical evolution of the Michigan Basin: Tectonophysics, number 36, pages 57-75.

Hinze, W. J. and D. W. Merritt, 1969, Basement rocks of the Southern Peninsula of Michigan, in Studies of the Precambrian of the Michigan Basin, H. B. Stonehouse, editor; Michigan Basin, Geological Society, pages 28-59.

Houghton, Douglass, 1841, Fourth annual report of the State Geologist: Michigan House of Representatives, Document number 27, pages 3-89.

Janssens, A., 1973, Stratigraphy of the Cambrian and Lower Ordovician rocks of Ohio; Bulletin 64: Ohio Geological Survey.

Lane, A. C., 1892, Microscopic characters of rocks and minerals of Michigan, in Report of the State Board of Geological Survey for the years 1871 and 1892: Michigan Geological Survey, pages 176-183.

Lilienthal, R. T., 1978, Stratigraphic cross-sections of the Michigan Basin - Report of Investigation 10: Michigan Geological Survey.

Martin, H. M., 1936, The Centennial Geological Map of Michigan (2 sheets, Southern and Northern Peninsula): Michigan Geological Survey, publication 39, geological series 33.

_____ and M. T. Straight, 1956, An index of Michigan Geology: Publication 50; Michigan Geological Survey.

Milstein, R. L., 1983, Maps, cross-sections and lithology: Part 1, in Selected Studies of Cambro-Ordovician Sediments in the Michigan Basin - Report of Investigation 26, D. M. Bricker et al., Michigan Geological Survey.

Milstein, R. L., 1987, Sesquicentennial Bedrock Geology Map of Southern Michigan: Michigan Geological Survey, scale 1:500,000, one sheet.

_____, 1988, Southern Peninsula: Precambrian Test Wells; Geologic Series Map #3976: Michigan Geological Survey, scale 1:500,000, one sheet.

_____, 1988, Isopach Map: Thickness of Eau Claire Member, Southern Peninsula; Geologic Series Map #3980: Michigan Geological Survey, scale 1:500,000, one sheet.

_____, 1988, Isopach Map: Thickness of Mt. Simon Sandstone, Southern Peninsula; Geologic Series Map #3981: Michigan Geological Survey, scale 1:500,000, one sheet.

_____, 1988, Isopach Map: Thickness of Franconia Sandstone, Southern Peninsula; Geologic Series Map #3987: Michigan Geological Survey, scale 1:500,000, one sheet.

_____, 1988, Isopach Map: Thickness of Dresbach (Galesville) Sandstone, Southern Peninsula; Geologic Series Map #3988: Michigan Geological Survey, scale 1:500,000, one sheet.

_____, 1988, Isopach Map: Thickness of Trempealeau Formation, Southern Peninsula; Geologic Series Map #3989: Michigan Geological Survey, scale 1:500,000, one sheet.

_____, 1988, Isopach Map: Thickness of Cambrian, Southern Peninsula; Geologic Series Map #4003: Michigan Geological Survey, scale 1:500,000, one sheet.

_____, 1988, Paleogeological Map of Southern Michigan Showing Distribution of Upper Cambrian Rocks; Geologic series map #4005: Michigan Geological Survey, scale 1:500,000, one sheet.

_____, 1988, Structure Contour Map: Precambrian Surface, Southern Peninsula; Geologic Series Map #4017: Michigan Geological Survey, scale 1:500,000, one sheet.

Nunn, J. A. and N. H. Sleep, 1984, Thermal contraction and flexure of intracratonal basins: A three-dimensional study of the Michigan Basin: Journal of Geophysical Research, number 76, pages 587-635.

Nunn, J. A. and others, 1984, Thermal subsidence and generation of hydrocarbons in Michigan Basin: American Association of Petroleum Geologists Bulletin, volume 68, number 3, March, pages 296-315.

Rominger, C. L., 1873, Paleozoic Rocks: Michigan Geological Survey, volume 1, part 3, 1869-1873, pages 7-102.

