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Voight, B., Hoff, R., Turner, A., Neal, W., Sandberg, C.A., and Suttner, L., 2018, Raymond C. Gutschick—Hero of the Kentland impact structure investigations, *in* Florea, L.J., ed., *Ancient Oceans, Orogenic Uplifts, and Glacial Ice: Geologic Crossroads in America’s Heartland: Geological Society of America Field Guide 51*, p. 409–426, [https://doi.org/10.1130/2018.0051\(16\)](https://doi.org/10.1130/2018.0051(16)).

Gutschick, R.C., 2018, Hydrodynamic role of groundwater in bolide impact: Evidence from the Kentland structure, Indiana, USA, *in* Florea, L.J., ed., *Ancient Oceans, Orogenic Uplifts, and Glacial Ice: Geologic Crossroads in America’s Heartland: Geological Society of America Field Guide 51*, p. 427–433, [https://doi.org/10.1130/2018.0051\(17\)](https://doi.org/10.1130/2018.0051(17)).

#### Contents:

Gutschick, R.C., 1961, The Kentland structural anomaly: Guidebook for field trips, Cincinnati meeting: Geological Society of America, p. 12–17.

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The Kentland Structural Anomaly, Indiana

By R. C. Gutschick, Univ. of Notre Dame

Introduction

The purpose of this article is to present a short account of the geology of the Kentland disturbed area in light of recent developments. Rock exposures are essentially confined to one deep quarry operated by the Newton County Stone Co. (McCray quarry of Shrock) which occupies about 40 acres in the NW 1/4, NE 1/4 section 25, T. 27 N., R. 9 W., Newton County, Indiana; although there are two other very small inactive quarries within one-fourth mile distance. Excellent earlier reports on the geology of this area can be found in Shrock and Malott, 1933; Shrock, 1937; Shrock and Raasch, 1937; and Boyer, 1953 (unpublished). Evidence for the anomalous structure is the presence in the three quarries of more than 575 feet of highly deformed Ordovician strata in an area that should otherwise normally have Lower Mississippian bedrock. The oldest rocks exposed in the quarry are estimated to be more than 1500 feet below the surface in the well 3 miles to the west at Kentland, Indiana (fig. 4). A veneer of glacial drift masks the bedrock and adequate subsurface information is lacking, which makes it difficult to define and understand the anomaly. A few of the more popular explanations of its origin include gaseous explosion associated with cryptovolcanism; hypervelocity and explosive impact of a meteorite; and uplift, folding and faulting due to regional tectonics.

Grateful appreciation is extended to Mr. T. R. Stevens, Manager, Newton County Stone Co., and his staff for their hospitality and assistance. The author is indebted to H. B. Willman, Illinois Geological Survey, for use of his unpublished manuscript on Kentland, permission to publish the stratigraphic information, and guidance in the field. Erhard M. Winkler kindly furnished the air photo base which facilitated the mapping, and John Patton, State Geologist, provided the subsurface information.

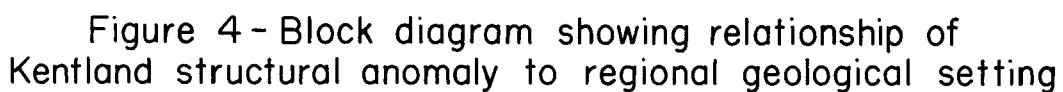
Stratigraphy

Hope of solving the structural relations in the quarry lies in the stratigraphic key. Fortunately, through the careful and ingenious work of Shrock, 1937, and more recently that of Templeton and Willman, 1961, a useful analysis of the stratigraphic sequence has been established (see fig. 5). Five groups including eleven formations (one unnamed) are recognized. Detailed studies of the Platteville group within the quarry by Ziemba, 1955; Carozzi, 1956; and Wanless, Ziebell, Ziemba, and Carozzi, 1957, are summarized on the stratigraphic chart. A thin veneer of Pleistocene glacial drift rests unconformably on the Ordovician rocks in the quarries. This transported mantle is generally less than 50 feet in southern Newton County but also attains thicknesses over 100 feet (McGrain, 1950).

Geologic Structure

The Kentland disturbed area lies along the south flank of the Kankakee arch so that strata generally have a N. 60° W. strike and dip gently to the southwest into the Illinois basin. A preliminary geologic map is included to indicate the general structural pattern in the quarry (fig. 6). Note that some mapping is on an oblique sloping surface from the top to the bottom of the quarry. Quarry operations concentrate on the carbonates and have delineated the gross structure, that of a complexly faulted syncline which plunges to the northwest. There is duplication or interruption of the stratigraphic sequence in the north and west sides of the quarry. This over-simplified picture is complicated on the south side by an anticlinal bulge of the

A.C.Thomas - J. Henkle #1 36-30N.-9W.  
Wheeler & Son - Town of Kentland #1  
21-27N.-9W.  
National Petroleum Co.- C. Bokma #1  
22-27N.-9W.  
A.C.Thomas - J.M.Fowler #1  
27-25N.-9W.  
Town of Fowler well 15-25N.-8W.  
D.P.Hynes - R. C. Atkinson #1  
3-25N.-7W. 7





Stop 1 (con.)

Shakopee (?), St. Peter, and Joachim formations which plunges to the north-west. This structure is modified by minor folding and broken by several faults. A fault block in the southeast corner has strata which dip to the north-east and probably represents the faulted east flank of the plunging anticline.

It has been noted that the St. Peter-Joachim sequence has been cut by high angle faults which are nearly parallel to the bedding. Quarry walls (SW, S and ENE) stripped to these beds exhibit the spectacular smooth curved slickensided fault surfaces.

Numerous other features suggest the intensity of deformation. The white to rust-stained St. Peter sandstone is intricately fractured, crushed, and pulverized. The dense, brittle beds in all formations exhibit conical fractures (shattercones). Because a large percentage of the cones are oriented with their apexes pointing upwards stratigraphically, Dietz (1959, 1960) has used this as evidence of force from above such as one would expect for meteorite impact. Many faults, joints, and dilutant structures have a breccia fill consisting of light gray fine-grained sandy dolomite matrix containing granule to pebble-sized subangular white chert, limestone, dolomite, and green and gray shale fragments. Breccias throughout the quarry are similar and seem to have a common source. No volcanic materials have been recognized nor have any meteorite fragments or high temperature polymorphs of silica such as coesite been found in the quarry.

Northwest side.

The structure along the west side of the ramp into the quarry is that of a faulted asymmetrical syncline involving Platteville, Galena, and Maquoketa rocks. The syncline

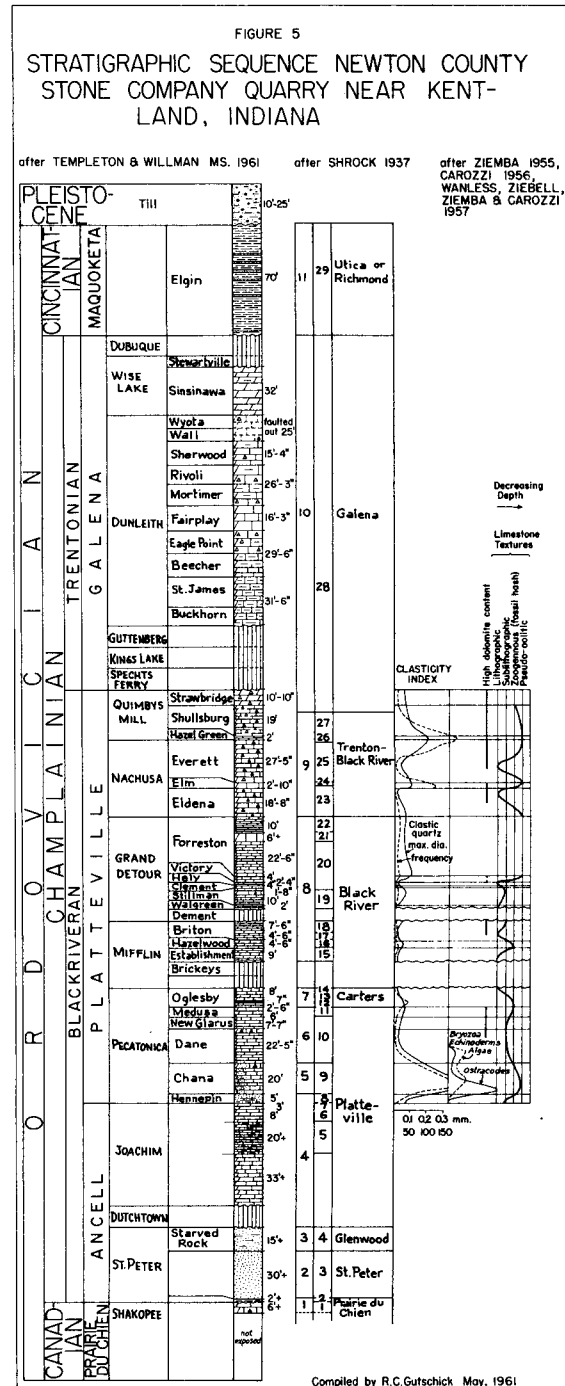


Figure 5.- Stratigraphic sequence, Newton County Stone Company quarry, Indiana.



## Stop 1 (con.)

plunges about 60 degrees to the northwest. Beds in the northeast limb are almost vertical, whereas dips of approximately 60 degrees are more common on the opposite side. The center of the syncline is split by a fault block of rusty-weathered dolomite which is bounded by two oblique-slip faults.

### West side of southwest part of quarry.

This wall represents the west limb of the quarry syncline which has been faulted to duplicate the Platteville sequence. Beds dip steeply to the north and include rocks from the bright green clay shale at the base of the St. Peter group to the lower Galena limestone. Numerous bedding slips appear to be present along the high inaccessible wall.

### South side.

The structure is one of an openly folded syncline on the west and anticline in the center plunging steeply to the northwest. Remnants of Platteville-Joachim carbonates can be seen in the synclinal trough along the steep high wall. Changes in attitude and stratigraphic sequence indicate a cross fault in this trough. The contact of the Joachim and St. Peter beds on the east flank of the syncline reveals the high angle faulting associated with this sequence. The boss-like rust-stained surface of the St. Peter sandstone also shows the smooth curved slickensided fault surface. There is a thin veneer of Joachim remaining on portions of this sloping surface which shows some of the minor folding associated with the anticline. One small plunging syncline can easily be spotted by the blotchy rust-stained Joachim carbonate bedding surface. These beds have been fractured by a prominent joint set with many of the tension openings filled with mortar-like breccia. Eastward several faults transect the beds one of which exposes the unconformity green shales between the Shakopee and St. Peter formations. The irregular knobby cherty top surface of the Shakopee formation is also exposed at this place.

### Southeast corner.

This re-entrant has northeast dipping Platteville strata separated from the northeast side of the plunging anticline by a cross fault. The partially duplicated section extends from the upper Joachim formation to the base of the Galena limestone. The north side of the re-entrant has an overturned block of weathered Galena dolomite resting with unconformity on a small outcrop of Elgin shale; otherwise, the exposures are poor and the relationship obscure.

### East wall.

This wall is characterized by north-south steeply dipping smooth curved fault surfaces and poor accessibility. Exposures are poor on the south side and relationships difficult to understand. The prominently exposed fault surface in the middle of the high east wall is an easterly dipping fault which drops a block of Galena and Elgin rocks downward and eastward. There are several fault surfaces on the north side of the east wall which dip westward and seem to involve rust-stained Joachim beds. In between the oppositely-dipping faults is a wedge of Platteville strata. More information is needed to the east to understand the structural relationship of this wall to that in the quarry.

### North wall.

The stratigraphic sequence exposed along the north wall is similar to the southwest part of the quarry. The section extends from Joachim rocks on the east to the Platteville-Galena contact beneath the ramp on the west side; however, three faults displace blocks of Galena strata to disrupt the normal sequence. St. Peter sandstone is reported to be present beneath glacial drift east of the northeast corner of the quarry.

## Geophysics

Published geophysical data on the Kentland area is indeed very meager. A magnetic intensity map made by Zinn in 1932 was included in Shrock, 1937. In 1953 the Indiana Geological Survey published a map of Indiana showing gravitational intensity. A map showing field intensity of transmitted radio waves was made by Pullen, 1953. In none of the above references was an interpretation made, but geophysical data is needed to establish the extent of the anomaly and to find out whether the Precambrian basement has been affected by disruption.

## Interpretation

Air photos in southern Newton County suggest the possibility of a WNW-ESE lineament (?) reflected through thin glacial cover south and southeast of the quarry (fig. 7). This interpretation lends plausibility to the geophysical pattern based upon radio field strength measurements from Station WAAF, Chicago (Pullen, 1953, p. 50, fig. 30). The plunge of the folds and lineations (slickensides and mullion structure) also suggests an upward and radial shove as does the stratigraphic sequence. It is possible that Cambrian strata may lie beneath the glacial drift to the southeast and that a stratigraphic throw of over 3000 feet may be expected. The uplifted block north of the lineament is in the form of a shattered half-dome whose strata slope radially into normal regional stratigraphic position to the west, north, and east. The origin of the energy necessary to produce this anomaly is still an enigma.

87.5 On leaving quarry, turn east (right) onto U.S. Route 24. Follow this route to Wabash. (Resume itinerary by William J. Wayne.)

90.9 Pass through junction with Indiana Route 55, South.

91.5 Pass through junction with Indiana Route 55, North.

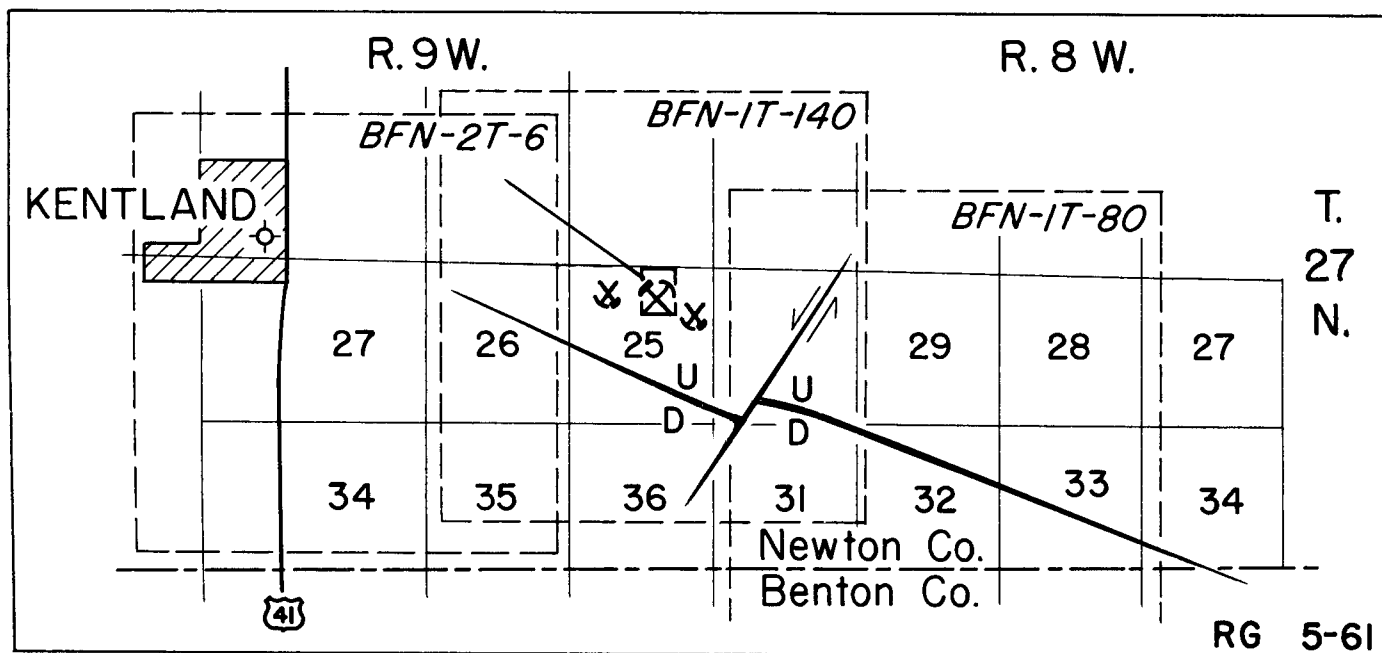


Figure 7.- Suggested possible gross structural control.

*To Bill Neal with best personal regards  
Ray Gutschick*

FIELD GUIDE

*William J. Neal*

GEOLOGY OF THE KENTLAND STRUCTURAL ANOMALY, NORTHWESTERN INDIANA

Study for Earth Science Students

Raymond C. Gutschick  
Department of Geology  
University of Notre Dame  
Notre Dame, Indiana

Progress report written for field trip Wednesday, November 15, 1972,  
arranged for 35th Annual Meeting of the Meteoritical Society, November 16-18,  
1972, University of Chicago, Chicago, Illinois.

November, 1972

## **FIELD GUIDE**

### **GEOLOGY OF THE KENTLAND STRUCTURAL ANOMALY, NORTHWESTERN INDIANA**

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## Foreword

The remarkable Kentland quarry is an especially valuable field laboratory for student study. One cannot overemphasize the unique opportunity available to observe various aspects of geology, in particular, structural detail which is seldom freshly exposed on this scale.

This guidebook represents a progress report on a current geological study of the quarries. Geological mapping has been done and is currently being done to keep progress with rapid quarry operations and stone removal. Geology of the westward extension is presented and represents unpublished information except for several short abstracts, the Indiana Geologists Fall, 1970 Guidebook, and the National Association of Geology Teachers East-Central Section Spring, 1971 Guidebook. A comprehensive report on the Geology of Kentland is planned and in preparation to be finished at the completion of the mapping.

The management of the Newton County Stone Company is especially proud of their efficient production and concern for safety in quarry operations. Through the cooperation and courtesy of Mr. Robert Prince, quarry manager, and his congenial staff, we are privileged to be their guests in having access to the geology in the large operating quarry.

We have certain responsibilities and cautions to carefully heed. Each visitor is required to register with his signature on a liability release form. It is imperative that we stay together as a group and avoid interference with regular quarry operations. In most places quarry walls are steep and hazardous so that good judgment and extreme care should be used in working close to or under them. This is most critical when they are wet as during and after a thaw or rainfall. Normally hard hats are required in the quarry and it makes good sense to use them. Be sure you take out of the quarry whatever you bring into it. Do not litter for the management wants to maintain a clean neat quarry. Collecting is permissible as is geological photography.

Quarry management recognizes the educational importance of such exposure as this to the geological field experience of students. Quarry operators go out of their way to cooperate; however they do have trepidations concerning control of large size groups and potentially dangerous irresponsible behavior. Since the operation is privately owned and controlled and the privilege of entry can be revoked at any time, in no way do we want to jeopardize these friendly relations. We have an obligation to future geological groups to maintain continued access to the quarry.

Your cooperation is appreciated by everyone concerned.

### Acknowledgements

I am especially grateful to Mr. Robert Prince, general quarry manager of the Kentland operation and his staff for permission to geologize in the quarry and for their generous cooperation and encouragement over the years. This also includes Mr. William Davidson, quarry superintendent, Mr. Harrison Forrest, Mr. Edward Meader, Mr. Phillip Pettijohn, and quarry workers who have been very friendly and helpful on numerous occasions.

In 1939, Dr. Francis P. Shepard gave me my first opportunity to visit Kentland quarry on a structural geology field trip. The first comprehensive report on the quarries by Drs. Robert Shrock and Gilbert Raasch published in 1937 has been a constant source of valuable information. Dr. Shrock has generously given me all of his early field notes which have much information that is no longer available in the quarry. Dr. H. B. Willman of the Illinois Geological Survey identified the Ordovician stratigraphic units to me on a personal field trip to the quarry in 1961. This came at a time when Drs. Willman and Templeton's definitive Champlainian Series study was in progress and well advanced. Recognition of Ordovician units is the key to the structural geometry of the anomaly.

The Indiana Geological Survey through the Director John Patton, Dr. Maurice Biggs and Thomas Dawson furnished much information on the subsurface data of the region. Dr. Judson Mead and Dr. Dan Tudor shared new information from their extensive detailed geophysical investigation of the Kentland anomaly. Drill logs and cores from this project were also made available to me.

Besides the 1937 report of Shrock, I have the advantage of Dr. Robert Boyer's Master's thesis which outlines the status of quarry geology in 1953. A field visit to Kentland in 1961 with Drs. Robert Dietz and Eugene Shoemaker to examine shattercones was very rewarding. Important low altitude air photos were furnished to me by Dr. Erhard Winkler, Department of Geology, University of Notre Dame. These 1960 photos cover the eastern portion of the quarry which provided the base for the 1961 report. Additional photos were made from the stone quarry company helicopter in 1970.

There are a number of undergraduate students in Notre Dame's Geology Department who studied various facets of quarry geology as part of our undergraduate research participation program. I am grateful to Richard Lippincott for a study of shattercones, Terry Coyle, who studied Silurian foraminifera faunas, Fred Weaver's study of the Lower Ordovician Shakopee Formation, and Mike Plamondon's work on the breccias in the quarry. Francis Bellini helped with plane table mapping in the quarry.

My wife, Alice, helped me in many ways on numerous trips to the Kentland quarry in all seasons.

The abandoned McKee and Means quarries were referred to by Gorby in 1886 and the currently active McCray quarry by Ward in 1906. There has been continuous quarry activity during the past 65 years. During this interval of time, countless geologists and students have examined and puzzled over the origin of this enigmatic structure. Local residents have also contributed by permitting access to their lands. I express my pleasure for the exhilaration which must come to all those students of the earth who have seen Kentland and to the local people who have put up with us.



Geology of the Kentland Structural Anomaly, Northwestern Indiana-  
Study for Earth Science Students

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Department of Geology  
University of Notre Dame  
Notre Dame, Indiana

**Abstract-** The Kentland anomaly is a complexly deformed structure confined to a relatively small area (approximately 5 square miles) in an otherwise undisturbed region of flat lying bedrock. Within an 80 acre quarry, 1000 or more feet of Ordovician and Silurian strata have been rotationally uplifted as much as 1800 feet vertically. The region adjacent to the anomaly has Lower Mississippian and Pennsylvanian bedrock which dips less than  $1^{\circ}$  to the southwest. The entire area is veneered with Pleistocene Wisconsin glacial till from the Saginaw ice lobe.

Strata in the main quarry include Lower Ordovician Shakopee Formation (oldest exposed), Middle Ordovician St. Peter Sandstone, Joachim Dolomite, Platteville Group, Galena Group, Upper Ordovician Maquoketa Shale, Lower Silurian Brassfield Limestone and Middle Silurian Salamonie Dolomite. Late Devonian New Albany Shale with Tasmanites occurs in fault breccias.

Quarry operations for the past 50 years in the NW $\frac{1}{4}$  NE $\frac{1}{4}$  sec. 25, T. 27 N., R. 9 W., Newton County, Indiana, have followed steeply dipping Ordovician strata downward as deep as 260 feet below the surface. The quarry is horseshoe-shaped which reflects the distribution of carbonate rocks to the major plunging syncline geologic structure.

The structure exposed in the three quarries involves folding and complex faulting. The major structure is that of a steeply dipping syncline which plunges to the NNW and involves strata from the Shakopee Dolomite to the Maquoketa Shale. A prominent thrust or reverse fault, the Kentland Quarry Fault, parallels this synclinal fold and bounds it on the south margin throughout the quarry. Shearing is close to but not parallel to the bedding in subjacent St. Peter Sandstone to the south and Joachim Dolomite on the north hanging wall. Movement has been rotational for the block rather than elevator uplift. Displacement between walls has been oblique slip on the flanks to dip slip close to the axis of the fold. The trough of the syncline is further complicated by a nested synclinal fault which duplicates the Middle Ordovician section of the Platteville and Galena Groups and parallels the parent syncline. The nested structure is best exposed on the north side of the quarry along the ramp and crusher-conveyor belt.

Both of the flanks of the syncline in the SE and SW corners of the quarry manifest a different style of faulting. Maquoketa and Silurian strata in the SW quarry corner are folded into a steeply plunging anticline which has battered flanks. The latter are represented by separate fault blocks with sharp structurally discordant beds. All this is separated from the west limb of the large plunging syncline by a long narrow linear graben of dark Maquoketa Shale.

Unfortunately the SE quarry corner is back-filled. Earlier exposure revealed a block of Middle Ordovician strata trending NW-SE and dipping to the NE. There was some faulting exposed parallel to the bedding trend but displacement was apparently small. The orientation of the beds in this block is very closely related to similar strata in the abandoned McKee quarry to the ESE.

Compared to the undisturbed regional surroundings, the Kentland structure represents intensely deformed and strongly fractured rocks. Shattercones are common in a variety of lithologies, quartz grains are highly fractured, coesite has been reported but not confirmed, and mylonitic breccias grout fault contacts and fissures like mortar.

Several methods of origin have been suggested and the non-committal term Cryptoexplosion has been used. Cryptovulcanism (deep seated aborted volcanic eruption), meteorite impact (astrobleme), and faulting have been proposed. While geologic confirmation is equivocal, structural and mineralogic evidence as reported favors meteorite impact as the cause; whereas, geophysical studies strongly suggest deformation from below.

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Introduction- Apparently the Kentland structure originally represented limited bedrock exposure in the middle of a relatively flat prairie farming area now surrounded by corn and soy bean field crops on ground moraine till plain. Shallow high quality bedrock prompted quarry operations in the early 1880 decade. Three quarries were started over the years, Fig. 1, but two of them became inactive before 1930 as noted by Shrock and Malott. The main McCray quarry has been continuously active since 1906 and rock removal has accelerated during the past decade with construction of the interstate highway system and greater farm use.

In the large pit, quarrying started in the NE part of the excavation and proceeded downwards to the depth of the 7th level (filled with water). Extension of the quarry to the west is outlined by the 6th floor level. A southeastward cul-de-sac operation encountered Middle Ordovician rocks but was abandoned in the upper levels and subsequently back-filled. Several years ago westward expansion followed productive Middle Ordovician carbonate beds to the present quarry outline. Currently the surficial material is being stripped to bedrock on the contiguous west side property to extend the quarry again in that direction. This will be an enlargement of the old abandoned Means quarry.

Development of the quarry is based on 40-foot shot-hole drilling depths. Blasting and removal of broken rock results in effective deepening about 35 feet for each round. Therefore in a general way, successive levels in the quarry from bedrock surface downwards represents approximately 35 foot vertical intervals.

A chronologic summary of developments of the quarries, discovery of Kentland, identification of the rocks and their paleontology, speculations as to the origin of the structure, geologic, mineralogic, and geophysical development, and current status of our understanding of Kentland is given as follows. References to these studies can be found in the bibliography at the end of the guide book.

### Chronologic Resumé of Significant Developments at Kentland

Natural outcrops, thin glacial drift, and local "dome"

- 1881- G. K. Greene- Discovery of Kentland exposures (reported in Collett, 1883).
- 1883- J. Collett- First report of disturbed strata near Kentland.
- 1886- S. S. Gorby- First reference to McKee and Means quarries, also fossils.
- 1906- L. C. Ward- Reference to McCray quarry.
- 1906- G. K. Greene- Affirmation of Ordovician age of rocks in McKee quarry based on fossils.
- 1922 Interpretation of disturbed structure as Niagara domes.
- 1922- E. R. Cumings- Questioned "Niagara domes (reef) origin of Kentland structure.
- 1927- E. R. Cumings and R. R. Shrock- Proposed diastrophic origin of Kentland structure.
- 1930- R. R. Shrock and C. A. Malott- Structural and paleontology study of quarries.
- 1932- J. Zinn- Magnetic intensity map of Kentland area (Map is reproduced in Shrock, 1937, p. 520, fig. 8).
- 1933- R. R. Shrock and C. A. Malott- More information on stratigraphy and structure also paleontology.
- (1928, 1935- W. Bucher on cryptovulcanism; 1936- Boon and Albritton on meteorite impact; Wilson and Born on meteorite impact).
- 1937- R. R. Shrock- Comprehensive detailed report on the stratigraphy and structure of the Kentland disturbance with presentation of multiple origin possibilities favoring cryptovulcanism.
- 1937- R. R. Shrock and G. O. Raasch- Detailed report on the paleontology of Ordovician rocks at Kentland.
- 1947- R. S. Dietz- Meteorite impact origin suggested by shattercone orientation.
- 1952- D. R. Lucas- Geophysical survey.
- 1953- M. W. Pullen- Kentland anomaly survey based on radio field intensity survey map.
- 1953- R. E. Boyer- Geological study of Kentland McCray quarry including geological map.
- 1955- E. A. Ziemba- Microfacies study of Ordovician Platteville Group.
- 1959- R. S. Dietz- Shattercones suggest meteorite impact origin.
- 1961- R. C. Gutschick- Progress report on geology of McCray quarry with map.
- 1961- A. J. Cohen, T. E. Bunch, and A. M. Reid- Reported discovery of coesite in St. Peter Sandstone at Kentland.
- 1963- J. S. Templeton and H. B. Willman- Clarification of Champlainian stratigraphy.
- 1966-present- D. Tudor et al (Indiana University and Indiana Geological Survey) Detailed subsurface and geophysical gravity survey study of Kentland anomaly area; 1972- abstract of this study is published and orally presented at G.S.A. meeting in DeKalb, Illinois.
- 1969, 1970, 1971- R. C. Gutschick- Abstracts, oral reports, and progress reports on study of geology of Kentland based in large part on deepening of main quarry and westward quarry extension based on new information. Progress geologic map Guidebook Indiana Geologists Field trip Oct. 17, 1970; National Association of Geology Teachers East-Central Section Field trip Apr. 17, 1971.

Method of study- Quarry geometry and structural detail is being mapped by plane table-alidade method. Colored air views have been taken of the quarries and numerous color transparencies taken on each visit have also recorded the progress of quarry operations. These are especially valuable for reference since the rocks and geology are removed and the information is otherwise lost. Enlarged photos and transparent overlays have been used to decipher the geometry of strata and faults in blocks throughout the quarry. The polaroid camera has also been used to advantage for on the spot photos and mark up of the details.

Rock colors are more striking and quarry faces are fresher and clearer after rainwash before much quarry dust is generated to obscure details. Freshly blasted faces also reveal sharp detail. Lighting (daylight or sunlight) for observation and photos is an important factor to bring out contrasts, shadows, or detail that might otherwise escape the viewers notice. Time of day and sun's shadows also produce striking changes. e.g., mullion surfaces along the Kentland Quarry Fault are much more pronounced with glancing incidence lighting.

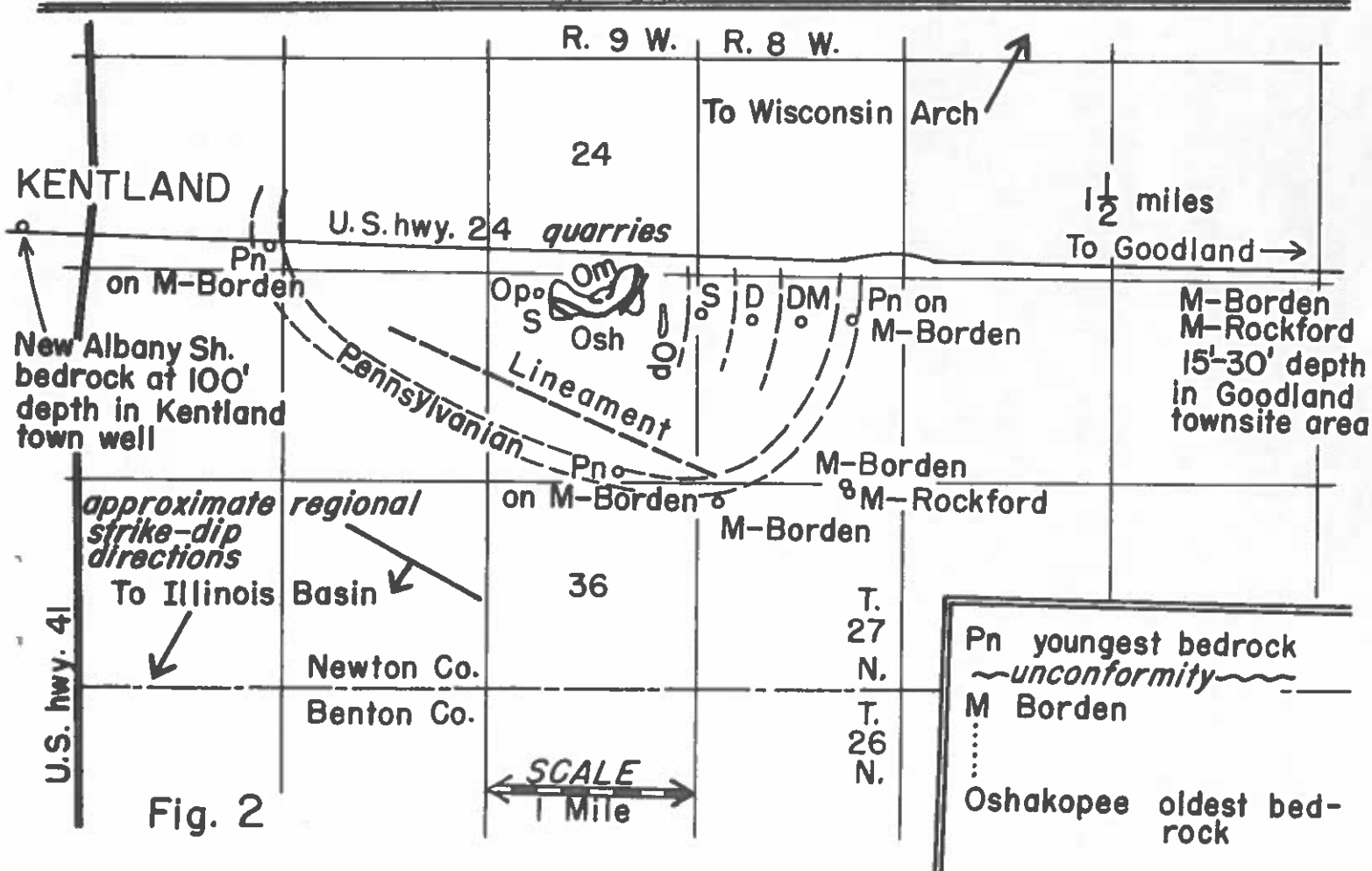
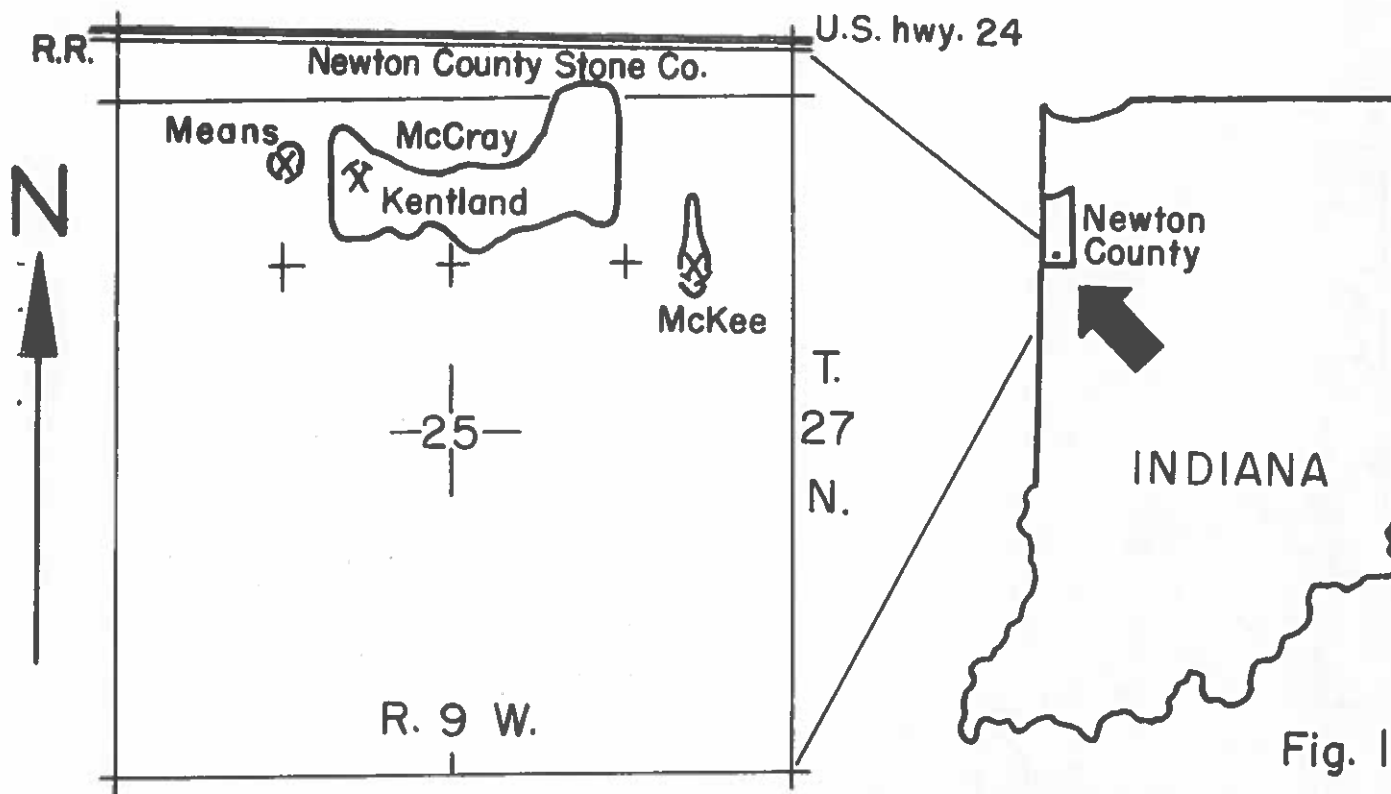
Weathering brings about changes in color or tone which accentuates certain features. Pyrite altered to limonite along mineralized fault surfaces pin-points the major structure, as for example along the Kentland Quarry Fault; also drip in the form of limonite weathered from pyrite nodules in the Hennepin Member. These drip stains along steeply dipping bedding and fault surfaces are seen throughout the quarry and can be used effectively to recognize key stratigraphic units and faults. The Galena-Maquoketa unconformable contact has a concentration of iron sulphides along it which alter to limonite and accentuates the presence of this surface. Ubiquitous ferrous iron in rock dolomite will weather buff-rusty with time as with the Galena and Shakopee rocks. White gypsum efflorescence covers some of the Galena and Maquoketa Shale exposures. It is also present in the Lower Platteville Pecatonica Dolomite. Bedding, fractures, and faults form weak recessive relief with time. This progressively accentuates such contacts.

Finally the frustration of discovering an unusually good exposure or feature only to have it quarried or covered in succeeding weeks is disheartening. On the other hand quarry advance enables one to project the geology from time to time which helps to fill in the three-dimensional puzzle.

Kentland regional geology- Location of the quarries in Section 25, T. 27 N., R. 9 W., Newton County, Indiana is given in Fig. 1. The geology and extent of the Kentland structure is shown in Fig. 2. This is based on limited subsurface information namely seven drill holes to bedrock and two town water wells in Kentland and Goodland. The former were drilled by the Indiana Geological Survey who also interpreted the cuttings and cores. Core drilling to bedrock in Tudor's program will provide much more detailed information on this bedrock anomaly.

For normal regional structure the bedrock consists of Lower Mississippian or Upper Devonian rocks which dip very slightly to the southwest into the Illinois Basin from off of the Wisconsin ("Kankakee") Arch. There may be a few Pennsylvanian outliers such as the one about one mile northwest of Remington, Indiana. The surface is covered with Pleistocene Wisconsin glacial drift so that rock outcrops are few indeed.

The Kentland structure, except for the quarry, is an elliptical faulted dome with concentric ring syncline. Formations from the Shakopee to the Borden



have been uplifted and tilted, presumably with quaquaversal dips; and an outlier "moat" of Pennsylvanian rock, represented by a thin band around the ring syncline structure, has been preserved. The Pennsylvanian remnant is unconformable on the Lower Mississippian Borden Group and is overlain unconformably by the Pleistocene drift.

The regional setting of the Kentland structure to the Illinois Basin and Wisconsin Arch is given in Fig. 3. Other anomalous disturbances are shown for this area. Attention is called to the Des Plaines and Glasford disturbances and to the Sandwich and Royal Center Faults.

A very generalized stratigraphic section is reconstructed for the area down to bedrock, Fig. 4. This gives the normal stratigraphic section encountered from the surface through the Pleistocene and Paleozoic rocks to the Precambrian basement. Formations exposed in the Kentland anomaly are indicated as are projections to structural datum surfaces, e.g., top of the Trenton Galena Group, top of the Knox Megagroup (top of the Shakopee Fm.), top of the Precambrian "Basement". The elevation of the Kentland quarry surface is approximately 700' above sea-level and the respective tops of the Galena, Shakopee, and Precambrian surfaces are 400', 1000', and 4700-4800' all below sealevel.

In order to appreciate the stratigraphic and structural dislocation of the Kentland structure, several structure contour maps are given for key datum surfaces. These are top of the Trenton Limestone, Fig. 5; top of the Knox Dolomite, Fig. 6; and top of the Precambrian Basement, Fig. 7. For the Kentland anomaly the Galena (Trenton) Dolomite is well exposed throughout the quarry; yet it should normally be at 400 feet below sealevel. The oldest rocks exposed in the quarry belong to the Shakopee Dolomite. Since the top of the Shakopee Fm. (top unit of the Knox Megagroup) should normally be at 1000 feet below sealevel and there is over 100 feet of this formation present, we can conclude that it has been uplifted at least 1800 feet above its normal position in the stratigraphic-structural section.

The structure map for the top of the Precambrian Basement is also presented, Fig. 7, taken from Bond et al, 1971, and Rudman, Summerson, and Hinze, 1965. There is much less structural control on this datum surface than for the Galena or Shakopee surfaces; therefore it is less reliable for comparison. It is presented here to relate to geophysical study by Tudor et al, 1972, for which they found that three-dimensional gravity modeling of their data suggests a basement uplift of 2000 to 3000 feet.

In Fig. 2 you will note that the rock formations exposed are of Ordovician and Silurian age and that drill holes on the east side of the quarries encountered successively younger rocks eastwards. Well sections in the town areas of Kentland and Goodland are normal. Air photos suggest a linear feature interpreted as a fault, Gutschick, 1961, which is apparently confirmed by Tudor's geophysical survey. This forms the south margin of the stratigraphic disruption. Other drill holes have encountered Pennsylvanian bedrock in a narrow belt around the anomaly; otherwise the bedrock is Lower Mississippian or Upper Devonian.

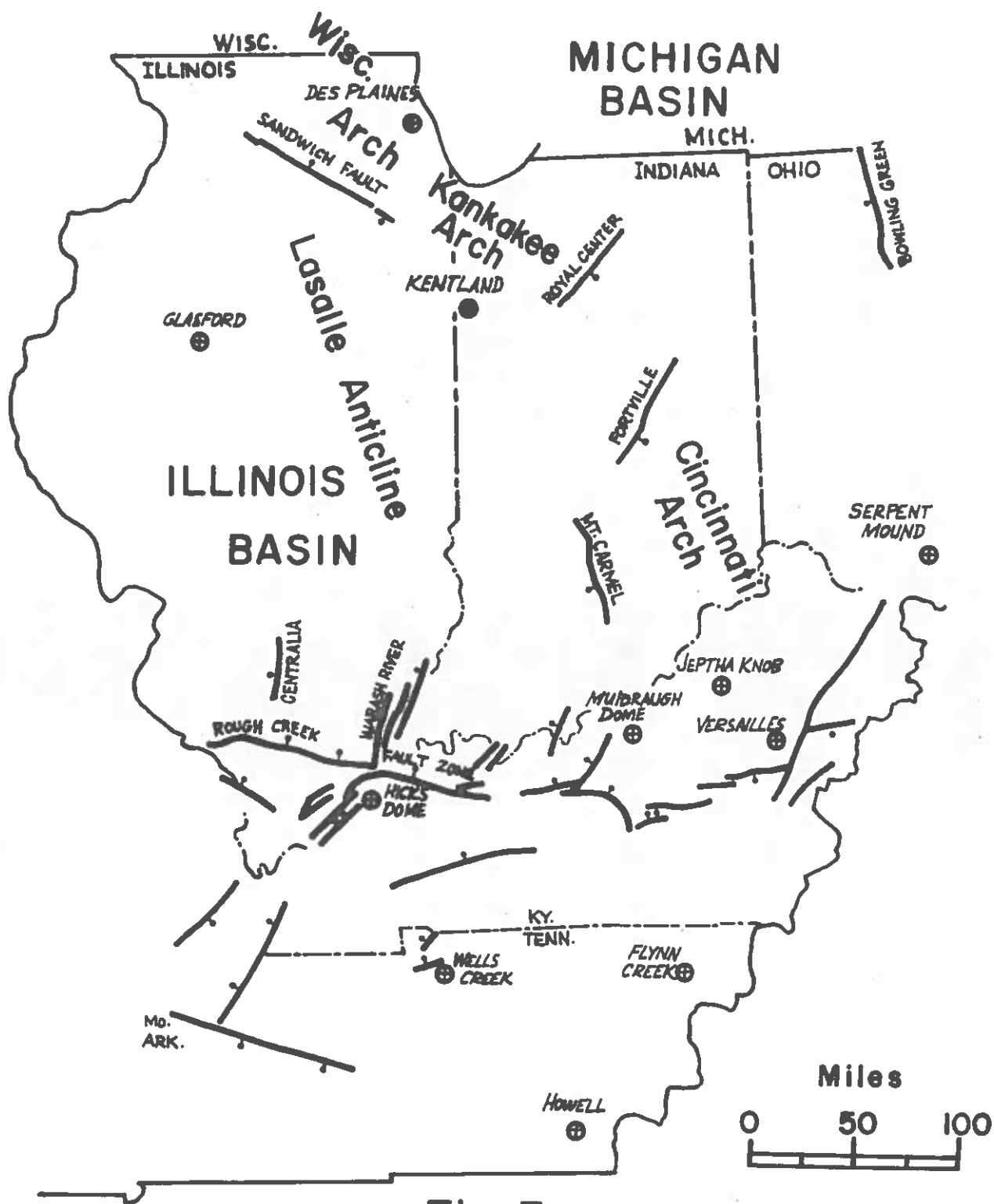
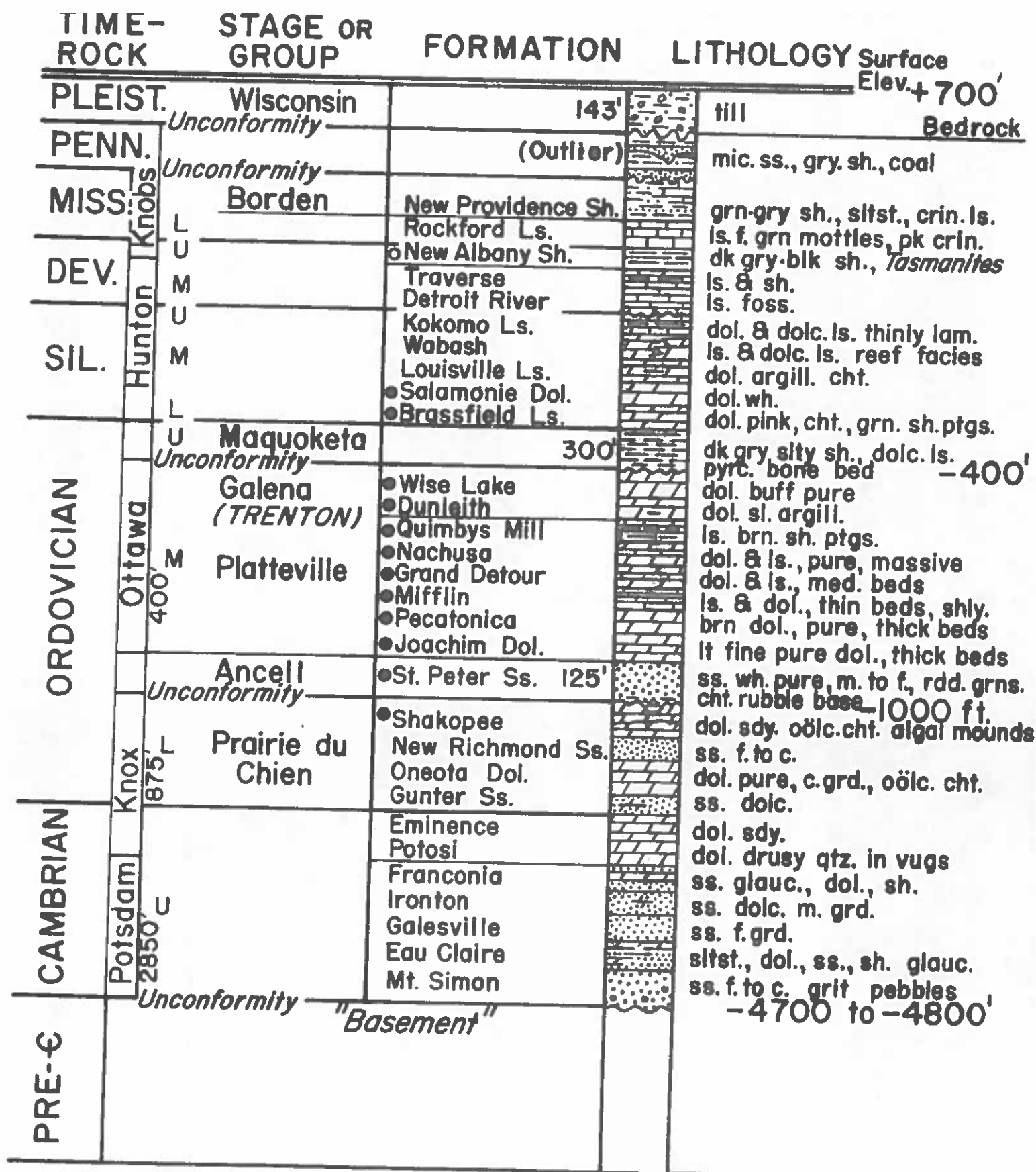


Fig. 3  
MAJOR FAULTS AND DISTURBANCES  
IN MIDWESTERN AREA



Thicknesses and depths are close estimates.  
 ● Present in Kentland quarry      ○ in breccia

## STRATIGRAPHIC SECTION AND PROJECTED BASEMENT IN THE KENTLAND AREA



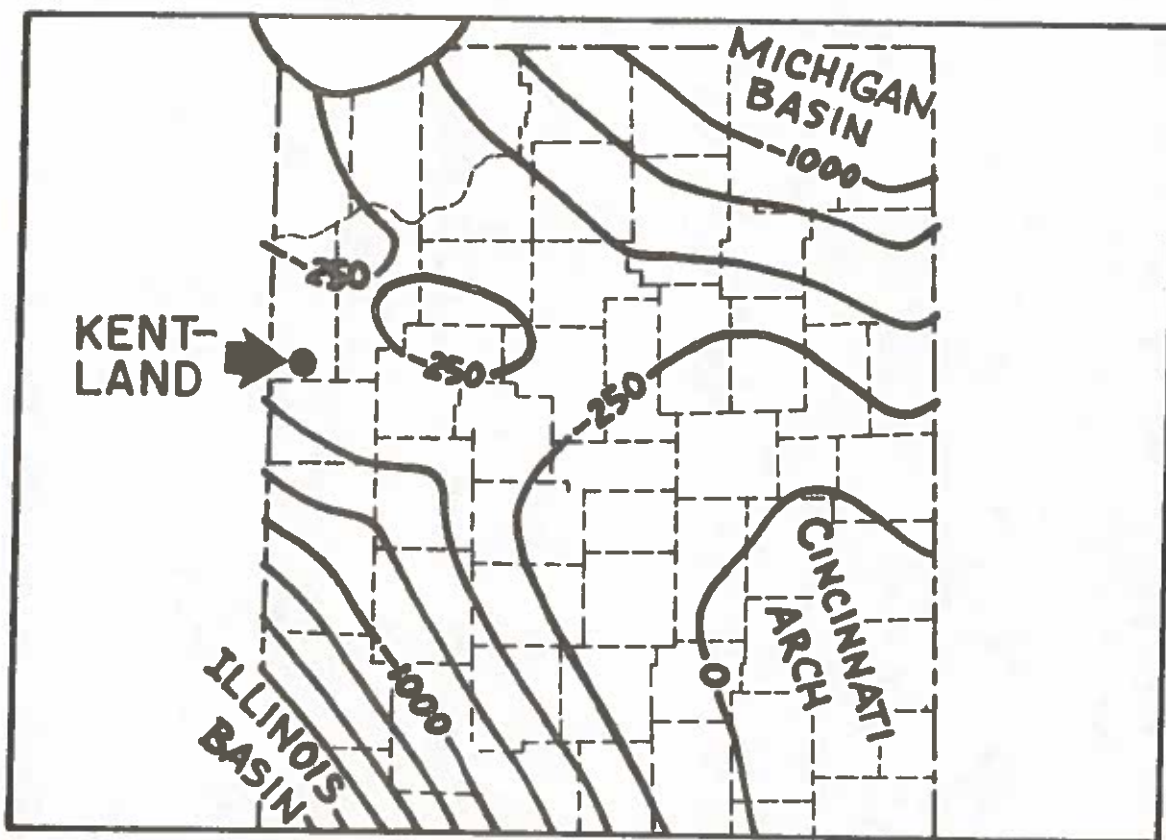


Fig. 5 Structure Map contoured on top of Trenton Limestone (Middle Ord. Galena Group at Kentland X)  
(From Dawson, 1952, *Ind. Geol. Survey Misc. Map 3*)

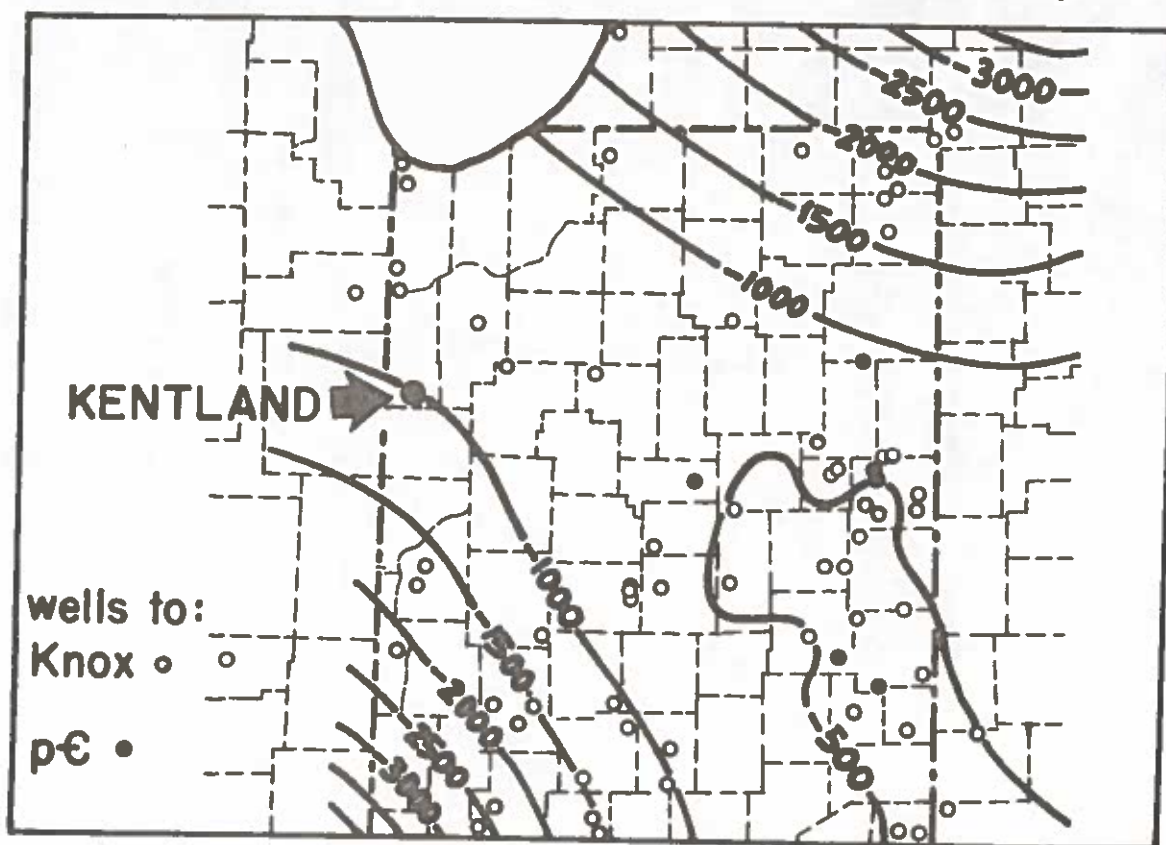


Fig. 6 Structure Map contoured on top of Knox Dolomite (Lower Ordovician Shakopee Fm.) (Dawson, 1960)