Sanford, B. V., and Quillian, R. G., 1959, Subsurface stratigraphy of Upper Cambrian rocks in southwestern Ontario: Paper 58-12; Geological Survey of Canada.

Schoolcraft, H. R., 1821, Narrative journal of travels through the northwestern regions of the United States: Albany, New York, 419 pages.

Shaver, R. H. and others, 1985, Midwestern basin and arches region: Correlation of stratigraphic units of North America (COSUNA) project: American Association of Petroleum Geologists.

Sorensen, H. O. and others, 1964, Stratigraphic succession in Michigan: Michigan Geological Survey, Chart 1.

Stonehouse, H. B., 1969, The Precambrian around and under the Michigan Basin, in Studies of the Precambrian of the Michigan Basin, H. B. Stonehouse, editor; Michigan Basin Geological Society, pages 15-27.

Syrjamaki, R. M., 1977, The Prairie du Chien Group of the Michigan Basin, Masters Thesis, Michigan State University.

Thwaites, F. T., 1923, The Paleozoic rocks found in deep wells in Wisconsin and North Illinois: Journal of Geology, 31, pages 529-555.

_____, 1934, Well logs in the Northern Peninsula of Michigan, showing the Cambrian section: Michigan Academy of Science, Arts and Letters; Papers, Volume 19, pages 413-426.

_____, 1943, Stratigraphic work in Northern Michigan, 1933-1941: Michigan Academy of Science, Arts and Letters, Papers, volume 28, pages 487-502.

Ulrich, E. O., 1924, Notes on new names in Table of Formations and on physical evidence of breaks between Paleozoic systems in Wisconsin: Transcripts – Wisconsin Academy of Science, 21, pages 72-90.

Wadsworth, M. E., 1892, Report of the State Board of Geological Survey for the years 1891 and 1892: Michigan Geological Survey, pages 83-85 and 156-167.

Yettaw, G. A., 1967, Upper Cambrian and older rocks of the Security-Thalmann Number 1 well, Berrien County, Michigan: Masters Thesis, Michigan State University.

Appendix

Precambrian Test Wells — Southern Peninsula of Michigan

Appendix: Precambrian Test Wells — Southern Peninsula of Michigan

Permit Number	Year	County	Township	Location	Operator Name	Well Name	Precambrian Depth	Precambrian Datum	Total Depth	Td Datum
35186	1982	Allegan	Ganges	09-02N-16W	Martin Properties	Howard Hunt Unit #1	5582	-4894	6000	-5312
26112	1965	Berrien	Berrien	10-06S-17W	Security Oil & Gas	Thalmann #1	4604	-3800	5647	-4843
29779	1974	Branch	Sherwood	07-05S-08W	Consumers Power Co., et al.	Lindsey–Hostetler #1	5375	-4485	5439	-4549
29969	1974	Branch	Sherwood	08-05S-08W	Consumers Power Co., et al.	H. Clark #1	5418	-4539	5475	-4586
37569	1984	Branch	Matteson	03-06S-08W	Atlantic Richfield Co. Inc.	ARCO & Johnson #1-3	5210	-4299	5252	-4341
38045	1984	Branch	Batavia	13-06S-07W	Atlantic Richfield Co. Inc.	ARCO & Gaglio #1-13	5206	-4248	5377	-4419
23478	1961	Charlevoix	Peaine	06-37N-10W	McClure Oil Co.	State Beaver Island #2	4718	-3977	4803	-4062
23435	1961	Charlevoix	Peaine	27-38N-10W	McClure Oil Co.	State-Beaver Island #1	4566	-3888	5383	-4705
30682	1975	Cheboygan	Waverly	24-35N-01W	Northern Michigan Expl. Co.	State Waverly #1-24	5617	-4816	5753	-4952
34292	1981	Grand Traverse	Blair	24-26N-11W	Shell Oil Co.	State Blair #2-24	10910	-9995	11020	-10105
29739	1975	Gratiot	North Star	08-10N-02W	McClure Oil Co.	Sparks, et al. #1-8	12176	-11414	17466	-16704
29191	1973	Huron	Sherman	26-15N-15E	Mobil Oil Co.	C. J. Volmering#1	8872	-8161	9086	-8375
28607	1971	Ingham	Vevay	29-02N-01W	Mobil Oil Corp.	Walter Kranz, Jr. #1	7690	-6751	7866	-6927
137-744-839	1975	Kalamazoo	Portage	14-03S-11W	UpJohn Co.	UpJohn #3	5594	-4709	5617	-4732