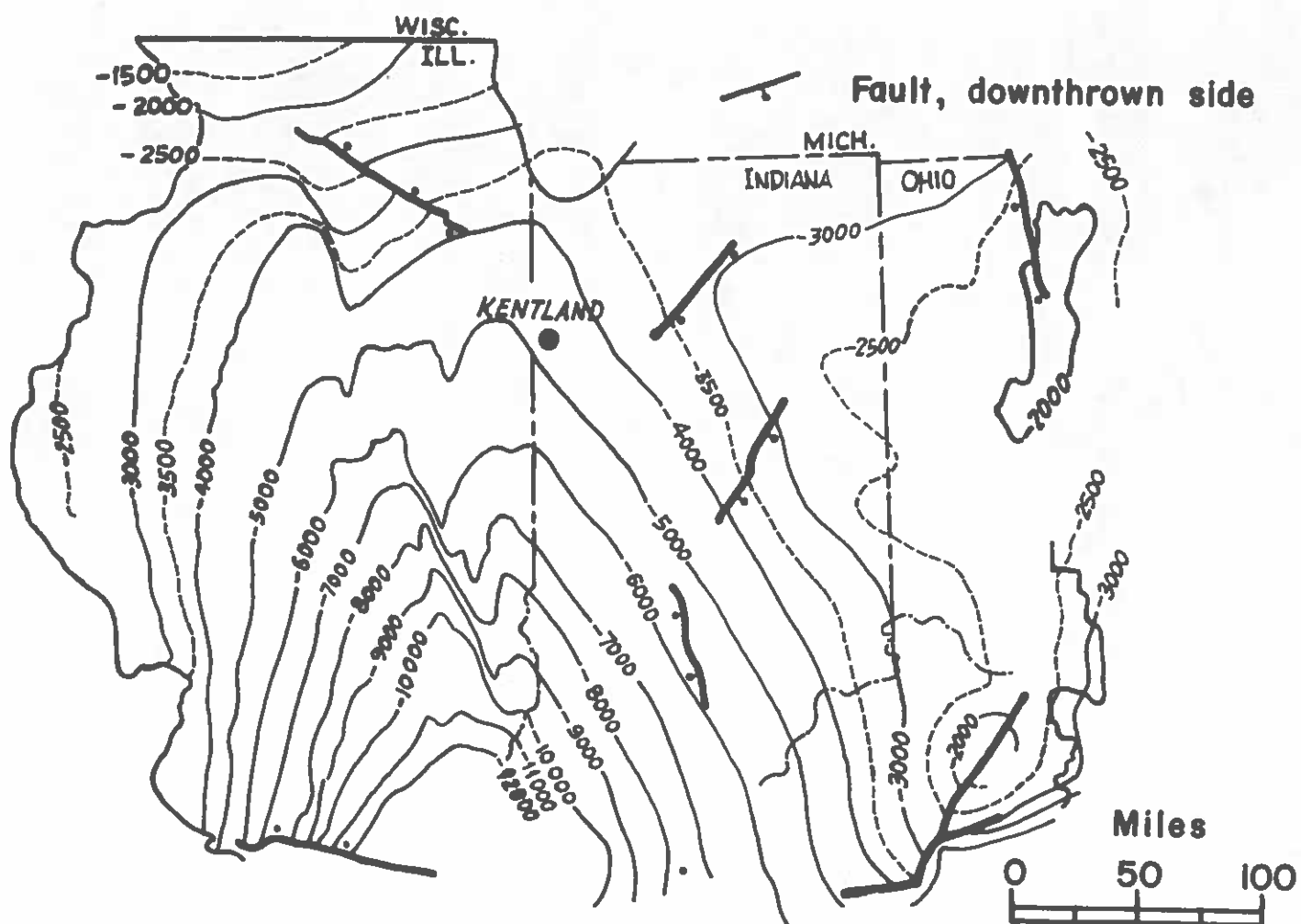


Fig. 7 STRUCTURE on Top of PRECAMBRIAN BASEMENT

## Geology of the Kentland Quarries

There are three quarries located in the north half of section 25, the main active quarry and two small long abandoned sites, Fig. 1. The large quarry is currently being expanded to the west to absorb the old Means quarry. Stripping of the glacial mantle to bedrock is now in progress and quarry operations will start very shortly on this tract to connect with the main quarry.

The relationship of the quarries to the topography of the area is given in Fig. 8, taken from the four adjacent quadrangles Kentland, Goodland, Earl Park, and Wadena. A more detailed set of maps for the quarry is given for the surface topography, Fig. 9; bedrock topography, Fig. 10; and thickness of the glacial drift, Fig. 11.

Stratigraphic Key (within quarries)- A detailed resumé of the stratigraphic section reconstructed from blocks in the quarries is shown in the columnar section diagram, Fig. 12. Strata range from Lower Ordovician Shakopee Dolomite to the Middle Silurian Salamonie Dolomite. Middle Devonian carbonates have not been recognized in the quarry and Upper Devonian New Albany Shale appears only as shale clasts in fault breccias. A fairly detailed composite section encompasses approximately 1000 feet in thickness of rock. Faulting has sheared out uppermost St. Peter Sandstone and lowermost Joachim Dolomite so that it is virtually impossible to recognize and identify complete sections of either of these formations. Quarry circumstances fail to expose a significant portion of the middle part of the Maquoketa Shale.

Shakopee Dolomite- About 125 feet of the Shakopee Dolomite has been pieced together although some of it is now covered by backfill for a ramp. The dolomite lithology, partly sandy, with rusty weathering, irregular thin- to medium-bedding, and some oolitic chert characterizes this formation. Large low algal stromatolite mounds are present and they are 10-12 feet in diameter by 1-2 feet high. Algal breccias are commonly associated with the stromatolitic layers. Chert nodule layers, some oolitic, and bright green shale partings are also present. Acid residues contain coarse rounded frosted quartz sand grains some of which are fractured and offset but the grains are whole and intact. This is the oldest formation recognized in the quarries.

St. Peter Sandstone- A pronounced unconformity separates the basal unit of the St. Peter Sandstone Kress Member from the underlying Shakopee Dolomite. The Kress Member which is 5-10± feet thick has much bright green clay, possibly K-bentonite, residual chert nodules with friable weathered oolites and white sand stringers. Much of the Kress lithology must represent unconformity insoluble residuals from the underlying Shakopee Fm. The St. Peter Sandstone is pure white quartz sandstone in which the grains are highly fractured and the rock exhibits closely spaced jointing. Bedding is obscure and thickness is difficult to determine. The rock usually is soft and friable. Throughout the quarry, its upper part is in fault contact which further complicates measurement of its true thickness. Cohen, Bunch, and Reid, 1961, report coesite in low concentration from this sandstone. About 80 feet of the lower part of the formation has been measured in the footwall of the Kentland Quarry Fault.

Joachim Dolomite- This important structural unit is characteristically very light gray, aphanitic, medium- to thick-bedded, pure, tough dolomite. Its complete thickness has not been observed since the lower part of the formation is involved in hanging wall fault contact along the Kentland Quarry Fault. The upper portion of the formation has thin wavy discontinuous shale films within the dolomite.

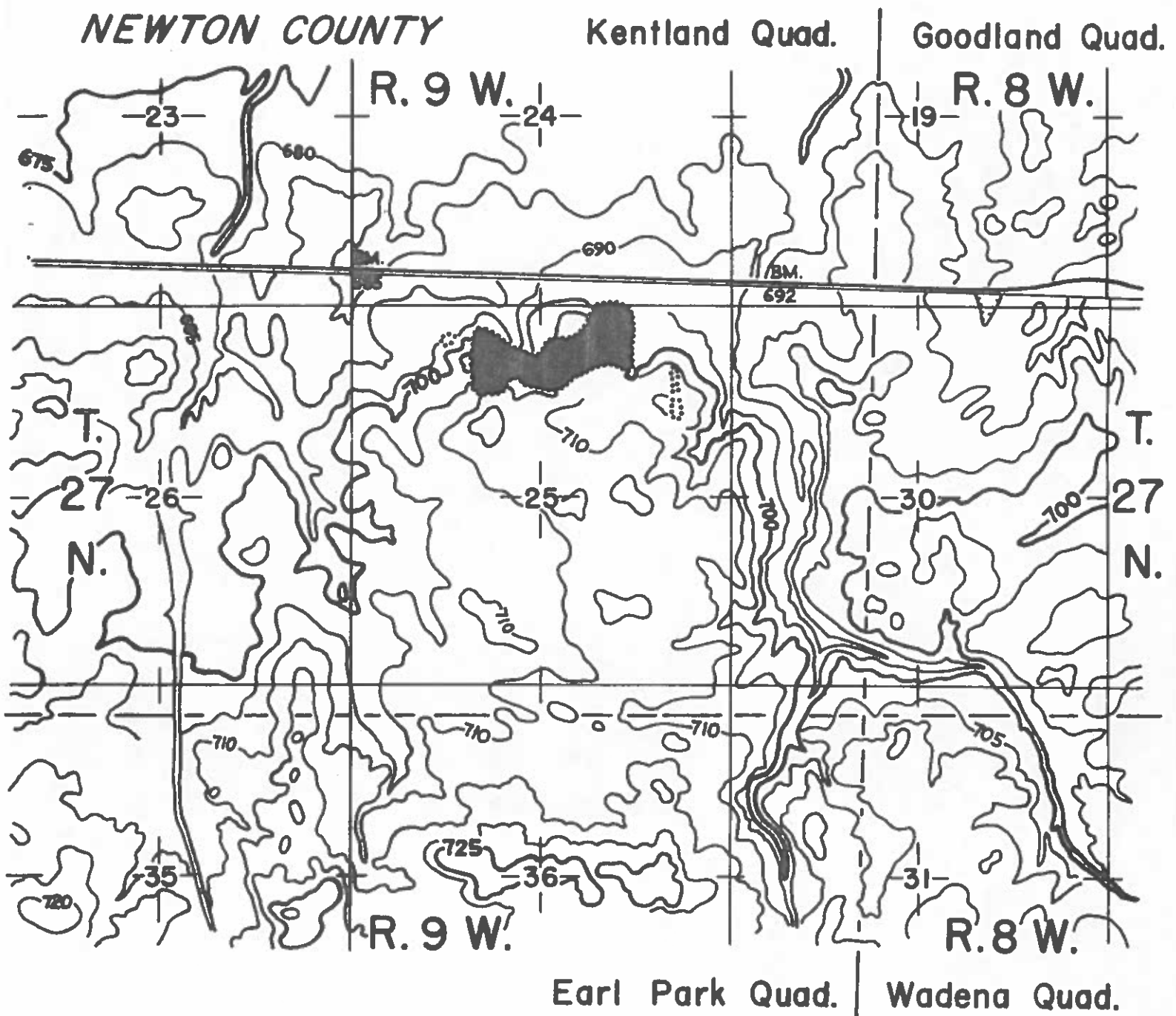


Fig. 8

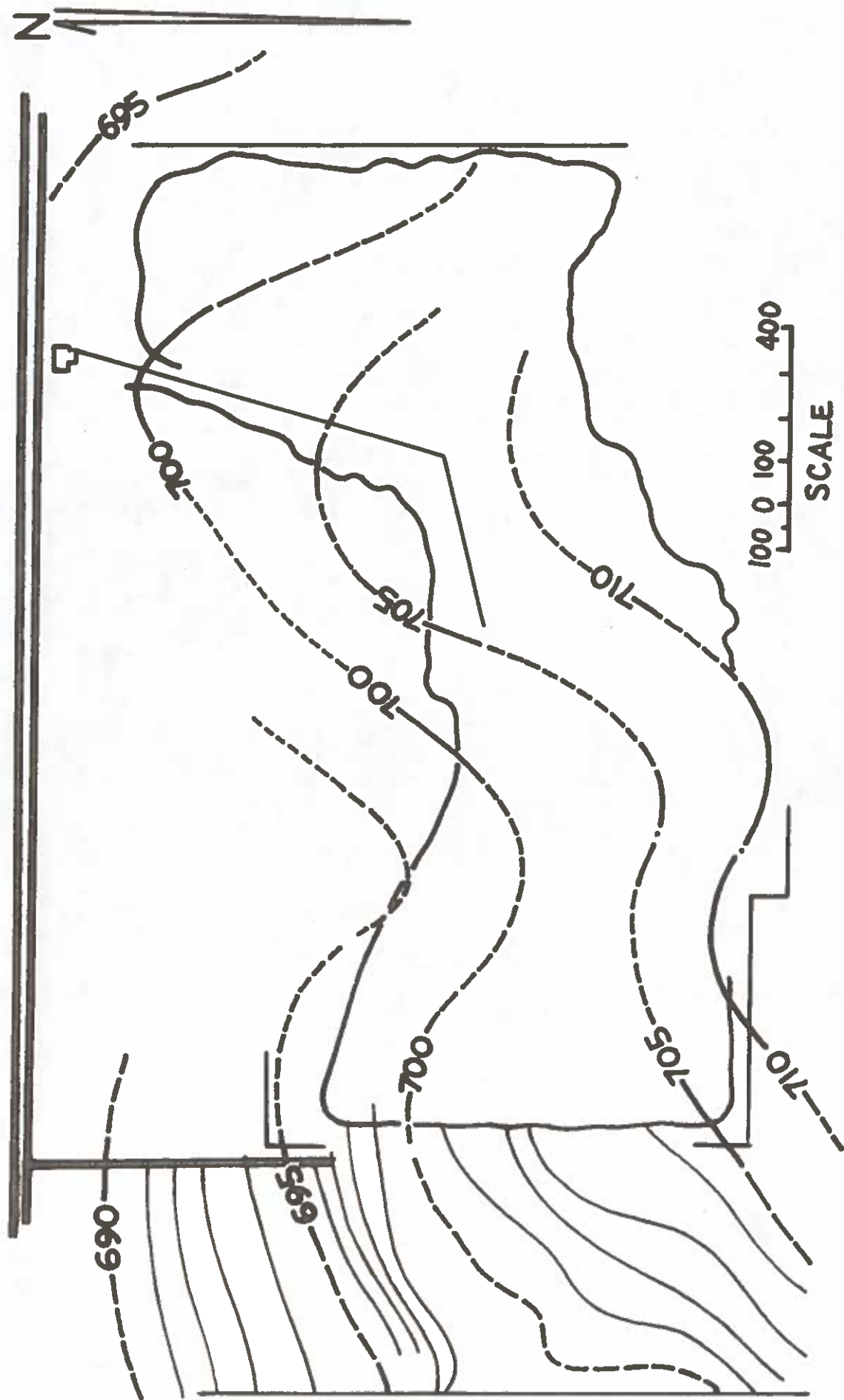


Fig. 9 TOPOGRAPHIC MAP

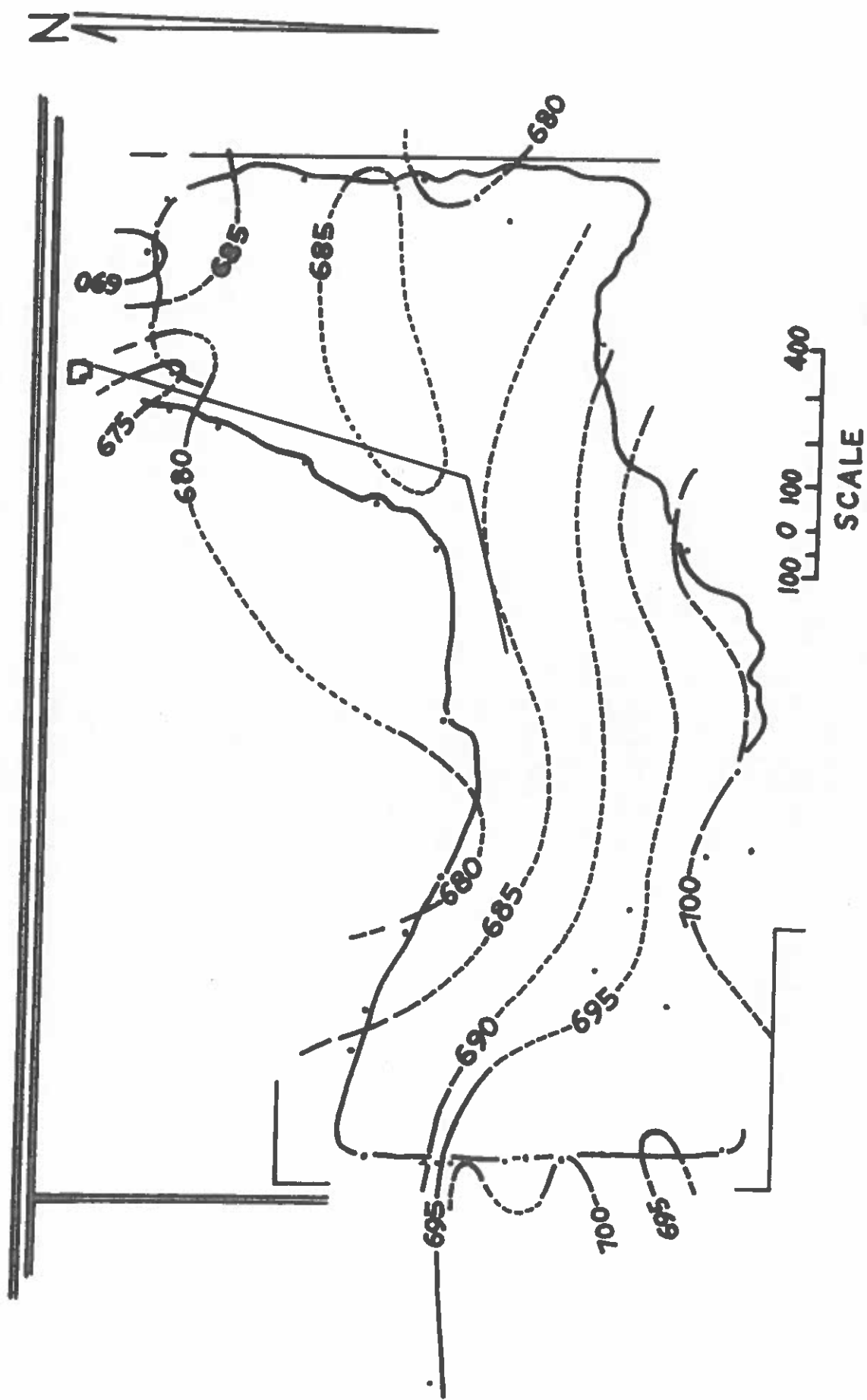


Fig. 10 BEDROCK TOPOGRAPHY

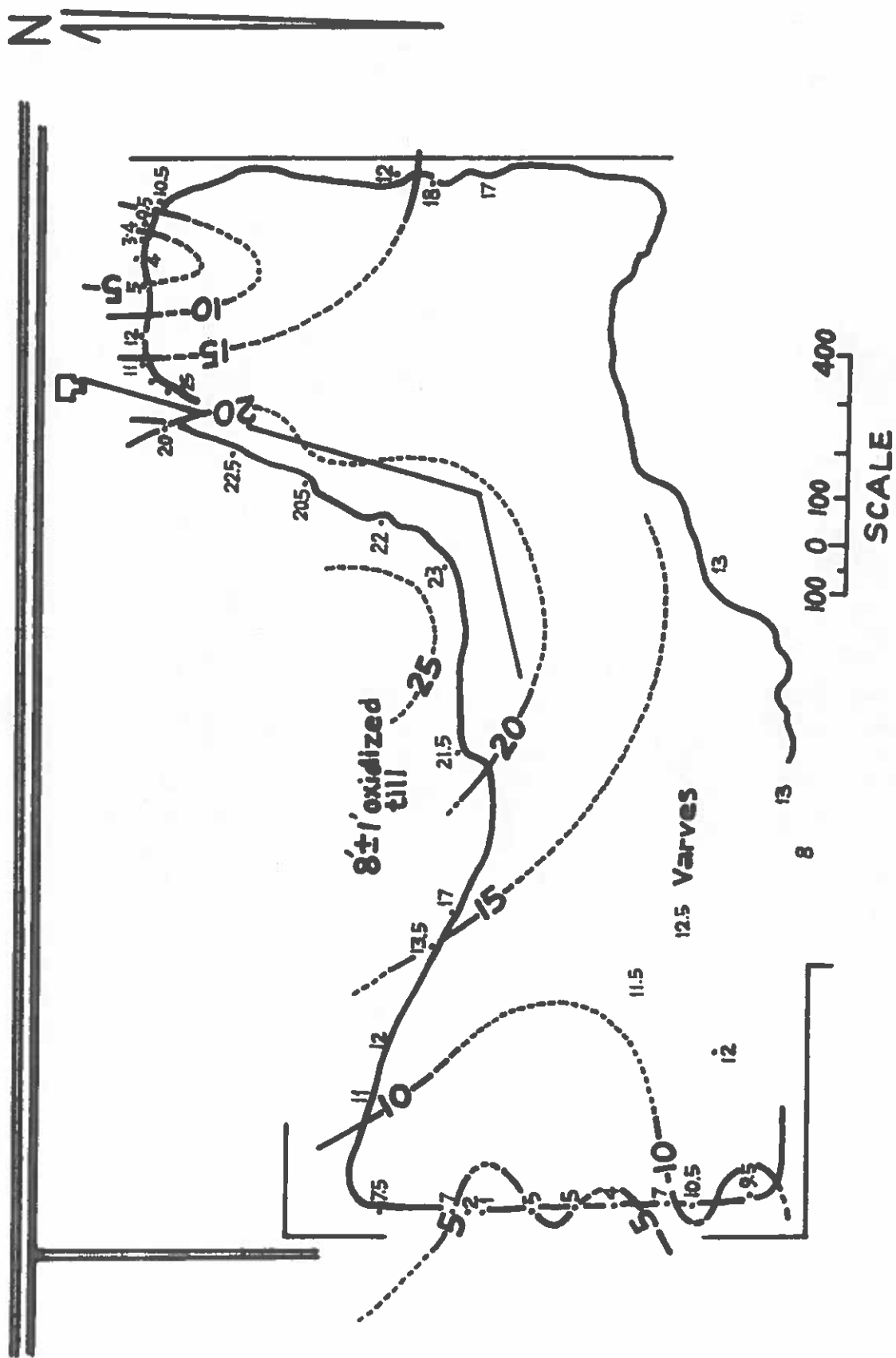
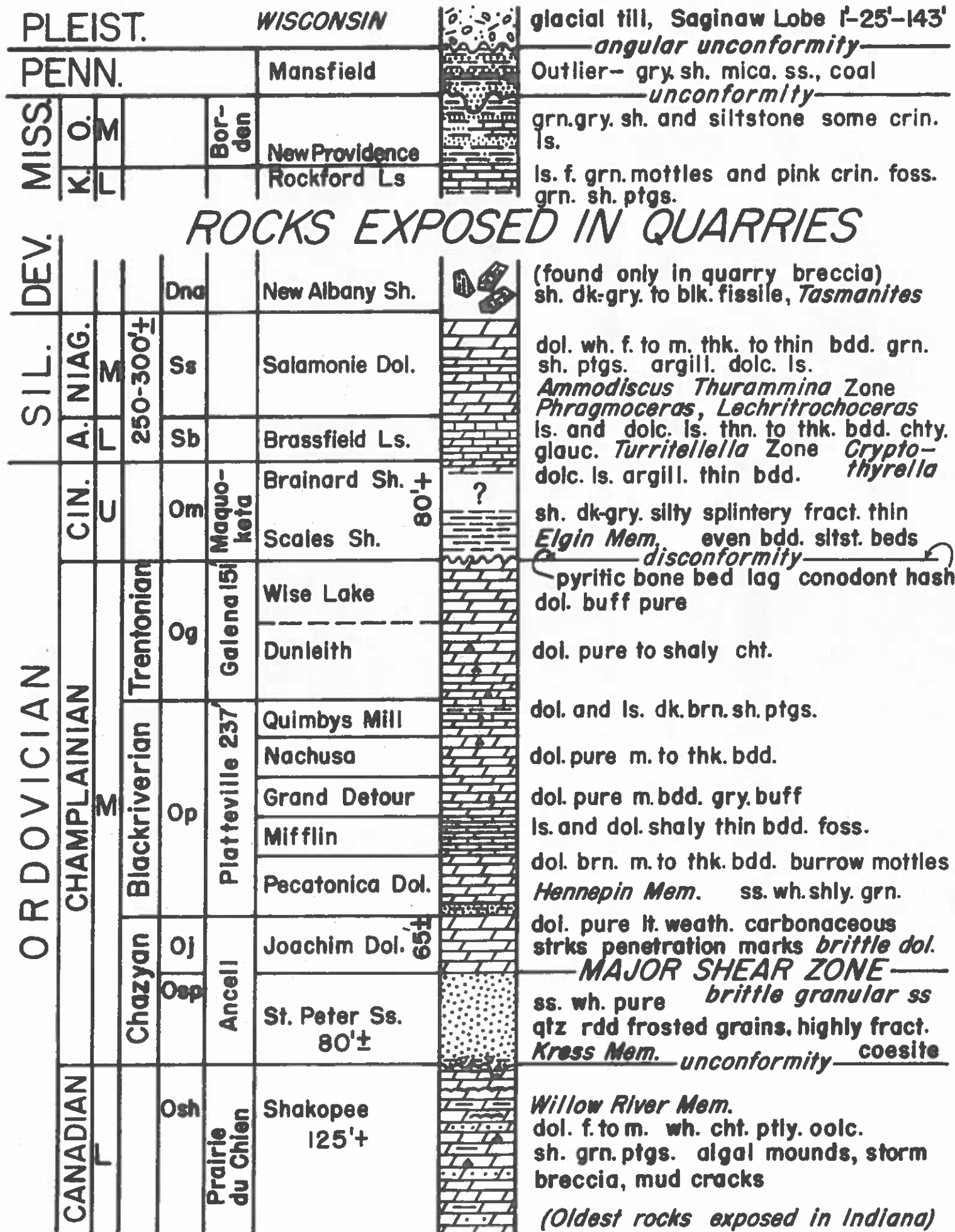


Fig. 11 ISOPACH MAP OF GLACIAL DRIFT

# MANTLE & BEDROCK IN AREA

Fig. 12





It is suspected that algae must have played an important role in forming this carbonate sediment. Some beds alternate in shades of pale green to light tan so that the grouping is useful for recognition of the Joachim. This is especially noticeable in the upper 10 feet of the formation and when the rocks are wet as after a rain.

Platteville Group- This sequence is well exposed, the units are fairly distinct, and they are well documented by Shrock, 1937; Ziemba, 1955; and Templeton and Willman, 1963, 1971. The distinctive basal green sandy Hennepin Member, 6 feet thick, separates the Platteville from the underlying Joachim Dolomite. Bedding slab exposures of the Hennepin layers stand out because of bleeding limonite streaks from weathered pyrite-marcasite crystalline concretions. Otherwise the Hennepin consists of white quartz sandstone with much interbedded green clay and shale irregularly bedded. The lower Platteville Pecatonica Fm. is brownish-gray, thick-bedded dolomite sharply separated from the overlying Mifflin Fm. which is light-gray, very fine grained, thin-bedded limestone or dolomite that contains green or brown shale partings. The Grand Detour and Nachusa Fms. consist of pure, medium- to thick-bedded dolomite and some limestone. Chert may also be present. The Quimbys Mill Fm. at the top of the Platteville Group is very fine grained, thin- to medium-bedded dolomite and limestone with dark brown shale partings. There are a number of key lithologies which help to determine position within the group. The Platteville-Galena contact can usually be placed within a few feet but it is transitional and not sharp. Templeton and Willman give a thickness of 237 feet for this group.

Galena Dolomite- The Galena Dolomite is light brownish-gray, medium- to thick-bedded dolomite and dolomitic limestone with characteristic rusty buff weathering. Textures, structures, and fossils seem to be altered due to diagenetic changes. White chert in the form of nodules and layers are present in some units. The dolomite surface develops gypsum efflorescence upon exposure. The upper contact with the overlying Maquoketa Shale is very sharply marked by disconformity. Sulphides have formed along the contact which develops into a conspicuous iron stained interval upon weathering of the pyrite. A thin (1"±) lag bone bed of rounded polished phosphatic bone and teeth fragments is found along the unconformity. The Galena Group is divided into several formational units by Templeton and Willman, 1963; however these are difficult to distinguish in the Kentland quarry. They assign a thickness of 151 feet to this group.

Maquoketa Shale- The lower part of the dark gray silty basal Scales Shale is well exposed along the ramp and conveyer belt in continuity with the Galena Group. Thin (>6") even beds of hard siltstone are interbedded with the shale and serve to delineate the structure within the member. A blocky fracture has developed in these rocks and the shale becomes splintery when weathered. The north wall on the west end of the syncline follows the Galena-Maquoketa contact and exposes the lower part of the shale.

The uppermost Maquoketa Brainard Shale is exposed in the south and west walls of the southwest part of the quarry. It is dove-gray, thin-bedded, argillaceous dolomitic limestone with shale partings. Before backfill, a continuous exposure of upper Maquoketa and Brassfield rocks revealed the contact between them. This seems to be slightly transitional change yet there is a thin (<1") brecciated sandy zone of separation.

The middle portion of the Maquoketa Group is not exposed anywhere in the quarries. The upper part is involved in faulting along the west wall where it has a striped appearance.

Brassfield Limestone- Enlargement of the quarry to the southwest south of the Kentland Quarry Fault and narrow belt of downfaulted dark Maquoketa Shale exposed a block of Silurian rocks. The west wall in the southwest part of the quarry has a continuous north dipping sequence of the lower half of the Silurian generally present in this area. The Brassfield is in contact with the top of the Ordovician although it is no longer exposed. This lower Silurian consists of rusty earthy weathered dolomite, thin-bedded, with white chert nodules. Above this the rock is dolomitic limestone in thicker, even-bedded layers. There is some pink crinoidal limestone, green shale partings, pyrite, and glauconite. Insoluble residues of these rocks contain arenaceous foraminifera of the Turritella zone characteristic of Lower Silurian age. The section is continuously exposed into the overlying Middle Silurian units.

Salamonie Dolomite- The rocks are light colored dolomitic limestones with green shale partings. Residues contain abundant Ammodiscus and Thurammina. Nautiloid cephalopods Phragmoceras and Lechritrochoceras are found also so that this fossil association is typical of Niagaran age rocks. Northwards in this section the rocks become more massive and they are involved in faulting so that it is not too clear whether there is more Silurian above the Salamonie beds. There is more than 200 feet of Silurian rocks exposed in this southwest quarry reentrant. Operations to the west may clarify this relationship within the middle portion of the Silurian. The upper part of the Silurian section and the lower part of the Devonian is not present in quarry exposures.

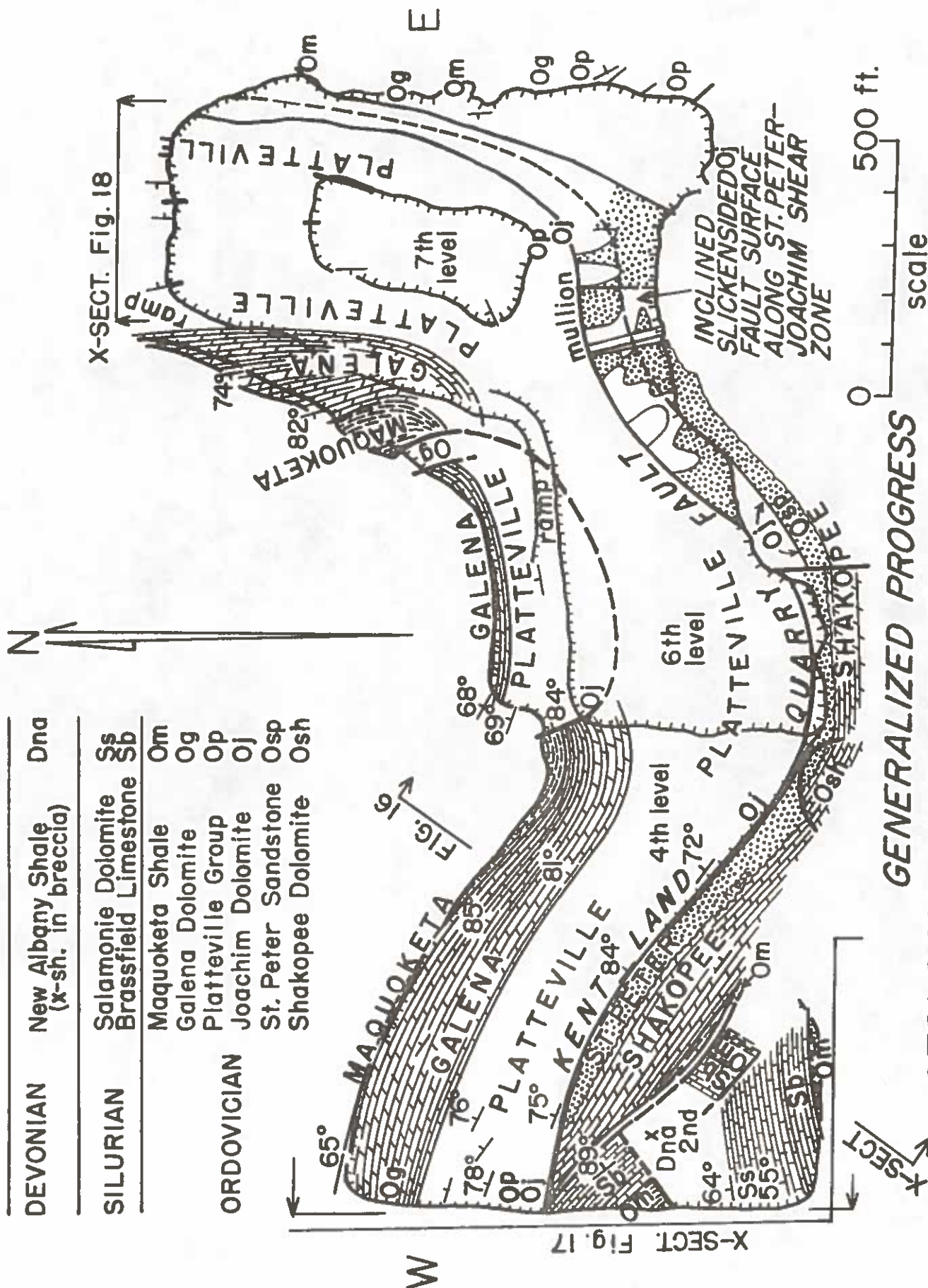
New Albany Shale- Although there is no known exposure of layered Devonian strata in the quarry, stromatoporoids chunks and dark-gray to black, bituminous shale clasts with Tasmanites occur in the fault breccias. The shale pieces are laminated with some reenish-gray layers. These can be found in the debris between levels 1 and 2 in the southwest part of the quarry. While the shale superficially resembles the dark Maquoketa shale, differences in texture, presence of Tasmanites, bituminous odor, and the thermal (D.T.A.) properties of each enable separate recognition of each shale.

Stratigraphy (outside of quarries)- The normal bedrock succession present in the Kentland area from the oldest to the youngest includes Upper Devonian New Albany Shale, Lower Mississippian Rockford Limestone, and rocks of the Borden Group. These may be beneath Pennsylvanian Mansfield Sandstone. This area is at the feather edge of the erosional retreat of the Pennsylvanian so that outliers or remnants are preserved in structurally downwarped or erosional channel situations. One such channel sandstone body is exposed in Fountain Park northwest of Remington, Indiana. Micaceous sandstone and shale associated with coal fragments have been recovered from beneath the drift in 3 shallow drill holes surrounding the Kentland structure, Fig. 2.

Paleozoic bedrock is completely veneered with Pleistocene Wisconsin glacial till which varies in thickness from 1 foot at the quarry to 143 feet in the ring syncline surrounding the quarry. To the south in adjacent Benton County, thickness of drift increases where it fills in the ancient pre-glacial Teays River valley system. Bedrock striations at the quarry are consistently S. 20° W. and there is one 4 foot diameter boulder in the till which has been overridden by the ice with a striate faceted top surface which also has S. 20° W. striae. This directional property fits the pattern of ice cover from the Saginaw Lobe.

*Glacial Till*

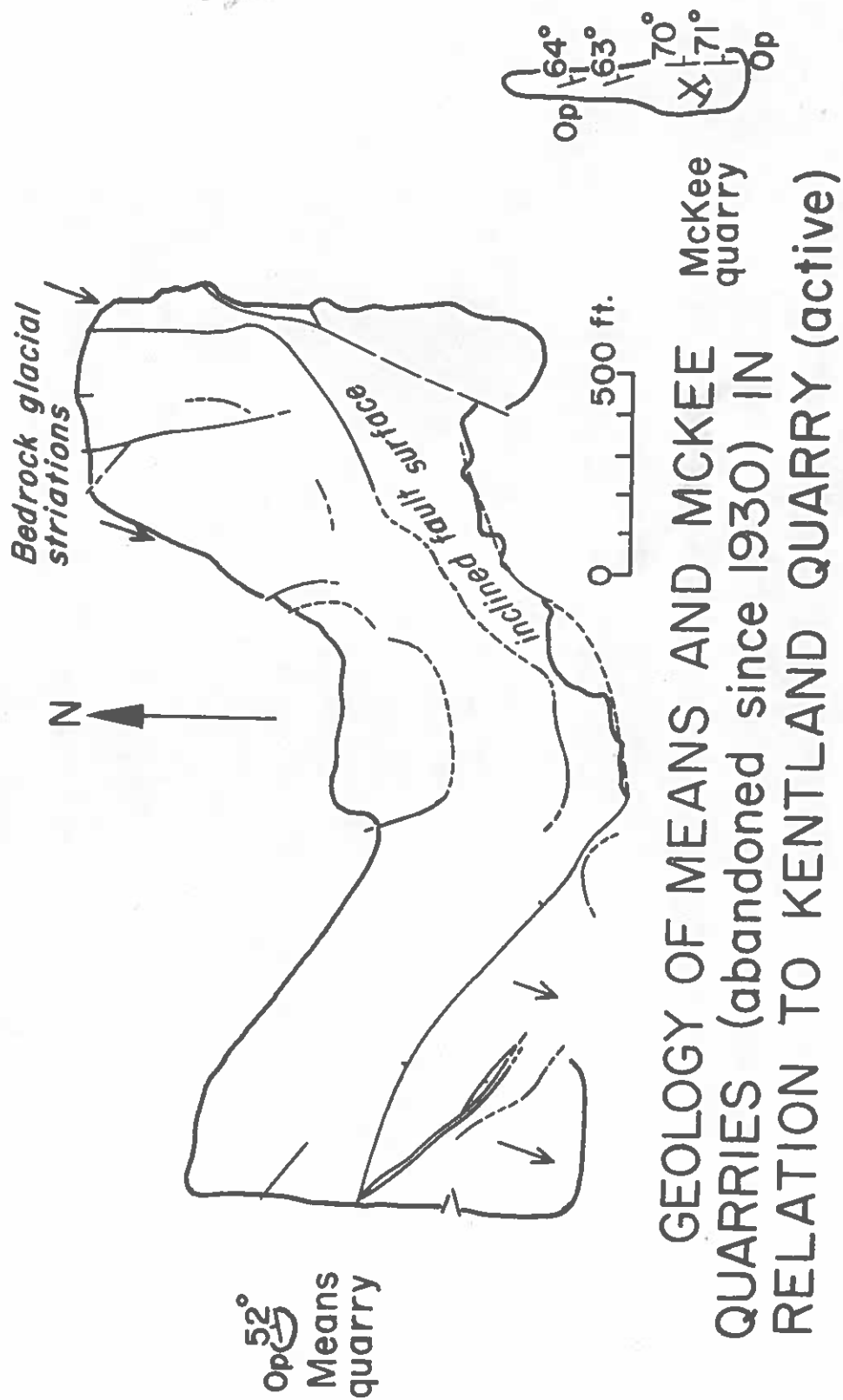
DEVONIAN	New Albany Shale (x-sh. in breccia)	Dna
SILURIAN	Salamonie Dolomite Brassfield Limestone	Ss Sb
ORDOVICIAN	Maquoketa Shale	Om
	Galena Dolomite	Og
	Platteville Group	Op
	Joachim Dolomite	Oj
	St. Peter Sandstone	Osp
	Shakopee Dolomite	Osh



GENERALIZED PROGRESS  
GEOLOGIC MAP OF KENTLAND QUARRY

N.D. 10-70 R. Gutschick  
11-72

Fig. 13



GEOLOGY OF MEANS AND MCKEE  
 QUARRIES (abandoned since 1930) IN  
 RELATION TO KENTLAND QUARRY (active)

Geologic Structure (in quarries)- The horseshoe-shaped outline of the quarry, Fig. 13, emphasizes the major plunging synclinal fold and the parallel Kentland Quarry Fault. Plunge of the fold is steeply to the NNW and the fault dips steeply to the north with the hanging wall up. Quarry operations closely follow the carbonate beds of the Platteville and Galena Groups. These are the best quality rocks. Faulting has duplicated these particular carbonate beds in the central and northeastern parts of the large quarry. You will note then that for the most part the rocks are steeply tilted to the north throughout the quarry.

The deep northeastern portion of the large quarry was the site of original initial quarry operations in which it was deepened with time. The report by Shrock in 1937 was based on the first level operations. Geological study by Boyer in 1953 was based on the 2nd level progress. Subsequently the quarry has been deepened to the 7th level which serves as the sump and it has been expanded. Earliest development took place in the NE $\frac{1}{4}$  NW $\frac{1}{4}$  NE $\frac{1}{4}$  of section 25 with expansion to the southwest in the SW $\frac{1}{4}$  NW $\frac{1}{4}$  NE $\frac{1}{4}$  area. During the past few years deepening of the eastern part of the quarry was suspended while the westward expansion was developed into the NE $\frac{1}{4}$  NW $\frac{1}{4}$  of the section. Quarry operations concentrated on the exploitation of the Platteville and Galena carbonates. The south wall of the quarry was formed along the Kentland Quarry Fault with St. Peter Sandstone on the footwall and the north wall was stopped short into the upper part of the Galena Dolomite in order to support the north dipping Maquoketa Shale. To the west fault geometry cut off the St. Peter Sandstone and carbonates of the Shakopee Fm. and the Silurian units were encountered south of the fault. These were quarried southwestward into the corner of the property where the top of the Maquoketa Group was encountered. Deepening in this part of the quarry was curtailed because the quality of the rock is not as good as the Mid-Ordovician carbonates. The latter make up the west wall of the quarry north of the Kentland Quarry Fault and these will continue to be exploited into the adjoining Means property.

The structure in the quarries is dominated by folding and faulting. The major structure is that of a steeply plunging synclinal fold with some suggestion of anticlinal continuation on either end. The western portion indicates change in strike of the beds and the Means quarry has rocks which dip to the northwest. Rocks in the abandoned McKee Quarry to the east dip eastward, Fig. 14. Other evidence of folding is present in the southwest corner of the quarry where the Maquoketa and Silurian rocks are tilted into a broad openly plunging anticline with faulted limbs. Along the north wall of the northeast part of the quarry, there is a plunging anticline but this may be due to drag related to complex faulting, Fig. 18.

Faulting is present throughout the quarry on a grand scale. The major fault structure which dominates the geometry is the Kentland Quarry Fault. This zone extends throughout the quarry and is folded along with the beds. It dips steeply to the north, northeast, and northwest. Thickness of the Platteville-Galena carbonates increases considerably in two places by fault duplication. In the central part of the quarry close to the axis of the plunging fold, there is a double section of Mid-Ordovician carbonates. This is probably due to a nested fault which drops a block of Platteville-Galena to the north along the axis of the fold. The structure in the northeast part of the quarry is complicated by faulting which duplicates the Platteville Group, Fig. 18.

East of the Kentland Quarry Fault zone along the east wall of the quarry there is faulting which puts Mid-Ordovician rocks along this wall. These seem to be structurally compatible with the same rocks in the McKee Quarry to the southeast. Unfortunately the reentrant to the southeast in the large quarry which at one time exposed the Platteville-Galena section is now backfilled and covers these rocks.

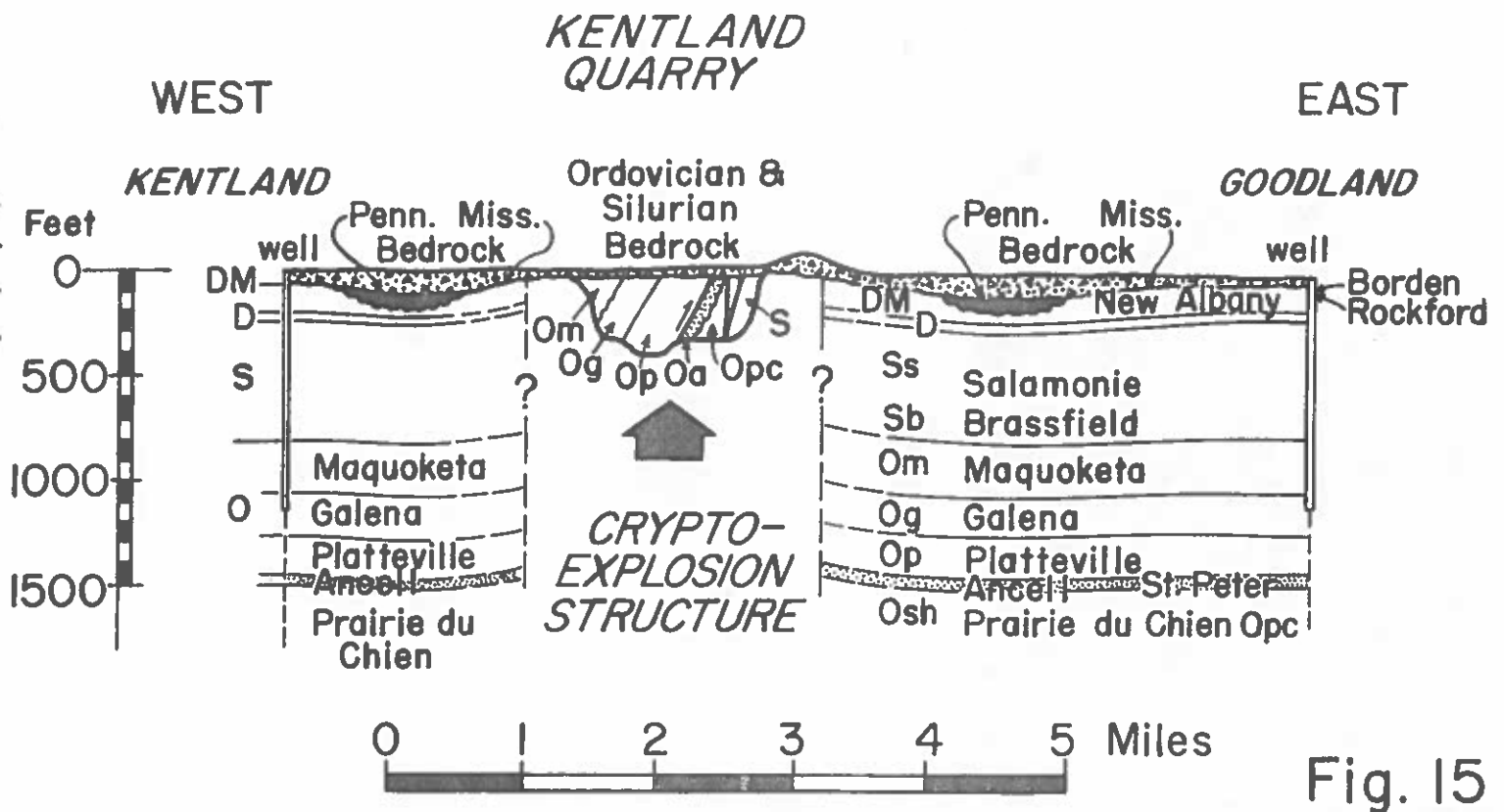


Fig. 15

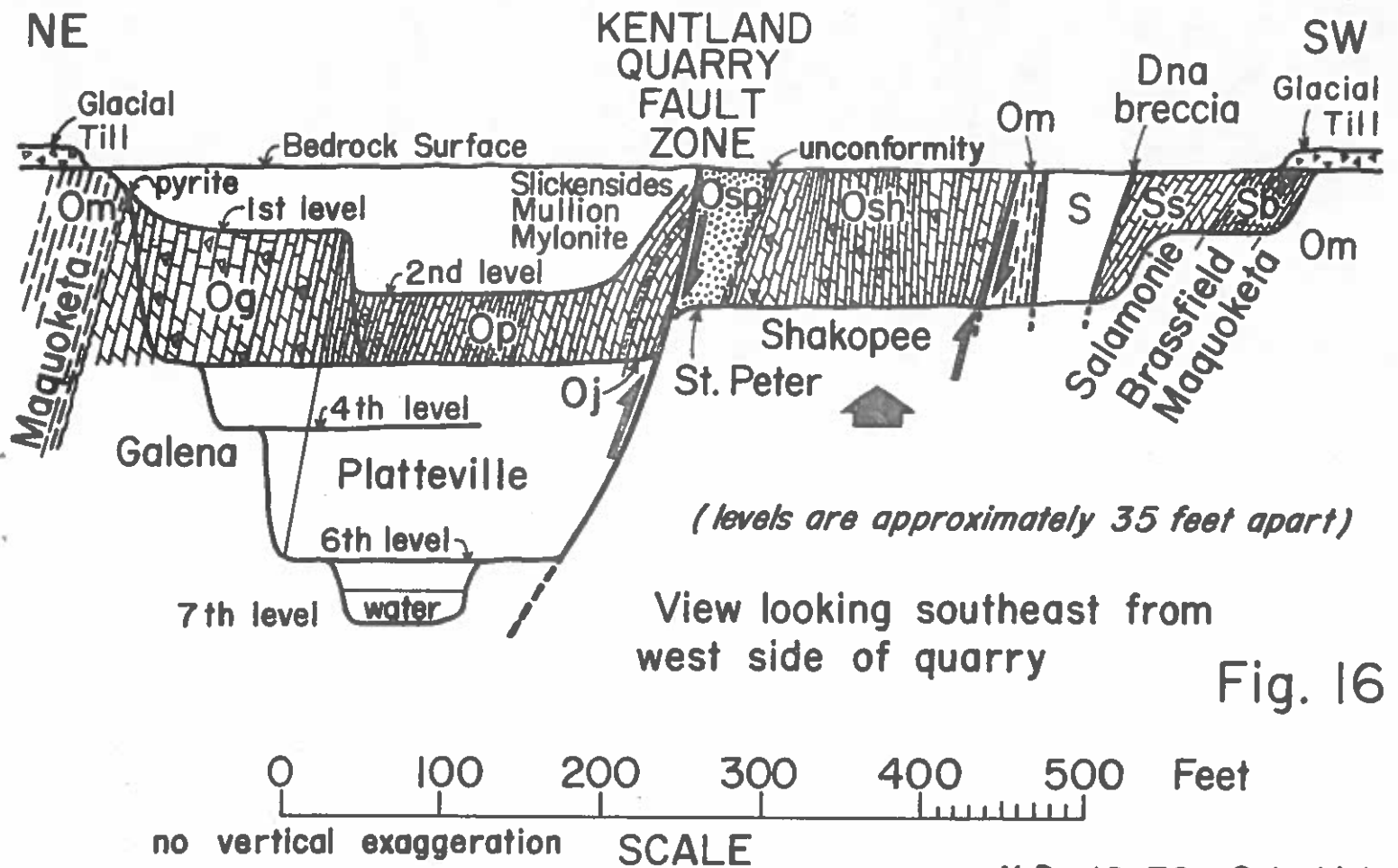
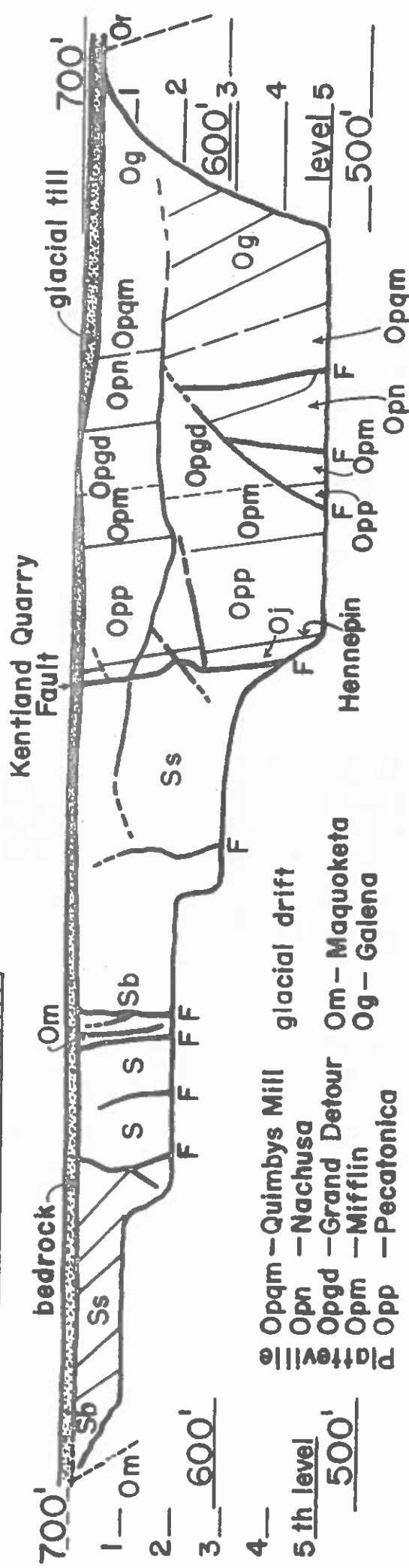
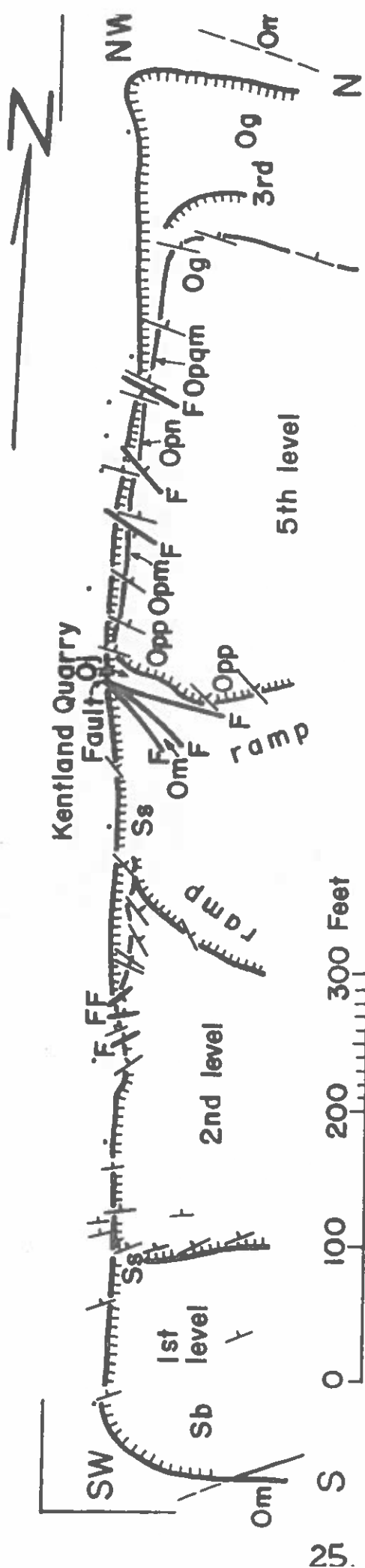


Fig. 16

# Old Means Quarry



Ss - Salamonie  
Sb - Brassfield

Opqm - Quimbys Mill  
Opn - Nachusa  
Opqd - Grand Detour  
Opm - Mifflin  
Opp - Pecatonica  
glacial drift  
Om - Maquoketa  
Og - Galena

VIEW LOOKING WEST

no vertical exaggeration

GEOLOGIC PROFILE OF WEST WALL

Fig. 17







In the central one-third of the quarry which includes the axial portion of the main syncline, there is a symmetry on both sides of this axis with respect to the stratigraphy and structure. Along the NNW plunging axis, the Shakopee is exposed high on the south wall and the Joachim, Platteville and Galena succession is repeated by a peculiar crescentic, nested fault mentioned above. Both flanks of this fault are transverse to the stratigraphy while the central axial portion is parallel to the strike of the beds. The fault surface is in the form of a plunging syncline somewhat parallel to the major syncline. One interpretation of this structure is that the fault is a normal dip-slip fault with the north hanging wall block down with respect to the south foot wall. Based on the geometry of the strata and the faults, this requires a large amount of throw and especially net slip. High on the south wall, there is an overhanging cornice of hanging wall which is transversely faulted close to the axis of the fold. This remnant contains upper Joachim and lower Platteville strata.