Permit Number	Year	County	Township	Location	Operator Name	Well Name	Precambrian Depth	Precambrian Datum	Total Depth	Td Datum
35186	1982	Allegan	Ganges	09-02N-16W	Martin Properties	Howard Hunt Unit #1	5582	-4894	6000	-5312
327-794-829	1980	Kalamazoo	Portage	14-03S-11W	UpJohn Co.	UpJohn #4	5554	-4680	5580	-4706
10448	1944	Lenawee	Riga	32-08S-05E	Walter H. Eckert	Harry Taylor #1	3865	-3150	3902	-3186
27986	1970	Livingston	Osceola	11-03N-05E	Mobil Oil Corp.	H. J. Messmore #1	7150	-6170	7589	-6609
33737	1980	Macomb	Richmond	24-05N-14E	Energy Acquisition Corp.	Grierson 1-24	5340	-4601	5389	-4650
11221	1945	Monroe	Berlin	29-05S-10E	Joseph W. Sturman	D. L. & R. L. Chapman #1	3342	-2745	3377	-2780
35948	1982	Monroe	Ida	01-07S-07E	Reef Petroleum Corp.	Cousino #1-1	3470	-2824	3512	-2866
7702	1954	Monroe	Ida	19-07S-07E	Jacob Beck	Mrs. James Sancrant #1	3595	-2926	5495	-4826
25494	1964	Monroe	Summerfield	16-07S-06E	Ferguson & Garrison	Merlin Shimp #1	3637	-2951	3671	-2985
33134	1980	Oceana	Claybanks	10-13N-18W	Amoco Production Co.	Schiller #1-10	6427	-5675	7240	-6488
052-737-870	1972	Ottawa	Holland	30-05N-15W	H. J. Heinz Co.	H. J. Heinz Co. #2	6152	-5533	6221	-5602
27199	1968	Presque Isle	North Allis	29-35N-02E	Pan American Petro. Corp.	D. E. Draysey #1	5877	-5069	5940	-5132
29372	1973	Presque Isle	Metz	13-33N-05E	Shell Oil Co.	Taratuta #1-13	6500	-5724	6738	-5962