The southwest part of the quarry is a complexly interesting one. It exposes the oldest rocks in the quarry along with the youngest rocks, Shakopee Dolomite and Silurian Salamonie Dolomite respectively. The footwall of the Kentland Quarry Fault consists of the Shakopee-St. Peter sequence. This is separated on the south from the Silurian block by a narrow linear wedge or sliver of dark Maquoketa Shale. The plunging anticline of Maquoketa-Silurian rocks south of this shale wedge has faulted limbs which have been rotated towards the axis of the fold. As a result, there are three blocks to this structure. Breccias at the intersection of the bounding faults of these blocks contain chunks of dark gray Upper Devonian New Albany Shale with Tasmanites. This is the youngest Paleozoic lithology recognized in the quarry.

Kentland Quarry Fault- The Kentland Quarry Fault which winds its way throughout the quarry is really a fault zone. The main shear is crisp and sharp within parts of the brittle, granular upper St. Peter Sandstone and the tenaciously tough, brittle, aphanitic lower Joachim Dolomite. The fault surface is smooth, undulating, slickensided, chattered, and has mullion structure well developed. The surface is generally in the form of a broad open plunging syncline; however there is a pronounced anticlinal bulge to the east of the axis of the syncline and a more gentle reverse curvature to the west. The fault is a steep reverse fault which dips around 75° northwards.

Perhaps the most impressive sight in the Kentland quarry is the magnificent continuous exposure of the smooth fault surface. The east wall displays a smooth undulating fault surface generally in the Joachim Dolomite. Quarry extraction is bounded on the east by this surface. Mullion and slickensides are strikingly evident on the anticlinal surface in the SE part of the quarry and also in the western part. The rusty white St. Peter Sandstone makes up a large surface immediately east of the main synclinal axis, and the west limb has a remarkable display of the surface accessible for detailed examination.

Movement of the hanging wall was dip-slip along the axis of the fold and oblique slip on the flanks. The obliqueness increases progressively westwards on the west flank of the structure indicating greater movement of the hanging wall inward towards the axis of the syncline. The east flank also has oblique slip towards the axis. Although the main movement of the fault was reverse with hanging wall up with respect to the footwall, apparently late relaxation of compression caused normal fault slippage. Slickensides indicate this last imprint on the fault surface. Mortar-like breccias are present along the entire length of the fault.

Another important feature of the Kentland Quarry Fault is the nature of the hanging wall adjacent to the fault, that is, where it is preserved and can be observed. The rocks within about 50 feet from the fault have been broken up by faulting. Oblique slip along the flanks of the synclinal fold has caused these parts to be jostled around with their strike oblique to the main fault. Remnants of the hanging wall high on the east side of the exhibit this very well. The easily recognized Hennepin key beds of rusty limonite-dripped bedding surfaces are duplicated 3 or 4 times in small blocks oblique to the main fault surface. Another block along

the ramp in the west portion of the quarry has a slickensided, mullion surface oblique to the main structure as part of the hanging wall.

It is difficult to calculate the total amount of movement along the Kentland Quarry Fault. The fault has very low obliquity with the bedding and it comes between stratigraphically adjacent or superposed strata- the St. Peter Sandstone and the Joachim Dolomite. Faulting within the quarry has cut out the upper part of the St. Peter Sandstone and the lower part of the Joachim Dolomite so that nowhere in the quarry can the thicknesses of these formations be measured. This relationship is illustrated in Fig. 16. Because of the near parallelism of the fault surface with the bedding especially in hanging wall carbonate beds and the variation in observed attitudes of these surfaces, it is even difficult to approximate the amount of displacement. Even though the stratigraphic throw is very small, the net slip must be reasonably large and significant.

Other Structures- There is one exposure of a low angle thrust fault along an old abandoned ramp on the south side of the quarry west of the fold axis. Shakopee Dolomite and St. Peter Sandstone in normal succession is moved northwards along a south-dipping fault surface. Stratigraphic displacement is less than 50 feet.

Slices and patches of dark Maquoketa Shale crop out in scattered places in the quarry east and southwest of the Kentland Quarry Fault. This refers to structurally displaced masses rather than the normal sequence along the north wall of the quarry. The small patches are wedged between faults or caught up between blocks along the fault surface so that their distribution is somewhat random.

Kentland Breccias- Throughout the quarry, faults, fractures, and fissures are filled with mortar-like breccias. The matrix is light gray to gray, fine-grained material and the clasts range in size from sand size to pieces greater than two feet in diameter. Larger blocks may be present. Fragments consist of limestone, dolomite, chert, dark-gray and light-green shale, fossil chunks (e.g. stromatoporoid heads 6" diameter of Silurian affinity), quartz grains, sulphides, and other materials. The clasts seem to be obviously derived from strata exposed in the quarry rocks. The nature of the breccias and their distribution, Fig. 19, gives one the intuitive impression that there was extensive pulverization of rock and dilation of volume accompanying catastrophic disruption of strata to grout the material into openings prior to and during collapse and settling of the blocks. Perhaps fluids may have also played some role. The similarity of the breccias throughout the quarry suggests that they had some common source.

Shatter Cones- The Kentland quarry is perhaps the type "shatter-cone" locality in this country. It was here on the basis of shatter cones that Dietz in 1947 noticed their preferred upward orientation and suggested meteorite impact. These structures are present in many places throughout the main quarry and also in the abandoned McKee quarry. Throughout quarry operations, examples have been found and reported only to be removed. They occur in just about every lithology and formation in the quarry although they are not found everywhere. Striking examples have been seen and photographed in the Joachim Dolomite, Platteville Group, and Maquoketa Shale. Generally the finer and denser the rock, the better the chance for shatter cones. Most commonly they are small, only a few inches in height; however very large ones have been observed, up to several meters. Examples are scattered in the quarry but swarms of small ones are present in Silurian carbonates in the southwest part of the quarry. Observations over the years indicate that most of the shatter cones point upward stratigraphically; yet there are some that point in both directions. Preferred orientation data has not been systematically plotted yet.

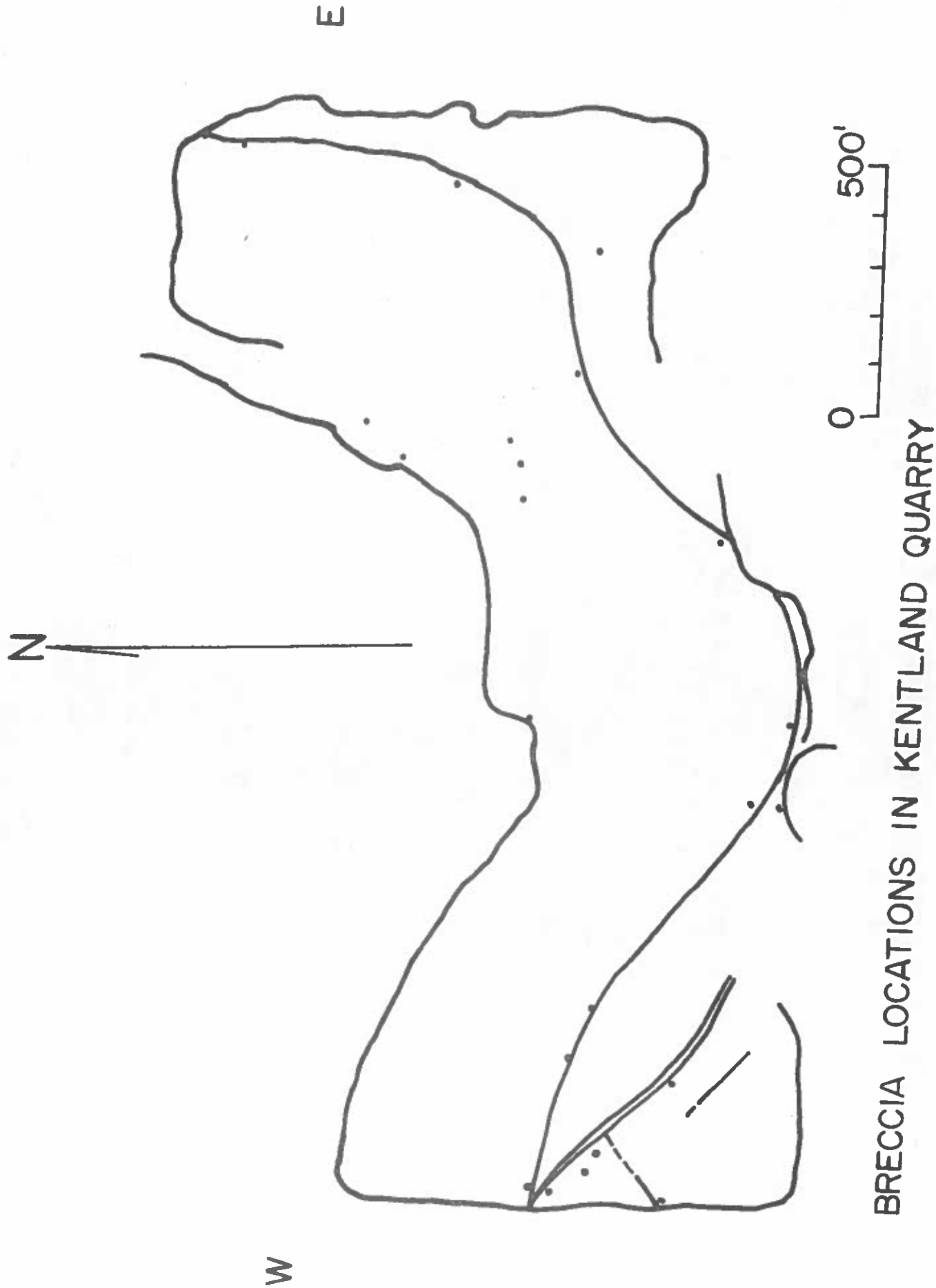


Fig. 19

Geophysics- A detailed geophysical study of the Kentland disturbed area has recently been made by Tudor et al, 1972. Many shot holes were drilled to bedrock which will furnish more information on the nature of bedrock geology. The following abstract is taken from their 1972 presentation.

"A geophysical survey and drilling program in the Kentland disturbed area, a drift-covered cryptoexplosion structure in northwestern Indiana, has provided new information bearing on the areal extent, form, geologic age, and the origin of the structure. The areal extent is interpreted from a detailed gravity survey consisting of more than 2600 closely spaced stations which shows the outline of the disturbed area to be subcircular with a maximum radius of approximately four miles. The deformation is interpreted as being typically cryptoexplosive with a central uplift of intensely fractured older rocks raised more than 1500 feet surrounded by at least one ring syncline at a radius of two miles, and a ring anticline with approximately 50 feet of structural relief at a radius of four miles.

A gravity positive anomaly of 3.5 to 4.0 milligals has a maximum depth to source of 7800 feet, and shows a mass excess. Three-dimensional gravity modeling suggest a basement uplift of 2000 to 3000 feet. The ring syncline is best displayed on the gravity residual from the sixth degree polynomial surface which shows a negative anomaly of 1.0 milligals. The interpretation of the negative anomaly is supported by two dimensional gravity modeling. An encircling outer positive anomaly of less than 0.5 milligals and a coincident low relief, structural high are the basis for interpreting the ring anticline.

The disturbance is interpreted as a cryptoexplosion structure because neither a cryptovolcanic nor a meteoritic impact origin can be demonstrated unequivocally."

Uplift of the sedimentary Paleozoic rocks in the quarry of 1800 feet and the indication from gravity information of an uplifted basement 2000 to 3000 feet suggests that the disturbance is deep seated. The magnitude of the uplift does not seem to diminish with depth.

Simple-minded Explanation of Dynamics of Disturbance- The oldest rocks are brought up in the central uplifted area where the dilation becomes greatest. High energy concentration in a short time span causes pulverization, brecciation, fracturing, faulting and centripetal transfer followed by ring collapse of the central area and synclinal depression of the surrounding area. Kentland quarry is the south part of this central collapse in which rocks are rotated vertically, e.g., the oldest Shakopee Dolomite and younger beds are brought up and tilted to the north. During this rotation, there is differential gliding of the rock layers one over the other as the mass is pitched northward. Shear failure takes place in the mechanically granulated rocks and the dense brittle beds. Juxtaposition of such lithologies in the St. Peter Sandstone and Joachim Dolomite is the logical zone of weakness to produce the Kentland Quarry Fault zone. Rotation of the block to the north causes younger beds to ride up older ones. Shearing takes place along the St. Peter-Joachim contact with curved surface dipping north concave side up. Reverse faulting results from this pattern and final relaxation produces some gravity movement.

Conclusions- In assessing the geology of this structure in order to speculate on its origin, one is impressed with its geometry, major anomalous structural disruption in an otherwise undisturbed area, and the rock mechanics of deformation. Strata such as the oldest exposed in the quarry, the Shakopee Dolomite, is out of its normal stratigraphic position by as much as 1800 feet vertically, Fig. 15. The elliptically- to circular-shaped disturbed area, Figs. 2 and 21, has a ring-shaped depression around an uplifted domed structure whose center is the Kentland quarry. The quarry exposes a somewhat semi-circular plunging syncline. Perhaps the quarry represents the south half of a central collapse structural depression. There is strong suggestion that a linear feature south of the quarry represents a fault which separates the disturbed area on the north from the undisturbed area south of it.

Folding and shearing are impressive in the central part of the disturbance exposed in the quarry. Fault surfaces are sharp and bold. Dense carbonates and granular quartz sandstone rocks are fracture shattered along the shear zone. Dense brittle rocks have shatter cone development throughout the quarry most commonly with their apex pointing stratigraphically upwards. There are some which point towards the bottom of the beds. Quartz grains are highly fractured and have deformation lamellae. Some fractured quartz grains are offset in step fashion and then recemented. Asterism in the X-ray pattern has been reported by Simon and Dachille, 1965. Coesite has been reported by Cohen, Bunch, and Reid, 1961, from the St. Peter Sandstone in the southeast part of the quarry; however it is reported to be present in very low concentration. Closely spaced fracturing (jointing) is common especially in the St. Peter Sandstone adjacent to the faults. Breccias are associated with faulting throughout the quarry. There is also negative evidence, or the lack of it. Neither volcanic materials nor metallic meteorite fragments have been found, and of course, there is no strong reason to expect to find these.

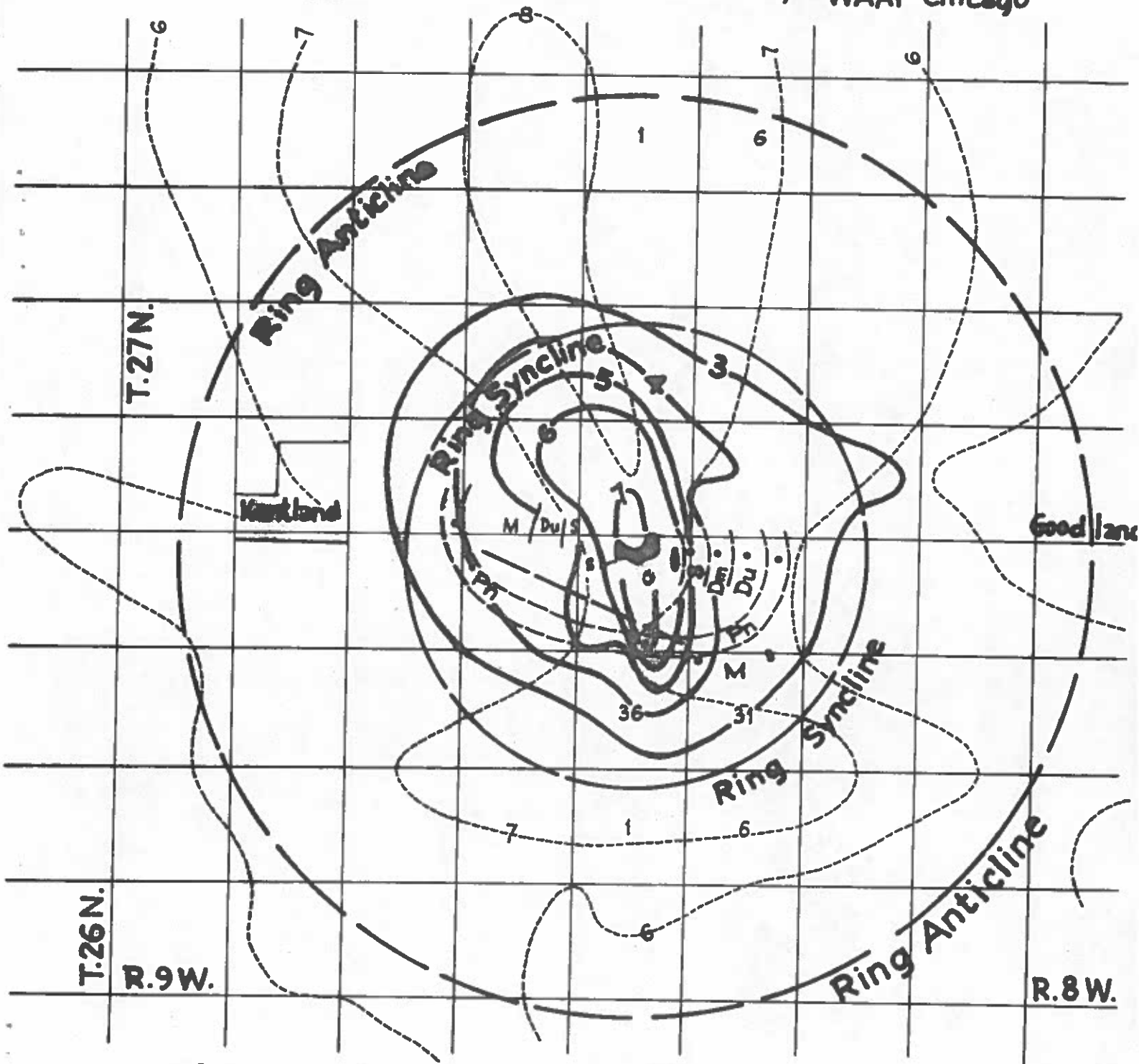
There are many interesting facets to the geology of Kentland and these include sedimentation, stratigraphy, paleontology, structural geology, mineralogy, petrology, petrography, rock mechanics, geophysics, geochemistry, and others. There are many problems and interesting projects which require perceptive observation, field and laboratory investigation, scientific judgment, and articulate exposition. There are many enigmatic and frustrating problems waiting for answers. Clearly Kentland structure and quarry exposures serve as a challenge and study for students.

Concerning its origin there are several possibilities which have not been resolved to complete satisfaction. Uplift and explosion caused by volcanism ("cryptovolcanism") in which gas-charged magmas pent up beneath a sedimentary cover blow out. This may include the basement and does not necessarily have to be accompanied by igneous extrusion. Diatremes are thought to have this origin. Another possibility is meteorite or comet impact. Much attention is being given to all aspects of this type of origin. Shattercones, breccias, and coesite along with structural dislocation all support this idea. Recent geophysical studies do not suggest decrease of energy with depth as would be required by impact origin. The presence of shattercones and reported coesite would cause one to expect the formation of glass due to shock metamorphism, Fig. 20. Neither solid- or liquid-state glass has been found. A third possibility is major faulting or intersecting fault disruption. Confining stresses and external forces may be built up in a small concentrated area to result in explosive release of the energy. This cannot be ruled out yet there is not enough known to substantiate such origin.

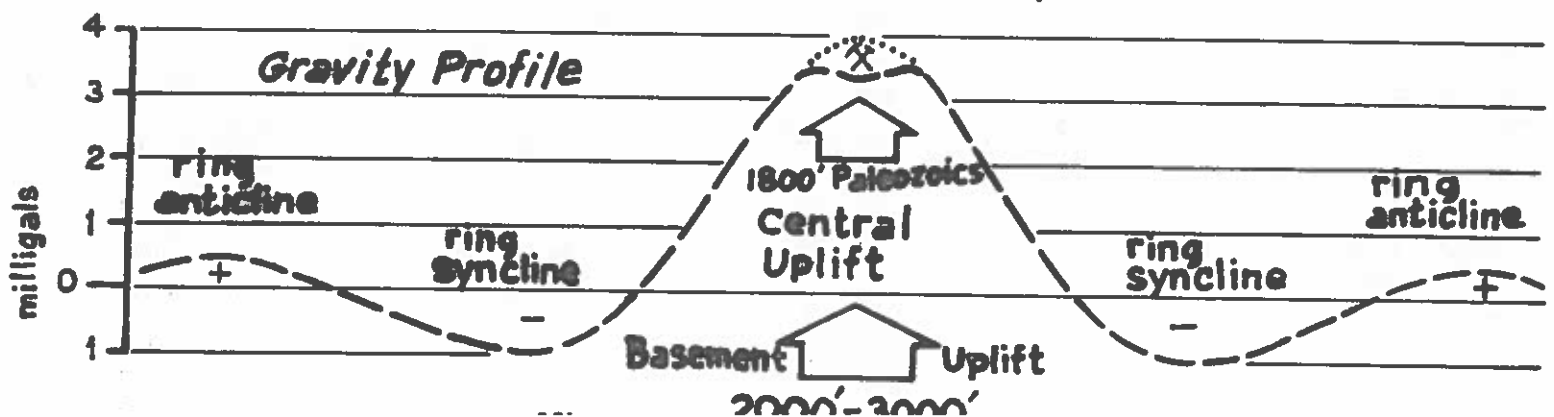
In summary, it is significant that geological and geophysical data has not proven the origin of this structure unequivocally. More information is needed.

**Radio Field Intensity Contour**  
(Pullen, 1953, p. 48, Fig. 29; p. 50, Fig. 30)

— 4 WIND Chicago  
- - - 7 WAAF Chicago



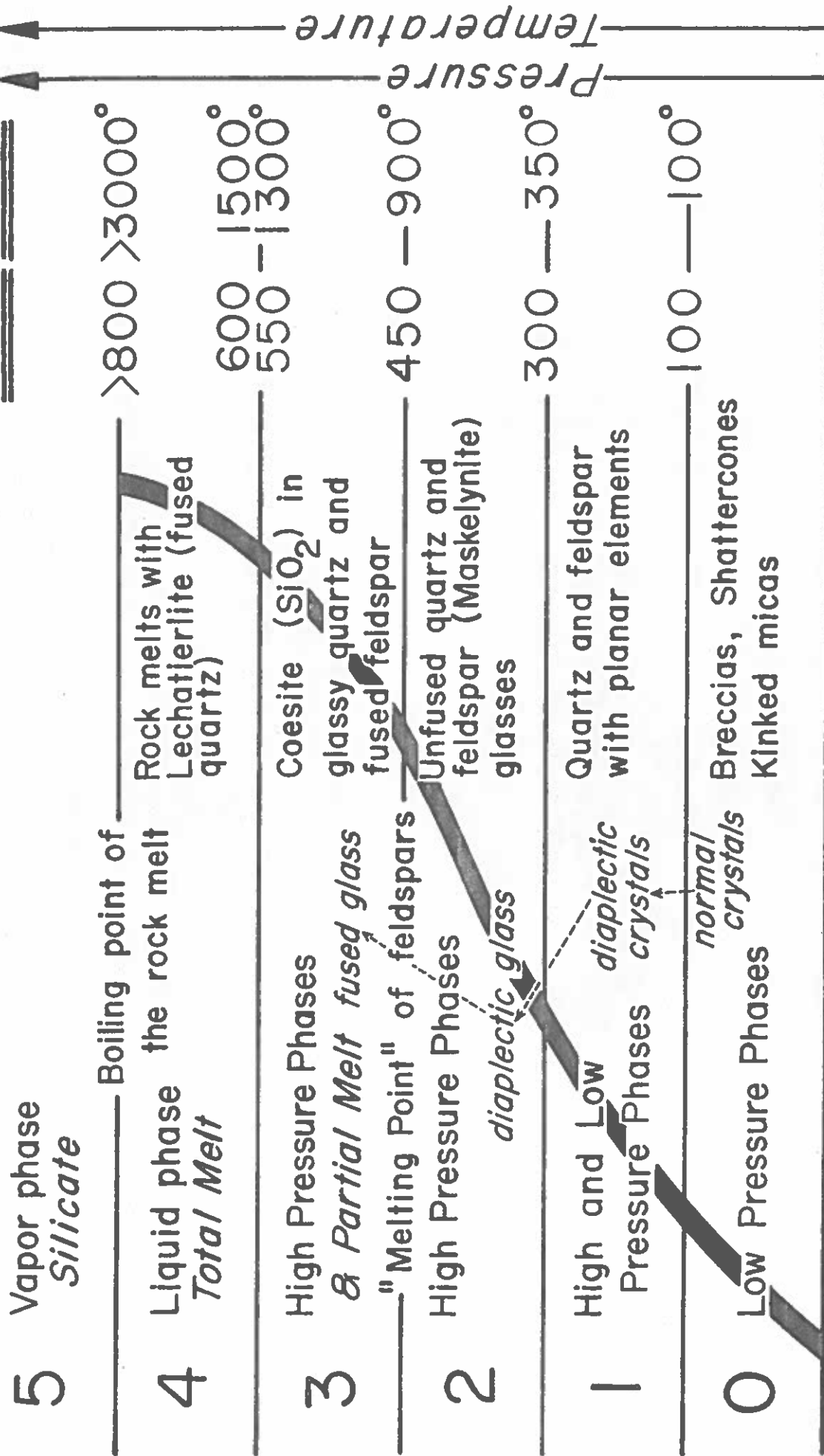
**Gravity Survey (Tudor et al, 1972, p. 353)**



# STAGES PRODUCTS

# EXAMPLES

Peak Post-  
Pres. shock  
(kb.) T. °C



post shock density

density within shock front

Fig. 20

Chao 1968  
after Stöffler 1971 & others



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Western Michigan University  
Department of Geology

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# KALAMAZOO 1976



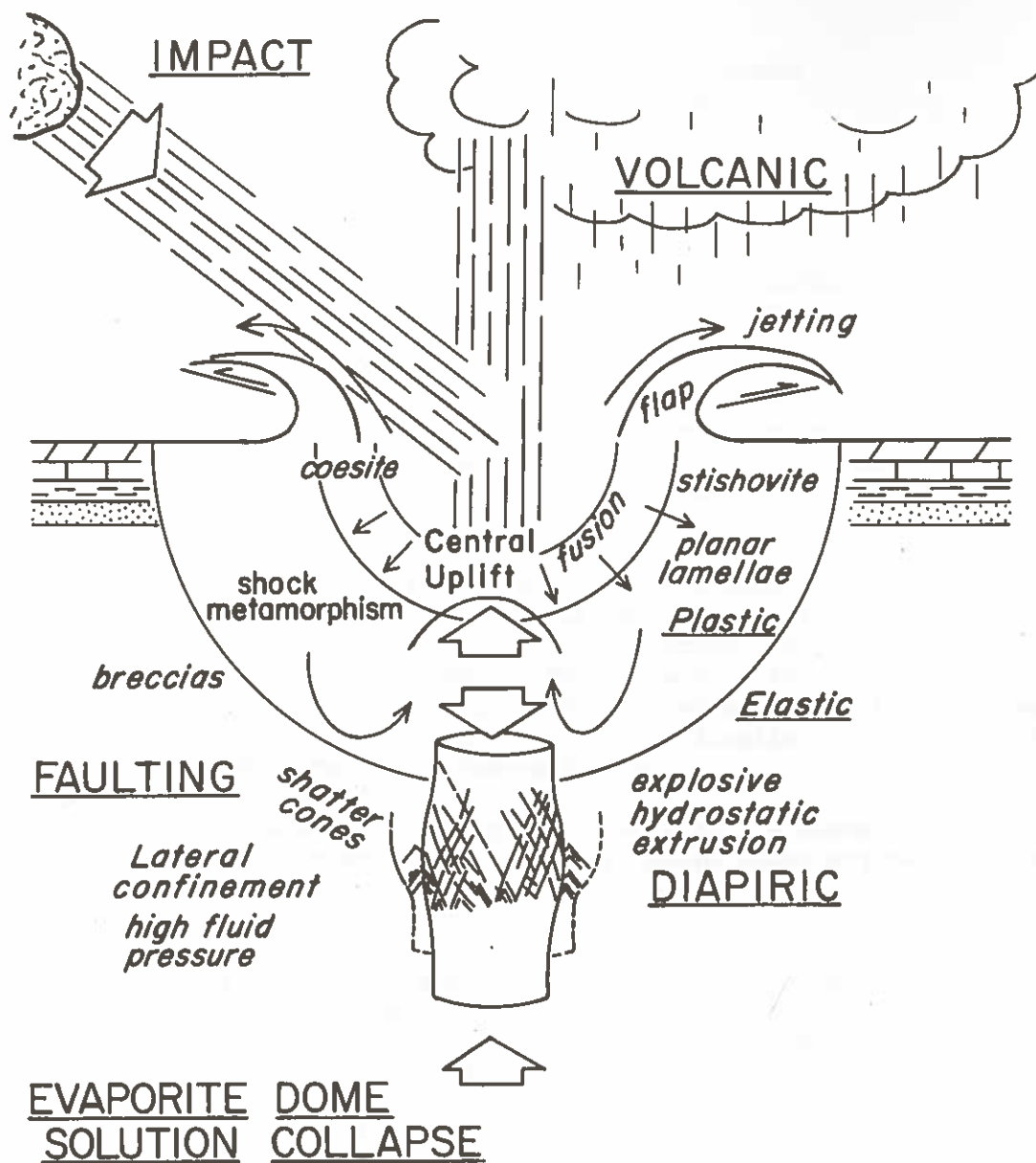
Geology of the Kentland  
Structural Anomaly,  
Northwestern Indiana

The Geological Society of America  
North Central Section

GEOLOGY OF THE KENTLAND STRUCTURAL ANOMALY, NORTHWESTERN INDIANA

Study for Earth Science Students

FIELD GUIDE



Raymond C. Gutschick  
Department of Earth Sciences  
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10th Annual Meeting, North Central Section, Geological Society of America  
Sponsored by the Department of Geology, Western Michigan University, Kalamazoo,  
Michigan. Field trip on Wednesday, April 28, 1976.

This field guidebook is dedicated

to

Dr. Robert Rakes Shrock  
Emeritus Professor of Geology  
Department of Earth and Planetary Sciences  
Massachusetts Institute of Technology  
Cambridge, Massachusetts

and

Dr. Robert Sinclair Dietz  
National Oceanic and Atmospheric Administration  
Oceanographic and Meteorological Laboratories  
Miami, Florida

Both Bobs derived immeasurable inspiration from the geology in the Kentland quarry which led to their contributions to the geology of cryptoexplosion structures and geology in general.

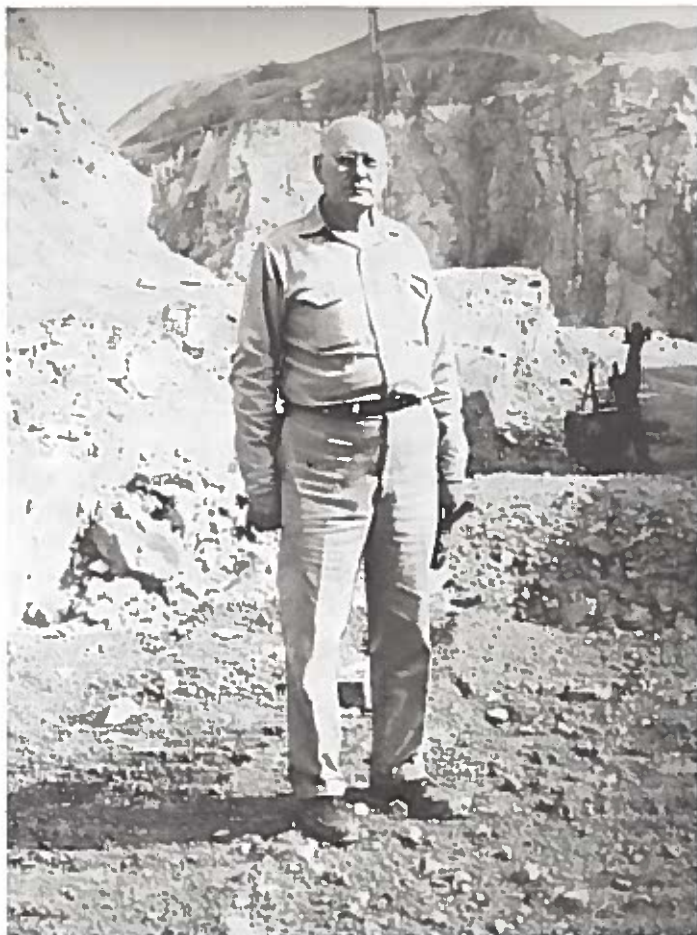
To Robert Shrock, field oriented geologist and paleontologist who put Kentland on the map with his early detailed study of the geology of this anomalous structure, for his fertile imagination, probing mind, and astute field observations, our thanks. The Society of Paleontologists and Mineralogists is also honoring him with the award of the Twenhofel Medal for 1976...Silurian bioherms, paleontology- index fossils, recognition of top and bottom of beds...Teacher...Administrator.

Photo- Bob Shrock at Kentland quarry...back to the scene of the mystery after more than 30 years, photo taken October 21, 1970.

To Robert Dietz, classmate and friend who in the 1940's related shatter cones at Kentland to impact origin and has subsequently searched the globe for related structures, for his bold imagination and courage of his convictions, our gratitude. His imaginative interpretation and predictions of the origin of the Sudbury structure is a classic example which undoubtedly germinated from his early interest in Kentland.

Photo- Bob Dietz at Kentland in they went that-a-way...shatter cones that is. Rock layers are carbonates in the Platteville Group along the north wall of the northeast part of the quarry.  
Photo taken November 7, 1959.





Robert Rakes Shrock

Robert Sinclair Dietz





## Foreword

The remarkable Kentland quarry is an especially valuable field laboratory for student study. One cannot overemphasize the unique opportunity available to observe various aspects of geology, in particular, structural detail which is seldom freshly exposed on this scale.

This guidebook represents a progress report on a current geological study of the quarries. Geological mapping has been done and is currently being done to keep progress with rapid quarry operations and stone removal. Geology of the westward extension is presented and represents unpublished information except for several short abstracts, the Indiana Geologists Fall, 1970 Guidebook, and the National Association of Geology Teachers East-Central Section Spring, 1971 Guidebook. A comprehensive report on the Geology of Kentland is planned and in preparation to be finished at the completion of the mapping.

The management of the Newton County Stone Company is especially proud of their efficient production and concern for safety in quarry operations. Through the cooperation and courtesy of Mr. Robert Prince, quarry manager, and his congenial staff, we are privileged to be their guests in having access to the geology in the large operating quarry.

We have certain responsibilities and cautions to carefully heed. Each visitor is required to register with his signature on a liability release form. It is imperative that we stay together as a group and avoid interference with regular quarry operations. In most places quarry walls are steep and hazardous so that good judgment and extreme care should be used in working close to or under them. This is most critical when they are wet as during and after a thaw or rainfall. Hard hats are required in the quarry and it makes good sense to use them. Be sure you take out of the quarry whatever you bring into it. Do not litter for the management wants to maintain a clean neat quarry. Collecting is permissible as is geological photography.

Quarry management recognizes the educational importance of such exposure as this to the geological field experience of students. Quarry operators go out of their way to cooperate; however, they do have trepidations concerning control of large size groups and potentially dangerous irresponsible behavior. Since the operation is privately owned and controlled and the privilege of entry can be revoked at any time, in no way do we want to jeopardize these friendly relations. We have an obligation to future geological groups to maintain continued access to the quarry.

Your cooperation is appreciated by everyone concerned.

### Acknowledgements

I am especially grateful to Mr. Robert Prince, general quarry manager of the Kentland operation and his staff for permission to geologize in the quarry and for their generous cooperation and encouragement over the years. This also includes Mr. William Davidson, quarry superintendent, Mr. Harrison Forrest, Mr. Edward Meader, Mr. Phillip Pettijohn, and quarry workers who have been very friendly and helpful on numerous occasions.

In 1939, Dr. Francis P. Shepard gave me my first opportunity to visit Kentland quarry on a structural geology field trip. The first comprehensive report on the quarries by Drs. Robert Shrock and Gilbert Raasch published in 1937 has been a constant source of valuable information. Dr. Shrock has generously given me all of his early field notes which has much information that is no longer available in the quarry. Dr. H. B. Willman of the Illinois Geological Survey identified the Ordovician stratigraphic units to me on a personal field trip to the quarry in 1961. This came at a time when Drs. Willman and Templeton's definitive Cahmplainian Series study was in progress and well advanced. Recognition of Ordovician units is the key to the structural geometry of the anomaly.

The Indiana Geological Survey through the Director John Patton, Dr. Maurice Biggs and Thomas Dawson furnished much information on the subsurface data of the region. Dr. Judson Mead and Dr. Dan Tudor shared new information from their extensive detailed geophysical investigation of the Kentland anomaly. Drill logs and cores from this project were also made available.

Besides the 1937 report of Shrock, I have the advantage of Dr. Robert Boyer's Master's thesis which outlines the status of quarry geology in 1953. A field visit to Kentland in 1961 with Drs. Robert Dietz and Eugene Shoemaker to examine shattercones was very rewarding. Important low altitude air photos were furnished to me by Dr. Erhard Winkler, Department of Geology, University of Notre Dame. These 1960 photos cover the eastern portion of the quarry which provided the base for the 1961 report. Additional photos were made from the stone quarry company helicopter in 1970 and 1975. Air photos and diapositives of quarry were furnished by the Indiana State Highway Commission.

There are a number of undergraduate students in Notre Dame's Geology Department who studied various facets of quarry geology as part of our undergraduate research participation program. I am grateful to Richard Lippincott for a study of shattercones, Terry Coyle, who studied Silurian foraminifera faunas, Fred Weaver's study of the Lower Ordovician Shakopee Formation, and Mike Plamondon's work on the breccias in the quarry. Francis Bellini helped with plane table mapping in the quarry.

My wife, Alice, helped me in many ways on numerous trips to the Kentland quarry in all seasons.

The abandoned McKee and Means quarries were referred to by Gorby in 1886 and the currently active McCray quarry by Ward in 1906. There has been continuous quarry activity during the past 65 years. During this interval of time, countless geologists and students have examined and puzzled over the origin of this enigmatic structure. Local residents have also contributed by permitting access to their lands. I express my pleasure for the exhilaration which must come to all those students of the earth who have seen Kentland and to the local people who have put up with us.

# Geology of the Kentland Structural Anomaly, Northwestern Indiana

## Study for Earth Science Students

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Abstract- The Kentland anomaly is a complexly deformed structure confined to a relatively small area (approximately 5 square miles) in an otherwise undisturbed region of flat lying bedrock. Within an 80 acre quarry, 1000 or more feet of Ordovician and Silurian strata have been rotationally uplifted as much as 1800 feet vertically. The region adjacent to the anomaly has Lower Mississippian and Pennsylvanian bedrock which dips less than  $1^{\circ}$  to the southwest. The entire area is veneered with Pleistocene Wisconsin glacial till from the Saginaw ice lobe.

Strata in the main quarry include Lower Ordovician Shakopee Formation (oldest exposed), Middle Ordovician St. Peter Sandstone, Joachim Dolomite, Platteville Group, Galena Group, Upper Ordovician Maquoketa Shale, Lower Silurian Brassfield Limestone and Middle Silurian Salamonie Dolomite. Late Devonian New Albany Shale with Tasmanites occurs in fault breccias.

Quarry operations for the past 50 years in the NW $\frac{1}{4}$  NE $\frac{1}{4}$  sec. 25, T. 27 N., R. 9 W., Newton County, Indiana, have followed steeply dipping Ordovician strata downward as deep as 260 feet below the surface. The quarry is horseshoe-shaped which reflects the distribution of carbonate rocks to the major plunging syncline geologic structure.

The structure exposed in the three quarries involves folding and complex faulting. The major structure is that of a steeply dipping syncline which plunges to the NNW and involves strata from the Shakopee Dolomite to the Maquoketa Shale. A prominent thrust or reverse fault, the Kentland Quarry Fault, parallels this synclinal fold and bounds it on the south margin throughout the quarry. Shearing is close to but not parallel to the bedding in subjacent St. Peter Sandstone to the south and Joachim Dolomite on the north hanging wall. Movement has been rotational for the block rather than elevator uplift. Displacement between walls has been oblique slip on the flanks to dip slip close to the axis of the fold. The trough of the syncline is further complicated by a nested synclinal fault which duplicates the Middle Ordovician section of the Platteville and Galena Groups and parallels the parent syncline. The nested structure is best exposed on the north side of the quarry along the ramp and crusher-conveyor belt.

Both of the flanks of the syncline in the SE and SW corners of the quarry manifest a different style of faulting. Maquoketa and Silurian strata in the SW quarry corner are folded into a steeply plunging anticline which has battered flanks. The latter are represented by separate fault blocks with sharp structurally discordant beds. All this is separated from the west limb of the large plunging syncline by a long narrow linear graben of dark Maquoketa Shale.

Unfortunately the SE quarry corner is back-filled. Earlier exposure revealed a block of Middle Ordovician strata trending NW-SE and dipping to the NE. There was some faulting exposed parallel to the bedding trend but displacement was apparently small. The orientation of the beds in this block is very closely related to similar strata in the abandoned McKee quarry to the ESE.

Compared to the undisturbed regional surroundings, the Kentland structure represents intensely deformed and strongly fractured rocks. Shattercones are common in a variety of lithologies, quartz grains are highly fractured, coesite has been reported but not confirmed, and mylonitic breccias grout fault contacts and fissures like mortar.

Several methods of origin have been suggested and the non-committal term Cryptoexplosion has been used. Cryptovulcanism (deep seated aborted volcanic eruption), meteorite impact (astrobleme), and faulting have been proposed. While geologic confirmation is equivocal, structural and mineralogic evidence as reported favors meteorite impact as the cause; whereas, geophysical studies strongly suggest deformation from below.

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Introduction- Apparently the Kentland structure originally represented limited bedrock exposure in the middle of a relatively flat prairie farming area now surrounded by corn and soy bean field crops on ground moraine till plain. Shallow high quality bedrock prompted quarry operations in the early 1880 decade. Three quarries were started over the years, Fig. 1, but two of them became inactive before 1930 as noted by Shrock and Malott. The main McCray quarry has been continuously active since 1906 and rock removal has accelerated during the past decade with construction of the interstate highway system and greater farm use.

In the large pit, quarrying started in the NE part of the excavation and proceeded downwards to the depth of the 7th level (filled with water). Extension of the quarry to the west is outlined by the 6th floor level. A southeastward cul-de-sac operation encountered Middle Ordovician rocks but was abandoned in the upper levels and subsequently back-filled. Several years ago westward expansion followed productive Middle Ordovician carbonate beds to the present quarry outline. Currently the surficial material is being stripped to bedrock on the contiguous west side property to extend the quarry again in that direction. This will be an enlargement of the old abandoned Means quarry. This operation was completed in 1973 and deepening of this westward extension is in progress.

Development of the quarry is based on 40-foot shot-hole drilling depths. Blasting and removal of broken rock results in effective deepening about 35 feet for each round. Therefore in a general way, successive levels in the quarry from bedrock surface downwards represents approximately 35 foot vertical intervals.

A chronologic summary of developments of the quarries, discovery of Kentland, identification of the rocks and their paleontology, speculations as to the origin of the structure, geologic, mineralogic, and geophysical development, and current status of our understanding of Kentland is given as follows. References to these studies can be found in the bibliography at the end of the guide book.

## Chronologic Resume of Significant Developments at Kentland

Natural outcrops, thin glacial drift, and local "dome"

- 1881- G. K. Greene- Discovery of Kentland exposures (reported in Collett, 1883).
- 1883- J. Collett- First report of disturbed strata near Kentland.
- 1886- S. S. Gorby- First reference to McKee and Means quarries, also fossils.
- 1906- L. C. Ward- Reference to McCray quarry.
- 1906- G. K. Greene- Affirmation of Ordovician age of rocks in McKee quarry based on fossils.
- 1922 Interpretation of disturbed structure as Niagara domes.
- 1922- E. R. Cumings- Questioned "Niagara domes (reef)" origin of Kentland structure.
- 1927- E. R. Cumings and R. R. Shrock- Proposed diastrophic origin of Kentland structure.
- 1930- R. R. Shrock and C. A. Malott- Structural and paleontology study of quarries.
- 1932- J. Zinn- Magnetic intensity map of Kentland area (Map is reproduced in Shrock, 1937, p. 520, fig. 8).
- 1933- R. R. Shrock and C. A. Malott- More information on stratigraphy and structure also paleontology.
- (1928, 1935- W. Bucher on cryptovulcanism; 1936- Boon and Albritton on meteorite impact; Wilson and Born on meteorite impact).
- 1937- R. R. Shrock- Comprehensive detailed report on the stratigraphy and structure of the Kentland disturbance with presentation of multiple origin possibilities favoring cryptovulcanism.
- 1937- R. R. Shrock and G. O. Raasch- Detailed report on the paleontology of Ordovician rocks at Kentland.
- 1947- R. S. Dietz- Meteorite impact origin suggested by shattercone orientation.
- 1952- D. R. Lucas- Geophysical survey.
- 1953- M. W. Pullen- Kentland anomaly survey based on radio field intensity survey map.
- 1953- R. E. Boyer- Geological study of Kentland McCray quarry including geological map.
- 1955- E. A. Ziemba- Microfacies study of Ordovician Platteville Group.
- 1959- R. S. Dietz- Shattercones suggest meteorite impact origin.
- 1961- R. C. Gutschick- Progress report on geology of McCray quarry with map.
- 1961- A. J. Cohen, T. E. Bunch, and A. M. Reid- Reported discovery of coesite in St. Peter Sandstone at Kentland.
- 1963- J. S. Templeton and H. B. Willman- Clarification of Champlainian stratigraphy.
- 1966-1971- D. Tudor et. al. (Indiana University and Indiana Geological Survey) Detailed subsurface and geophysical gravity survey study of Kentland anomaly area; 1972- abstract of this study is published and orally presented at G.S.A. meeting in DeKalb, Illinois.
- 1969, 1970, 1971- R. C. Gutschick- Abstracts, oral reports, and progress reports on study of geology of Kentland based in large part on deepening of main quarry and westward quarry extension based on new information. Progress geologic map Guidebook Indiana Geologists Field trip Oct. 17, 1970; National Association of Geology Teachers East-Central Section Field trip Apr. 17, 1971.
- 1972- Progress geologic update of Guidebook for 35th Annual Mtg. Meteoritical Society Field Trip, Nov. 15, 1972.



Method of study- Quarry geometry and structural detail is being mapped by plane table-alidade method. Colored air views have been taken of the quarries and numerous color transparencies taken on each visit have also recorded the progress of quarry operations. These are especially valuable for reference since the rocks and geology are removed and the information is otherwise lost. Enlarged photos and transparent overlays have been used to decipher the geometry of strata and faults in blocks throughout the quarry. The polaroid camera has also been used to advantage for on the spot photos and mark up of the details.

Rock colors are more striking and quarry faces are fresher and clearer after rainwash before much quarry dust is generated to obscure details. Freshly blast faces also reveal sharp detail. Lighting (daylight or sunlight) for observation photos is an important factor to bring out contrasts, shadows, or detail that might otherwise escape the viewers notice. Time of day and sun's shadows also produce striking changes, e.g., mullion surfaces along the Kentland Quarry Fault are much more pronounced with glancing incidence lighting.

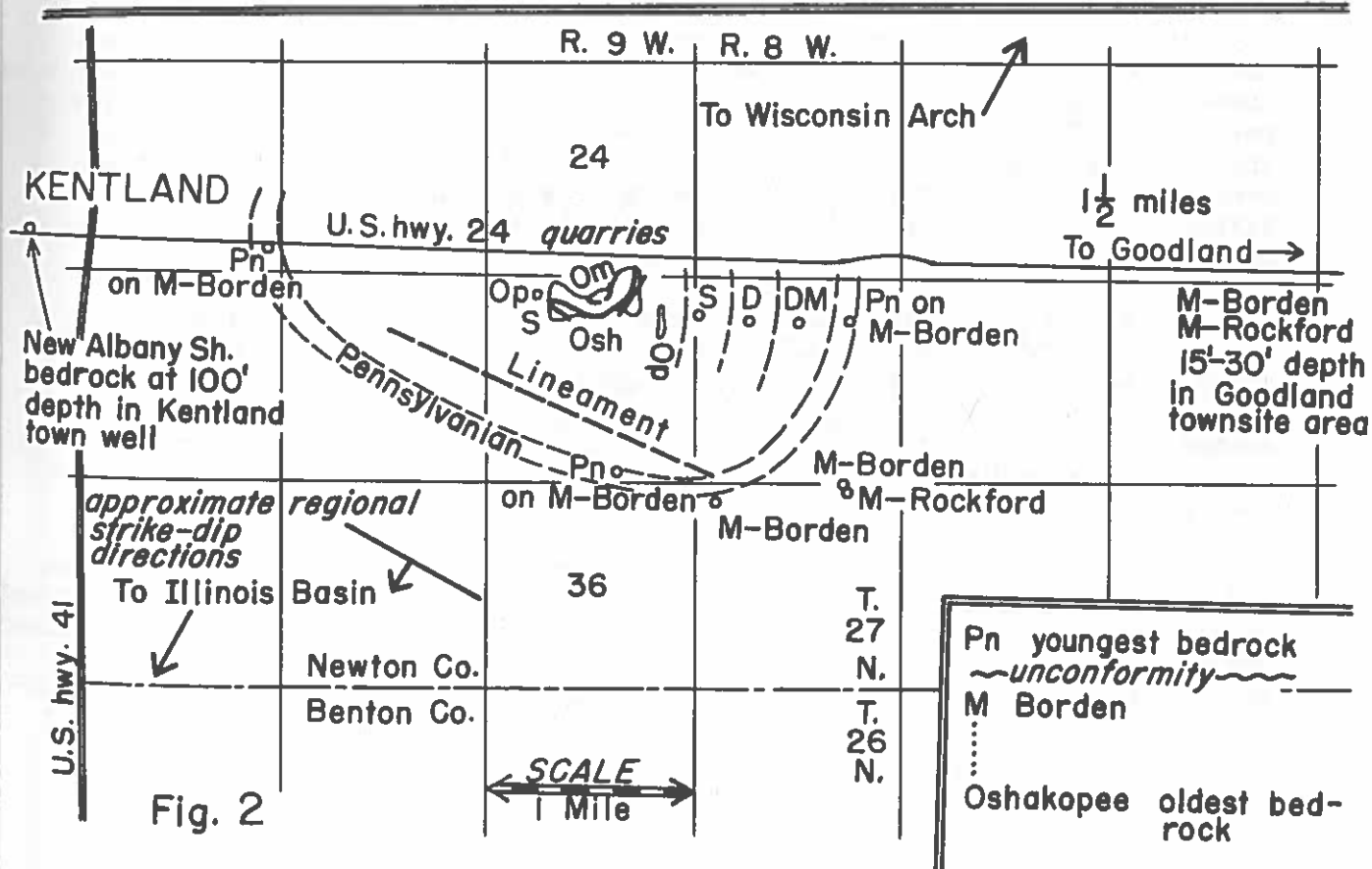
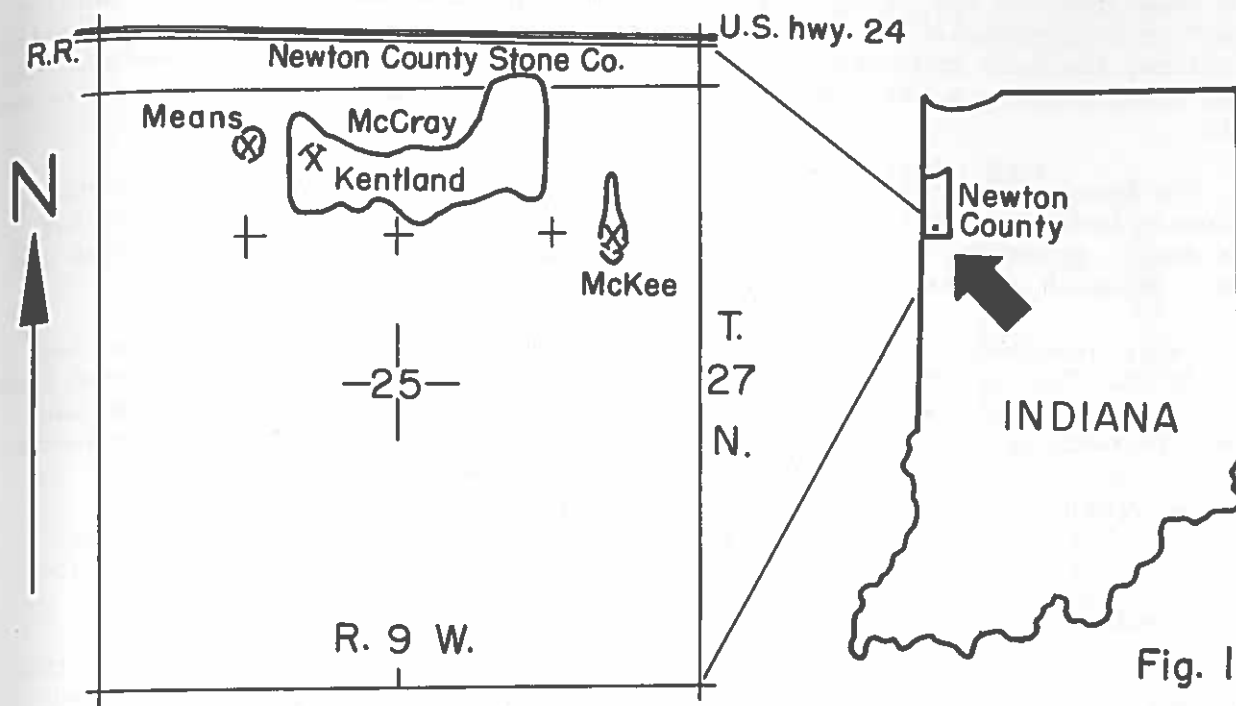
Weathering brings about changes in color or tone which accentuates certain features. Pyrite altered to limonite along mineralized fault surfaces pin-point the major structure, as for example along the Kentland Quarry Fault; also drip in the form of limonite weathered from pyrite nodules in the Hennepin Member. These drip stains along steeply dipping bedding and fault surfaces are seen throughout the quarry and can be used effectively to recognize key stratigraphic units and faults. The Galena-Maquoketa unconformable contact has a concentration of iron sulphides along it which alter to limonite and accentuates the presence of this surface. Ubiquitous ferrous iron in rock dolomite will weather buff-rusty with time as with the Galena and Shakopee rocks. White gypsum efflorescence covers some of the Galena and Maquoketa Shale exposures. It is also present in the Low Platteville Pecatonica Dolomite. Bedding, fractures, and faults form weak recessive relief with time. This progressively accentuates such contacts.

Finally the frustration of discovering an unusually good exposure or feature only to have it quarried or covered in succeeding weeks is disheartening. On the other hand quarry advance enables one to project the geology from time to time which helps to fill in the three-dimensional puzzle.

Kentland regional geology- Location of the quarries in Section 25, T. 27 N., R. 9 W., Newton County, Indiana is given in Fig. 1. The geology and extent of the Kentland structure is shown in Fig. 2. This is based on limited subsurface information namely seven drill holes to bedrock and two town water wells in Kentland and Goodland. The former were drilled by the Indiana Geological Survey who also interpreted the cuttings and cores. Core drilling to bedrock in Tudor's program will provide much more detailed information on this bedrock anomaly.

For normal regional structure the bedrock consists of Lower Mississippian or Upper Devonian rocks which dip very slightly to the southwest into the Illinois Basin from off of the Wisconsin ("Kankakee") Arch. There may be a few Pennsylvanian outliers such as the one about one mile northwest of Remington, Indiana. The surface is covered with Pleistocene Wisconsin glacial drift so that rock outcrops are few indeed.