Permit Number	Year	County	Township	Location	Operator Name	Well Name	Precambrian Depth	Precambrian Datum	Total Depth	Td Datum
35186	1982	Allegan	Ganges	09-02N-16W	Martin Properties	Howard Hunt Unit #1	5582	-4894	6000	-5312
30974	1976	Sanilac	Bridghamp-ton	20-12N-15E	McClure Oil & MI Natural Resouces	Hewett & Shadd Unit # 1-20	8859	-8074	8975	-8190
33999	1980	Sanilac	Buel	19-20N-15E	Mid-America Oil & Gas	Woodruff #1-19	8298	-7533	8511	-7746
BD-151	1971	Saint Clair	Saint Clair	07-05N-17E	Consumers Power Co.	C. P. C. #1-7 BDW	4707	-4069	4733	-4095
BD-152	1971	Saint Clair	Saint Clair	07-05N-17E	Consumers Power Co.	C. P. C. #2-7 BDW	4684	-4052	4702	-4070
196	1929	Saint Clair	Saint Clair	26-05N-16E	St. Clair Oil & Gas Corp.	Hurst #1	4730	-4080	4770	-4110
BD-139	1964	Saint Clair	Casco	31-04N-15E	Consumers Power Co.	Consumers Power Co. BD #1	4605	-3989	4627	-4011
30376	1975	Saint Clair	Ira	14-03N-15E	MI Consolidated Gas Co.	Osterland #1-14	4449	-3846	4550	-3947
25780	1965	Saint Clair	Clay	17-02N-16E	L. Bernhardt	Puzzuoli #1	4152	-3572	4188	-3608
31335	1977	Saint Joseph	N. Ottawa	11-06S-10W	Marathon Oil Co.	Lloyd Cupp #1-11	5074	-4182	5283	-4391
828-814-881	1981	Washtenaw	Scio	26-02S-05E	Gelman Sciences Inc.	Stofer & Marshall #1	5770	-4835	4804	-4869
34223	1981	Washtenaw	Northfield	28-01S-06E	Hunt Energy Corp.	Worrell #1-28	6294	-5352	6330	-5388
10141	1944	Washtenaw	Salem	16-01S-07E	Colvin & Associates, & Electric Steel Co.	Wm. F. Voss Comm. #1	6374	-5459	6410	-5495

Permit Number	Year	County	Township	Location	Operator Name	Well Name	Precambrian Depth	Precambrian Datum	Total Depth	Td Datum
35186	1982	Allegan	Ganges	09-02N-16W	Martin Properties	Howard Hunt Unit #1	5582	-4894	6000	-5312
10792	1944	Washtenaw	Salem	27-01S-07E	I. C. Chamnes	Troy & Roddenberry Comm. #1	6075	-5189	6094	-5208
11341	1945	Washtenaw	Superior	12-02S-07E	Colvin & Associates, & Electric Steel Co.	Viola Meinzinger #1	5670	-4852	5692	-4874
10430	1944	Wayne	Huron	16-04S-09E	Colvin & Associates, & Electric Steel Co.	Theisen Estate #1	3985	-3360	4046	-3421
BD 146	1969	Wayne	Woodhaven	22-04S-10E	Marathon Oil Co.	Woodhaven BD #1	3710	-3105	3752	-3143
184-754-882	1975	Wayne	Detroit	28-02S-11E	Rouge Steel	Rouge Steel #D-2	4258	-3658	4308	-3708
069-737-882	1975	Wayne	Detroit	26-02S-11E	Detroit Coke Corp.	Detroit Coke #1	4200	-3600	4231	-3631
155-744-882	1976	Wayne	Detroit	26-02S-11E	Detroit Coke Corp.	Detroit Coke #2	4105	-3505	4113	-3513
38965	1985	Saint Clair	Emmett	34-07N-14E	Miller Bros. & Atlantic Richfield	ARCO & Patton #1-34	6270	-5466	6311	-5507
38964	1986	Saint Clair	Berlin	30-06N-13E	Atlantic Richfield & Miller Bros.	ARCO & Senyk #1-30	6545	-5744	6676	-5875
39755	1986	Saint Clair	Ira	10-03N-15E	Northern MI Exploration Co.	Salisbury & Paganes #1-10	4520	-3912	4571	-3963
40414	1987	Hillsdale	Scipio	03-05S-03W	Marathon Oil Co.	Rowe #A-8	5866	-4759	5917	-4810

Permit Number	Year	County	Township	Location	Operator Name	Well Name	Precambrian Depth	Precambrian Datum	Total Depth	Td Datum
35186	1982	Allegan	Ganges	09-02N-16W	Martin Properties	Howard Hunt Unit #1	5582	-4894	6000	-5312
40438	1987	Livingston	Handy	02-03N-03E	Terra Energy & Smith Petroleum	Phillips #1-2	7400	-6460	7454	-6514
40793	1988	Saint Clair	China	01-04N-16E	Amoco Production & Dome Petroleum	St. Clair NGL #1-1	4714	-4109	4785	-4180