The Kentland structure, except for the quarry, is an elliptical faulted dome with concentric ring syncline. Formations from the Shakopee to the Borden



have been uplifted and tilted, presumably with quaquaversal dips; and an outlier "moat" of Pennsylvanian rock, represented by a thin band around the ring syncline structure, has been preserved. The Pennsylvanian remnant is unconformable on the Lower Mississippian Borden Group and is overlain unconformably by the Pleistocene drift.

The regional setting of the Kentland structure to the Illinois Basin and Wisconsin Arch is given in Fig. 3. Other anomalous disturbances are shown for this area. Attention is called to the Des Plaines and Glasford disturbances and to the Sandwich and Royal Center Faults.

A very generalized stratigraphic section is reconstructed for the area down to bedrock, Fig. 4. This gives the normal stratigraphic section encountered from the surface through the Pleistocene and Paleozoic rocks to the Precambrian basement. Formations exposed in the Kentland anomaly are indicated as are projection to structural datum surfaces, e.g., top of the Trenton Galena Group, top of the Knox Megagroup (top of the Shakopee Fm.), top of the Precambrian "Basement". The elevation of the Kentland quarry surface is approximately 700' above sea-level and the respective tops of the Galena, Shakopee, and Precambrian surfaces are 400', 1000', and 4700-4800' all below sea level.

In order to appreciate the stratigraphic and structural dislocation of the Kentland structure, several structure contour maps are given for key datum surfaces. These are top of the Trenton Limestone, Fig. 5; top of the Knox Dolomite, Fig. 6; and top of the Precambrian Basement, Fig. 7. For the Kentland anomaly the Galena (Trenton) Dolomite is well exposed throughout the quarry; yet it should normally be at 400 feet below sea level. The oldest rocks exposed in the quarry belong to the Shakopee Dolomite. Since the top of the Shakopee Fm. (top unit of the Knox Megagroup) should normally be at 1000 feet below sea level and there is over 100 feet of this formation present, we can conclude that it has been uplifted at least 1800 feet above its normal position in the stratigraphic-structural section.

The structure map for the top of the Precambrian Basement is also presented Fig. 7, taken from Bond et. al., 1971, and Rudman, Summerson, and Hinze, 1965. There is much less structural control on this datum surface than for the Galena or Shakopee surfaces; therefore it is less reliable for comparison. It is presented here to relate to geophysical study by Tudor et. al., 1972, for which they found that three-dimensional gravity modeling of their data suggests a basement uplift of 2000 to 3000 feet.

In Fig. 2 you will note that the rock formations exposed are of Ordovician and Silurian age and that drill holes on the east side of the quarries encountered successively younger rocks eastwards. Well sections in the town areas of Kentland and Goodland are normal. Air photos suggest a linear feature interpreted as a fault, Gutschick, 1961, which is apparently confirmed by Tudor's geophysical survey. This forms the south margin of the stratigraphic disruption. Other drill holes have encountered Pennsylvanian bedrock in a few holes around the anomaly; otherwise the bedrock is Lower Mississippian or Upper Devonian.



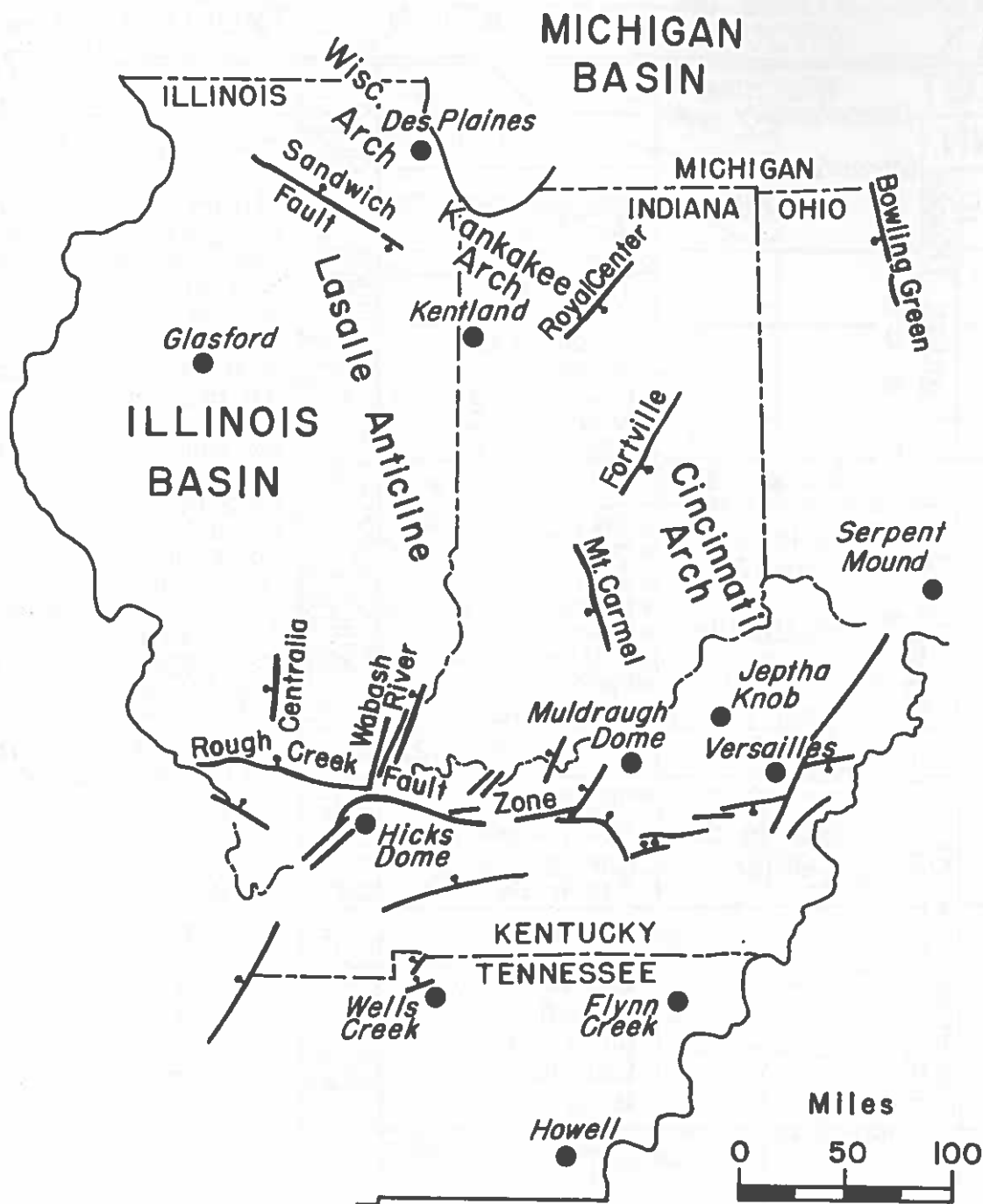
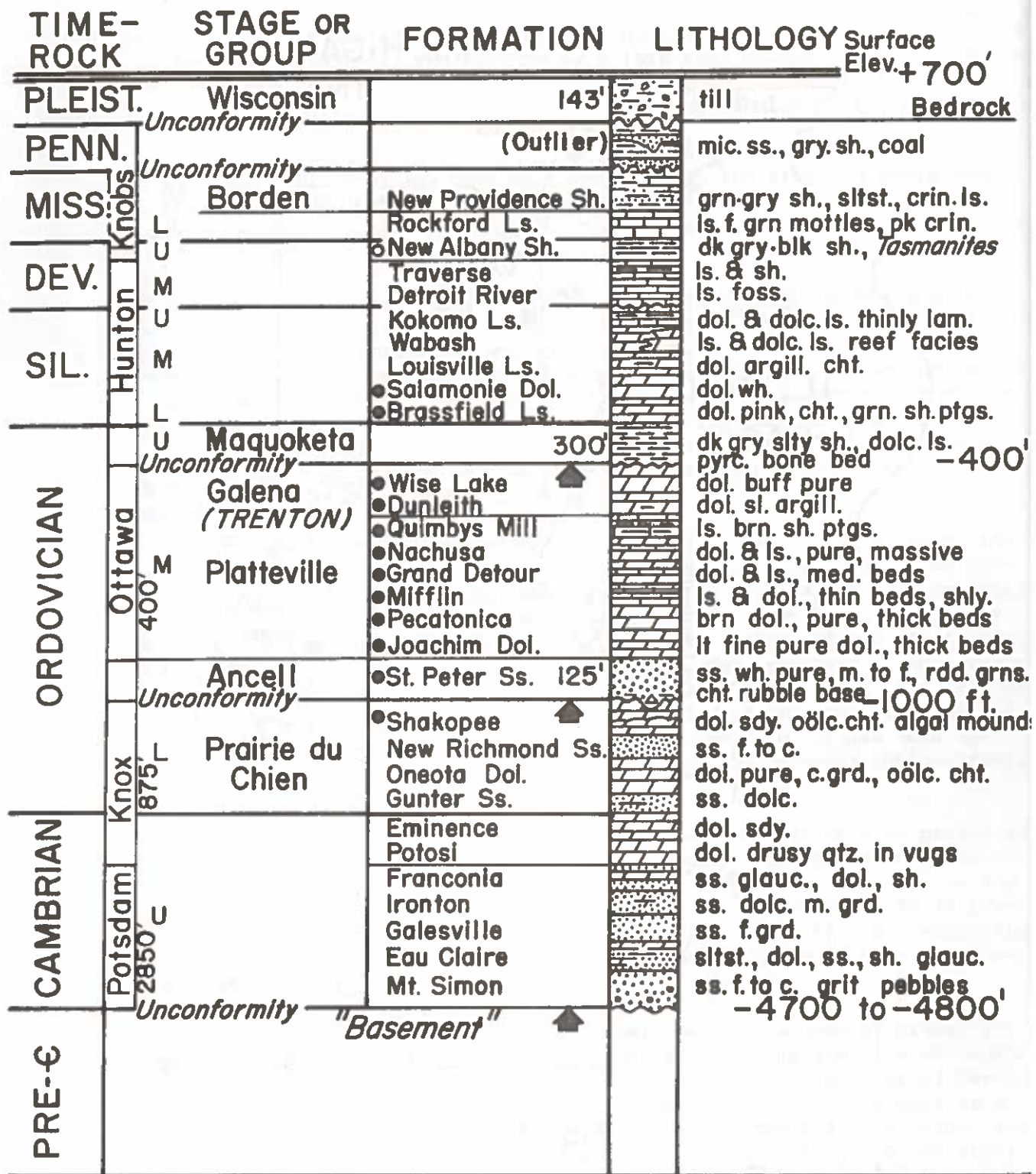


Fig. 3  
Major Faults and Disturbances in  
Midwestern Area



Thicknesses and depths are close estimates.  
 • Present in Kentland quarry      o in breccia

▲ Datum for geologic structural maps

## STRATIGRAPHIC SECTION AND PROJECTED BASEMENT IN THE KENTLAND AREA

Fig. 4

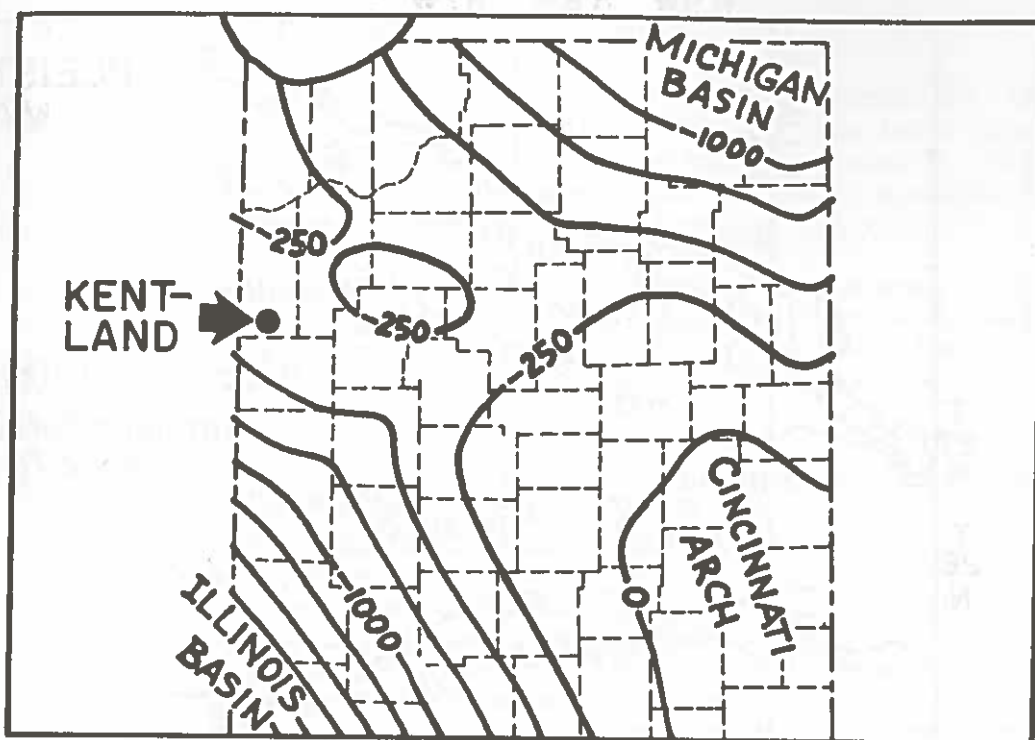


Fig. 5 Structure Map contoured on top of Trenton Limestone (Middle Ord. Galena Group at Kentland X)  
(From Dawson, 1952, *Ind. Geol. Survey Misc. Map 3*)

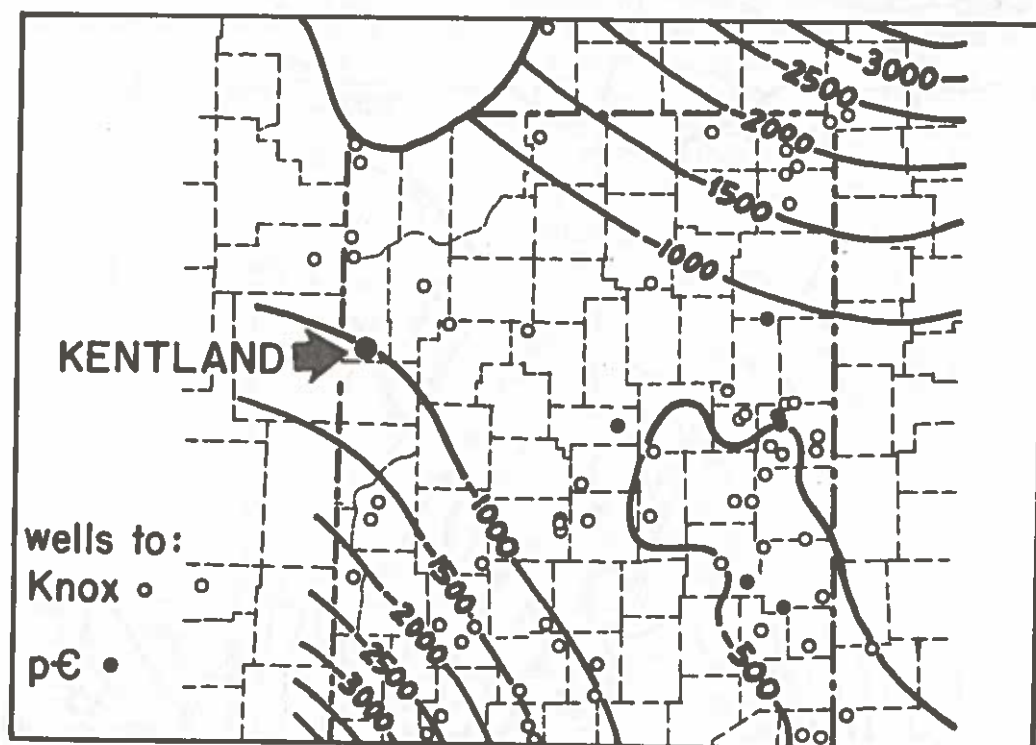
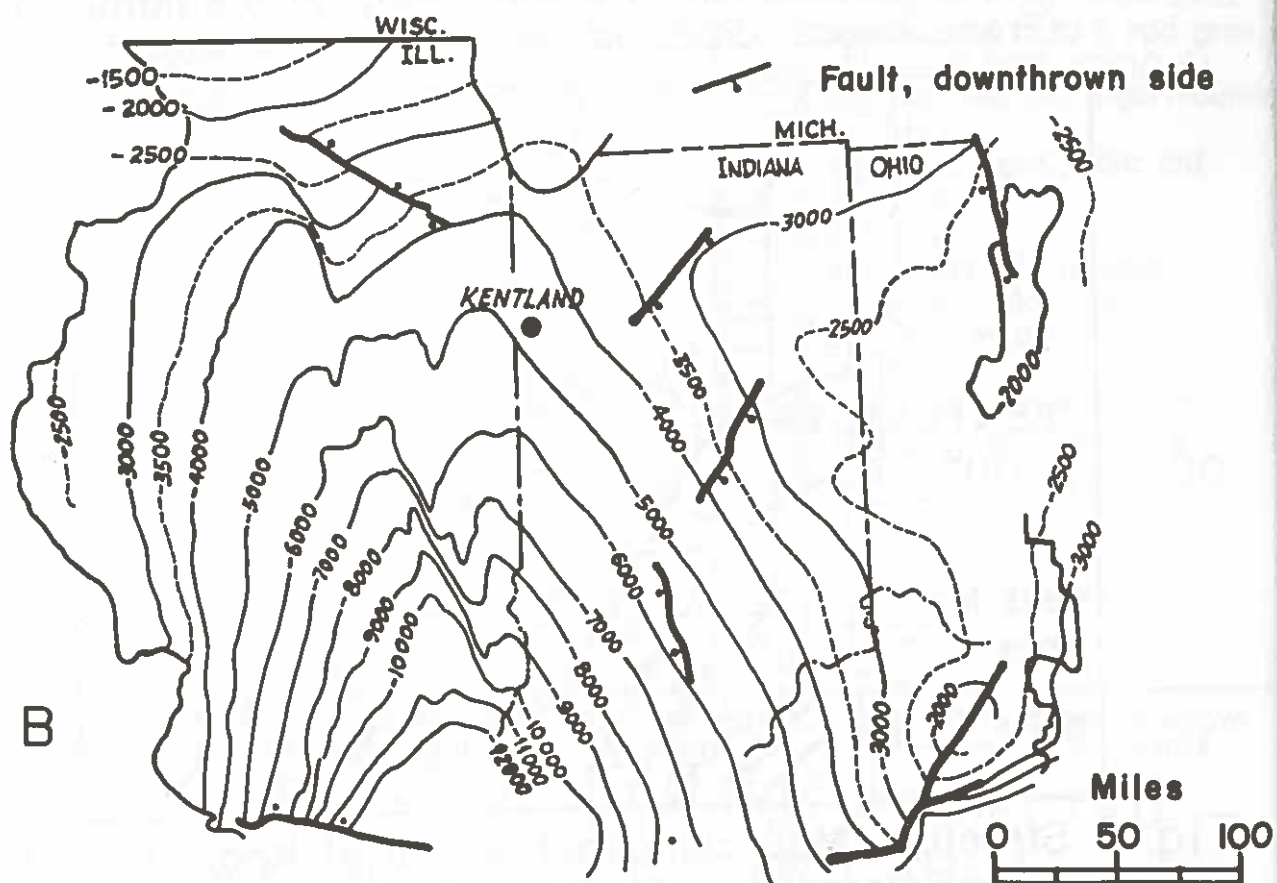
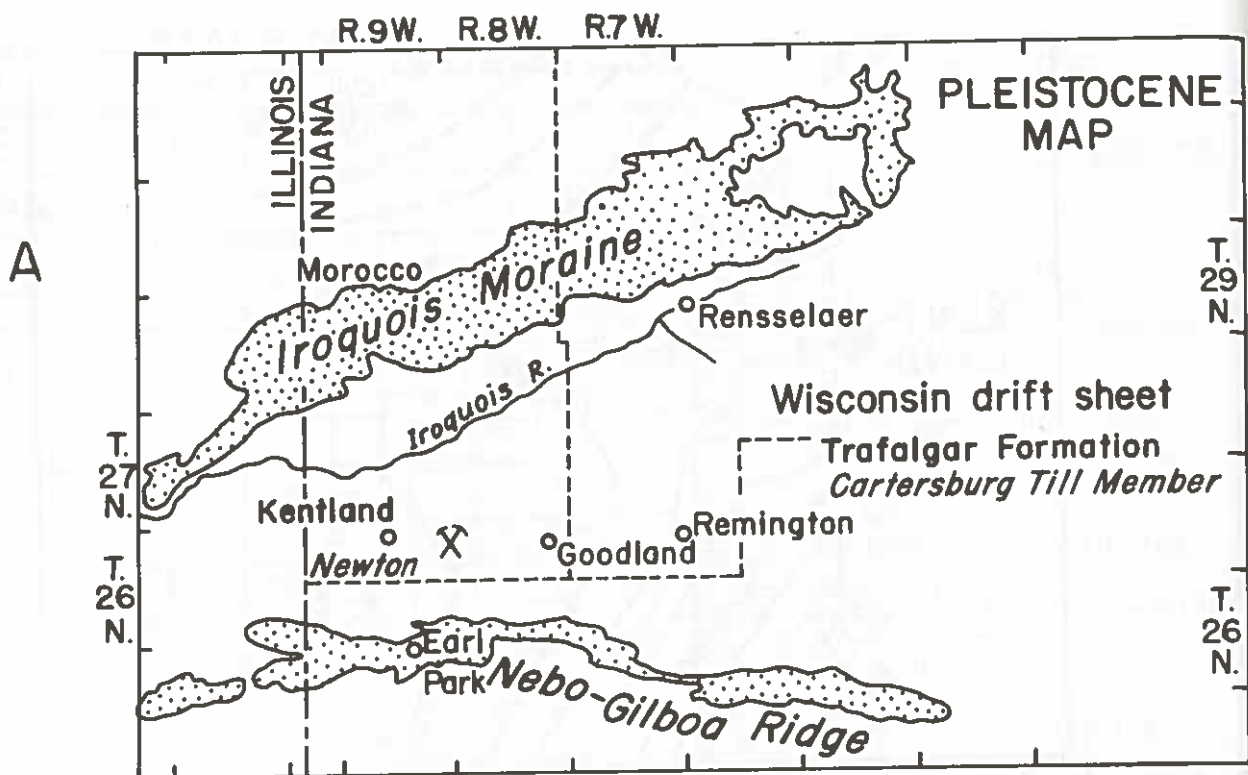


Fig. 6 Structure Map contoured on top of Knox Dolomite (Lower Ordovician Shakopee Fm.) (Dawson, 1960)



**Fig. 7 STRUCTURE on Top of PRECAMBRIAN BASEMENT**

12. AAPG Mem. 15, 1971

## Geology of the Kentland Quarries

There are three quarries located in the north half of section 25, the main active quarry and two small long abandoned sites, Fig. 1. The large quarry is currently being expanded to the west to absorb the old Means quarry. Stripping of the glacial mantle to bedrock is now in progress and quarry operations will start very shortly on this tract to connect with the main quarry.

The relationship of the quarries to the topography of the area is given in Fig. 8, taken from the four adjacent quadrangles Kentland, Goodland, Earl Park, and Wadena. A more detailed set of maps for the quarry is given for the surface topography, Fig. 9; bedrock topography, Fig. 10; and thickness of the glacial drift, Fig. 11.

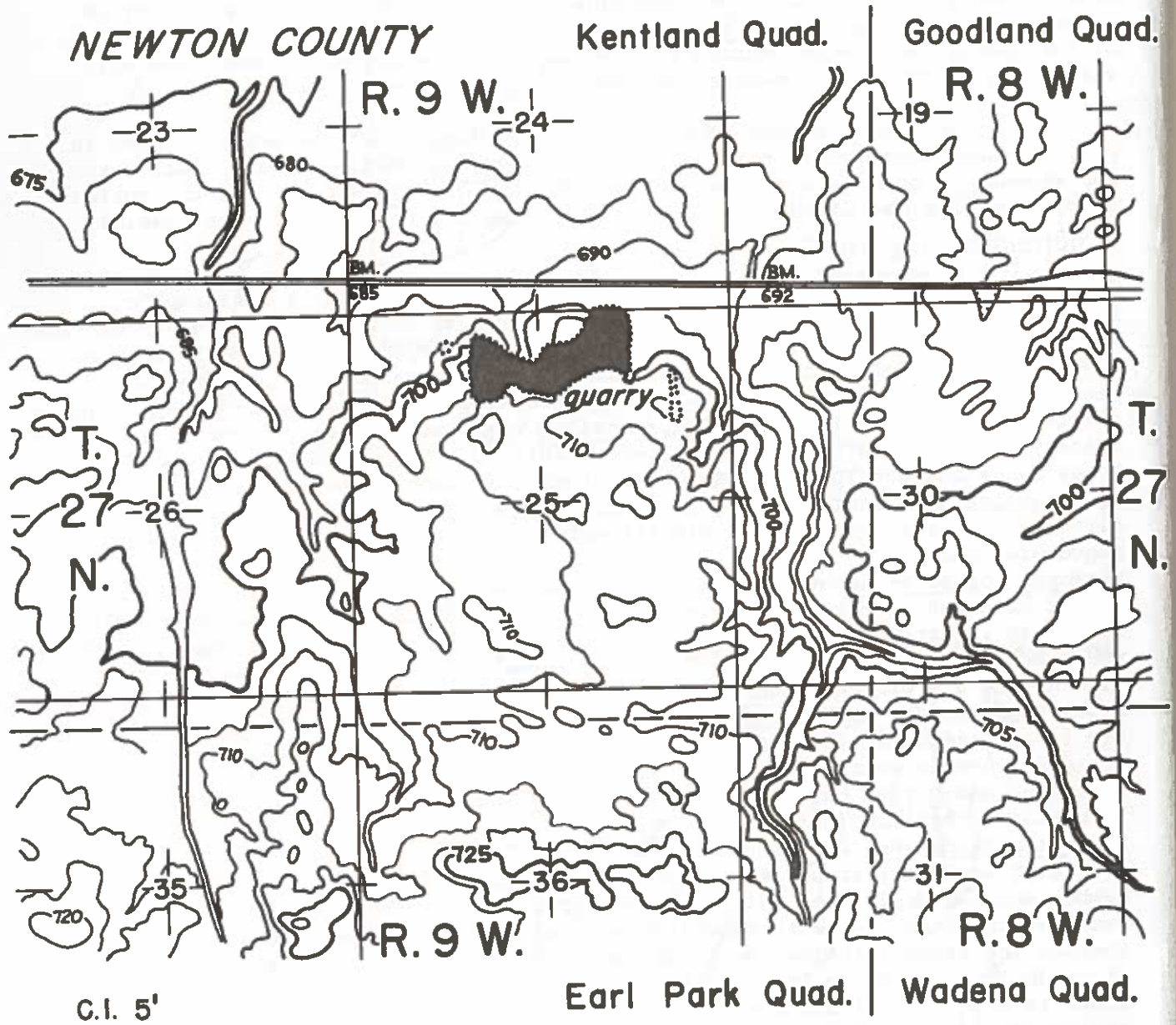
Stratigraphic Key (within quarries)- A detailed resume of the stratigraphic section reconstructed from blocks in the quarries is shown in the columnar section diagram, Fig. 12. Strata range from Lower Ordovician Shakopee Dolomite to the Middle Silurian Salamonie Dolomite. Middle Devonian carbonates have not been recognized in the quarry and Upper Devonian New Albany Shale appears only as shale clasts in fault breccias. A fairly detailed composite section encompasses approximately 1000 feet in thickness or rock. Faulting has sheared out uppermost St. Peter Sandstone and lowermost Joachim Dolomite so that it is virtually impossible to recognize and identify complete sections of either of these formations. Quarry circumstances fail to expose a significant portion of the middle part of the Maquoketa Shale.

Shakopee Dolomite- About 125 feet of the Shakopee Dolomite has been pieced together although some of it is now covered by backfill for a ramp. The dolomite lithology, partly sandy, with rusty weathering, irregular thin- to medium-bedding, and some oolitic chert characterizes this formation. Large low algal stromatolite mounds are present and they are 10-12 feet in diameter by 1-2 feet high. Algal breccias are commonly associated with the stromatolitic layers. Chert nodule layers, some oolitic, and bright green shale partings are also present. Acid residues contain coarse rounded frosted quartz sand grains some of which are fractured and offset but the grains are whole and intact. This is the oldest formation recognized in the quarries.

St. Peter Sandstone- A pronounced unconformity separates the basal unit of the St. Peter Sandstone Kress Member from the underlying Shakopee Dolomite. The Kress Member which is 5-10+feet thick has much bright green clay, possibly K-bentonite, residual chert nodules with friable weathered oolites and white sand stringers. Much of the Kress lithology must represent unconformity insoluble residuals from the underlying Shakopee Fm. The St. Peter Sandstone is pure white quartz sandstone in which the grains are highly fractured and the rock exhibits closely spaced jointing. Bedding is obscure and thickness is difficult to determine. The rock usually is soft and friable. Throughout the quarry, its upper part is in fault contact which further complicates measurement of its true thickness. Cohen, Bunch, and Reid, 1961, report coesite in low concentration from this sandstone. About 80 feet of the lower part of the formation has been measured in the footwall of the Kentland Quarry Fault.

Joachim Dolomite- This important structural unit is characteristically very light gray, aphanitic, medium- to thick-bedded, pure, tough dolomite. Its complete thickness has not been observed since the lower part of the formation is involved in hanging wall fault contact along the Kentland Quarry Fault. The upper portion of the formation has thin wavy discontinuous shale films within the dolomite.





Topographic Map

Fig. 8

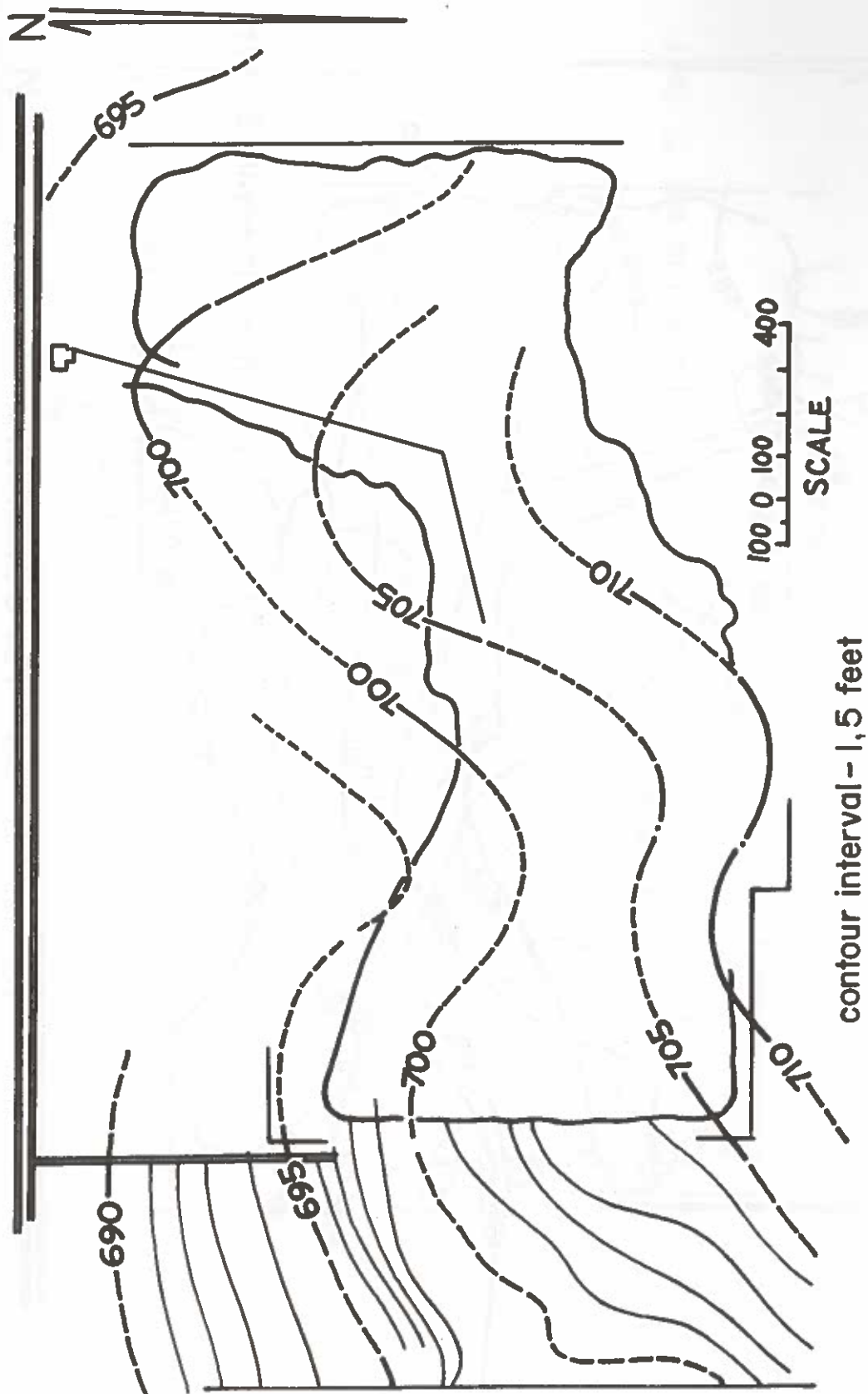


Fig. 9 TOPOGRAPHIC MAP

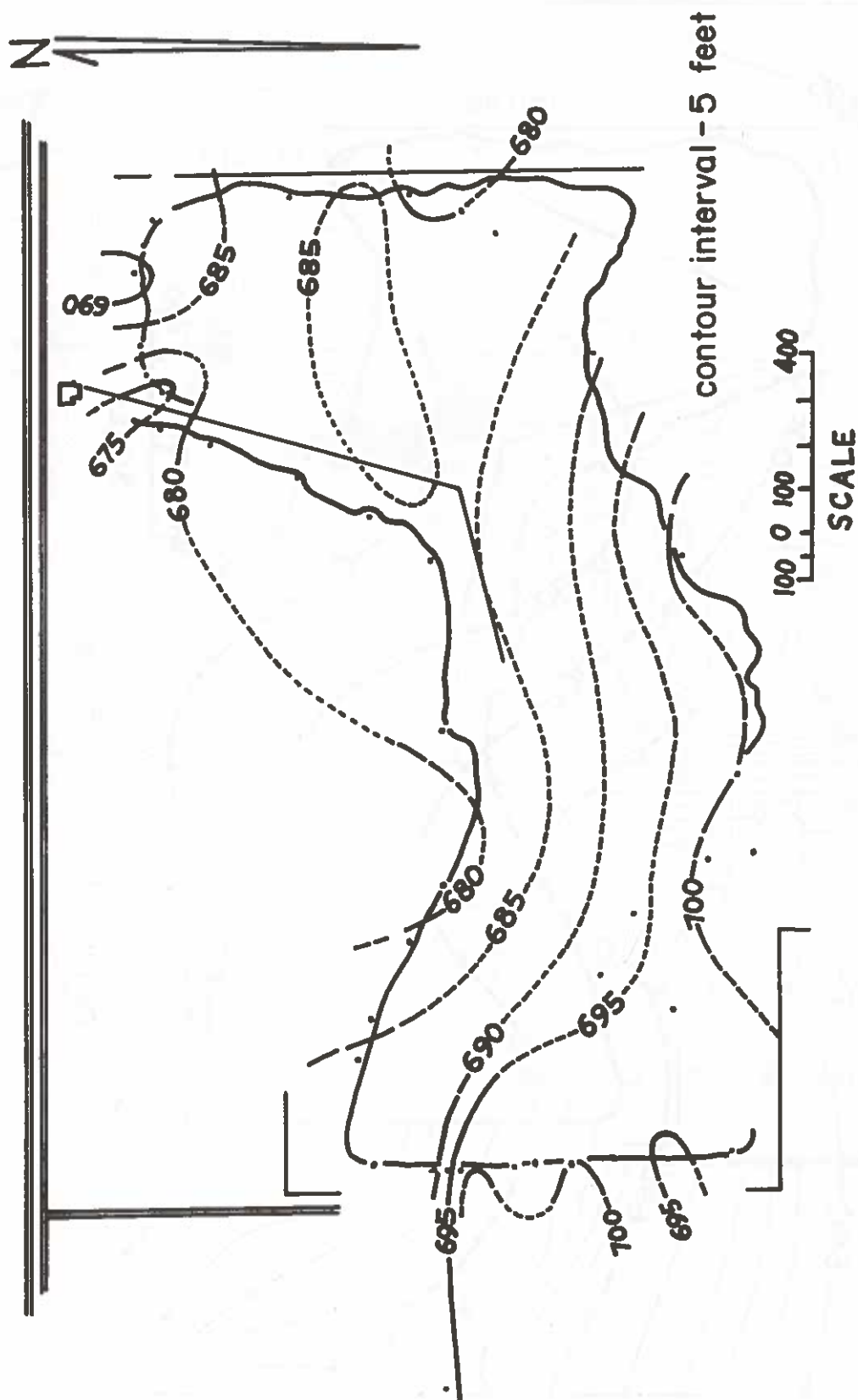


Fig. 10 BEDROCK TOPOGRAPHY



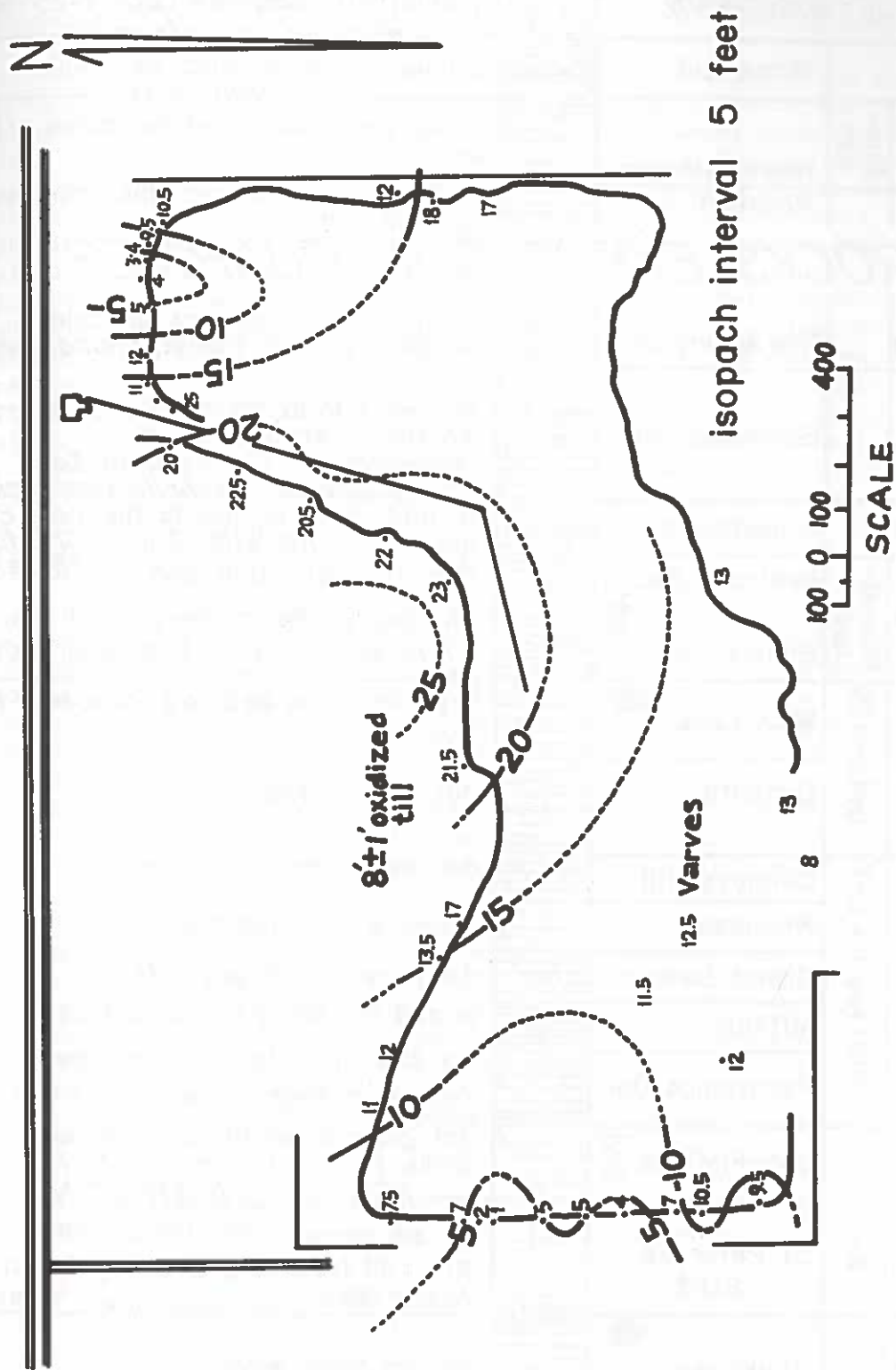


Fig. 11 ISOPACH MAP OF GLACIAL DRIFT

## Fig. 12



It is suspected that algae must have played an important role in forming this carbonate sediment. Some beds alternate in shades of pale green to light tan so that the grouping is useful for recognition of the Joachim. This is especially noticeable in the upper 10 feet of the formation and when the rocks are wet as after a rain.

Platteville Group- This sequence is well exposed, the units are fairly distinct, and they are well documented by Shrock, 1937; Ziemba, 1955; and Templeton and Willman, 1963, 1971. The distinctive basal green sandy Hennepin Member, 6 feet thick, separates the Platteville from the underlying Joachim Dolomite. Bedding slab exposures of the Hennepin layers stand out because of bleeding limonite streaks from weathered pyrite-marcasite crystalline concretions. Otherwise the Hennepin consists of white quartz sandstone with much interbedded green clay and shale irregularly bedded. The lower Platteville Pecatonica Fm. is brownish-gray, thick-bedded dolomite sharply separated from the overlying Mifflin Fm. which is light-gray, very fine grained, thin-bedded limestone or dolomite that contains green or brown shale partings. The Grand Detour and Nachusa Fms. consist of pure, medium- to thick-bedded dolomite and some limestone. Chert may also be present. The Quimbys Mill Fm. at the top of the Platteville Group is very fine grained, thin- to medium-bedded dolomite and limestone with dark brown shale partings. There are a number of key lithologies which help to determine position within the group. The Platteville-Galena contact can usually be placed within a few feet but it is transitional and not sharp. Templeton and Willman give a thickness of 237 feet for this group.

Galena Dolomite- The Galena Dolomite is light brownish-gray, medium- to thick-bedded dolomite and dolomitic limestone with characteristic rusty buff weathering. Textures, structures, and fossils seem to be altered due to diagenetic changes. White chert in the form of nodules and layers are present in some units. The dolomite surface develops gypsum efflorescence upon exposure. The upper contact with the overlying Maquoketa Shale is very sharply marked by disconformity. Sulphides have formed along the contact which develops into a conspicuous iron stained interval upon weathering of the pyrite. A thin (1"+) lag bone bed of rounded polished phosphatic bone and teeth fragments is found along the unconformity. The Galena Group is divided into several formational units by Templeton and Willman, 1963; however these are difficult to distinguish in the Kentland quarry. They assign a thickness of 151 feet to this group.

Maquoketa Shale- The lower part of the dark gray silty basal Scales Shale is well exposed along the ramp and conveyor belt in continuity with the Galena Group. Thin (>6") even beds of hard siltstone are interbedded with the shale and serve to delineate the structure within the member. A blocky fracture has developed in these rocks and the shale becomes splintery when weathered. The north wall on the west end of the syncline follows the Galena-Maquoketa contact and exposes the lower part of the shale.

The uppermost Maquoketa Brainard Shale is exposed in the south and west walls of the southwest part of the quarry. It is dove-gray, thin-bedded, argillaceous dolomitic limestone with shale partings. Before backfill, a continuous exposure of upper Maquoketa and Brassfield rocks revealed the contact between them. This seems to be slightly transitional change yet there is a thin (<1") brecciated sandy zone of separation.

The middle portion of the Maquoketa Group is not exposed anywhere in the quarries. The upper part is involved in faulting along the west wall where it has a striped appearance.

Brassfield Limestone- Enlargement of the quarry to the southwest south of the Kentland Quarry Fault and narrow belt of downfaulted dark Maquoketa Shale exposed a block of Silurian rocks. The west wall in the southwest part of the quarry has a continuous north dipping sequence of the lower half of the Silurian generally present in this area. The Brassfield is in contact with the top of the Ordovician although it is no longer exposed. This lower Silurian consists of rusty earthy weathered dolomite, thin-bedded, with white chert nodules. Above this the rock is dolomitic limestone in thicker, even-bedded layers. There is some pink crinoidal limestone, green shale partings, pyrite, and glauconite. Insoluble residues of these rocks contain arenaceous foraminifera of the Turritella zone characteristic of Lower Silurian age. The section is continuously exposed into the overlying Middle Silurian units.

Salamonie Dolomite- The rocks are light colored dolomitic limestones with green shale partings. Residues contain abundant Ammodiscus and Thurammina. Nautiloid cephalopods Phragmoceras and Lechritrochoceras are found also so that this fossil association is typical of Niagaran age rocks. Northwards in this section the rocks become more massive and they are involved in faulting so that it is not too clear whether there is more Silurian above the Salamonie beds. There is more than 200 feet of Silurian rocks exposed in this southwest quarry reentrant. Operations to the west may clarify this relationship within the middle portion of the Silurian. The upper part of the Silurian section and the lower part of the Devonian is not present in quarry exposures.

New Albany Shale- Although there is no known exposure of layered Devonian strata in the quarry, stromatoporoids chunks and dark-gray to black, bituminous shale clasts with Tasmanites occur in the fault breccias. The shale pieces are laminated with some greenish-gray layers. These can be found in the debris between levels 1 and 2 in the southwest part of the quarry. While the shale superficially resembles the dark Maquoketa shale, differences in texture, presence of Tasmanites, bituminous odor, and the thermal (D.T.A.) properties of each enable separate recognition of each shale.

Stratigraphy (outside of quarries)- The normal bedrock succession present in the Kentland area from the oldest to the youngest includes Upper Devonian New Albany Shale, Lower Mississippian Rockford Limestone, and rocks of the Borden Group. These may be beneath Pennsylvanian Mansfield Sandstone. This area is at the feather edge of the erosional retreat of the Pennsylvanian so that outliers or remnants are preserved in structurally downwarped or erosional channel situations. One such channel sandstone body is exposed in Fountain Park northwest of Remington, Indiana. Micaceous sandstone and shale associated with coal fragments have been recovered from beneath the drift in 3 shallow drill holes surrounding the Kentland structure, Fig. 2.

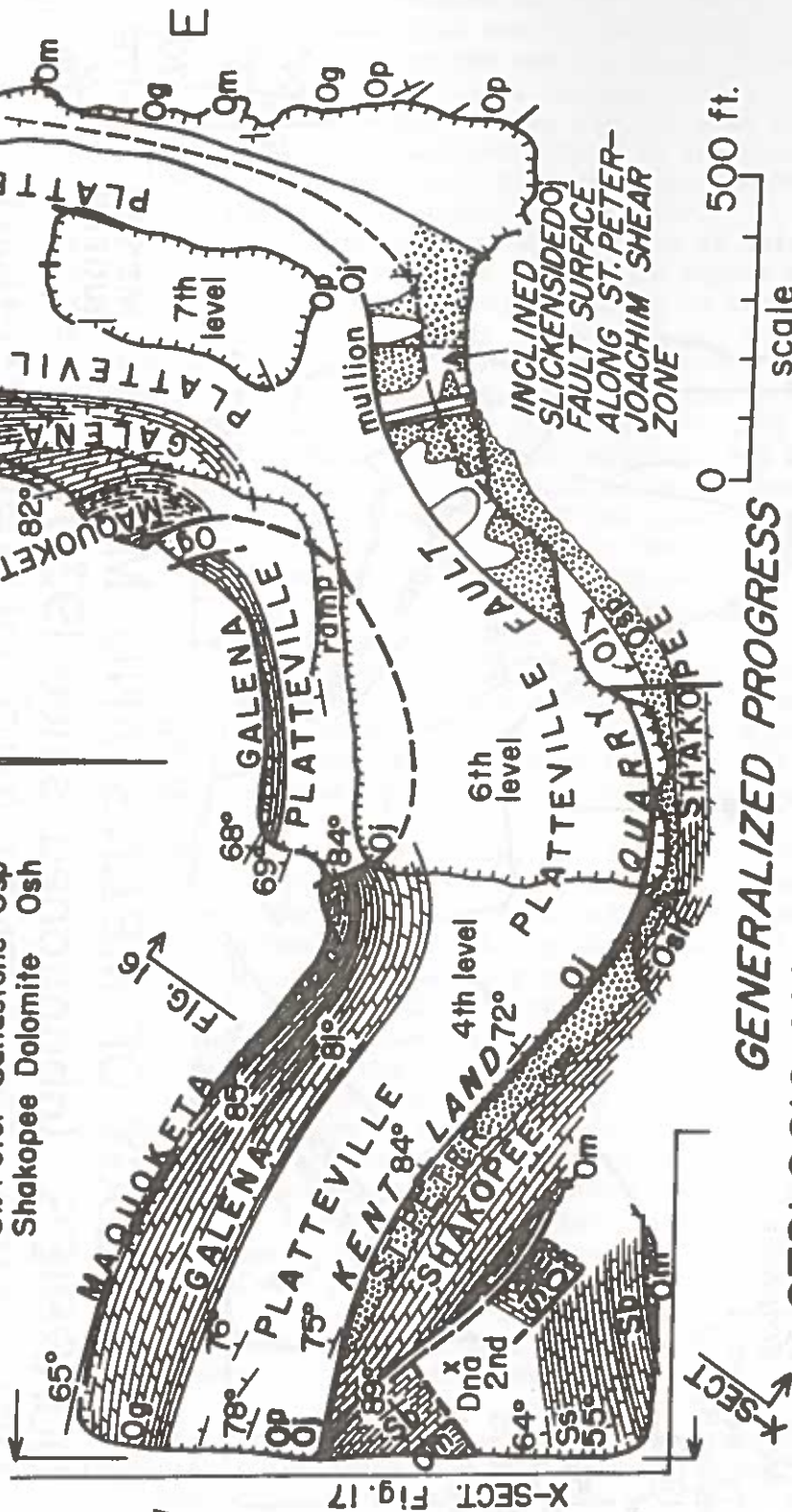
Paleozoic bedrock is completely veneered with Pleistocene Wisconsin glacial till which varies in thickness from 1 foot at the quarry to 143 feet in the ring syncline surrounding the quarry. To the south in adjacent Benton County, thickness of drift increases where it fills in the ancient pre-glacial Teays River valley system. Bedrock striations at the quarry are consistently S. 20° W. and there is one 4 foot diameter boulder in the till which has been overridden by the ice with a striate faceted top surface which also has S. 20° W. striae. This directional property fits the pattern of ice cover from the Saginaw Lobe.

Note that several interpretations for distribution of the few occurrences of Pennsylvanian rocks are possible. Down-folding in a moat-like synclinal fold around the Kentland dome is shown in Fig. 2. Erosional stream channel system outliers is proposed in Fig. 23. Fault controlled down-thrown blocks is given by Tudor, 1971.



# Glacial Till

DEVONIAN	New Albany Shale (x-sh. in breccia)	Dna
SILURIAN	Salamonie Dolomite Brassfield Limestone	Ss Sb
ORDOVICIAN	Maquoketa Shale Galena Dolomite Platteville Group Joachim Dolomite St. Peter Sandstone Shakopee Dolomite	Om Og Op Oj Osp Osh



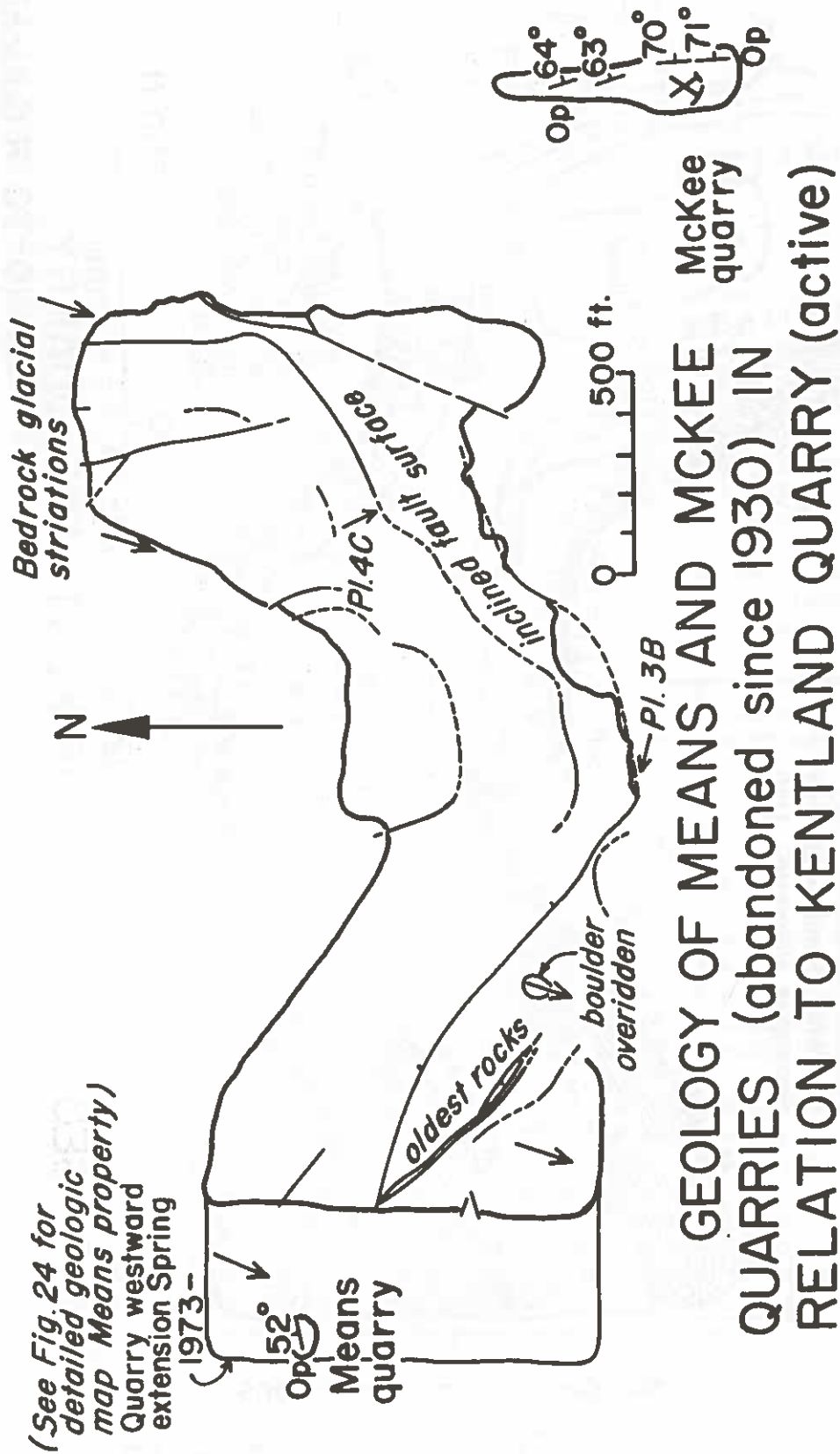
W (Geologic map of Means property see Fig. 24)

21.

Fig. 13

## GENERALIZED PROGRESS GEOLOGIC MAP OF KENTLAND QUARRY

N.D. 10-70 R. Gutschick 11-72



Geologic Structure (in quarries)- The horseshoe-shaped outline of the quarry, Fig. 13, emphasizes the major plunging synclinal fold and the parallel Kentland Quarry Fault. Plunge of the fold is steeply to the NNW and the fault dips steeply to the north with the hanging wall up. Quarry operations closely follow the carbonate beds of the Platteville and Galena Groups. These are the best quality rocks. Faulting has duplicated these particular carbonate beds in the central and northeastern parts of the large quarry. You will note then that for the most part the rocks are steeply tilted to the north throughout the quarry.

The deep northeastern portion of the large quarry was the site of original initial quarry operations in which it was deepened with time. The report by Shrock in 1937 was based on the first level operations. Geological study by Boyer in 1953 was based on the 2nd level progress. Subsequently the quarry has been deepened to the 7th level which serves as the sump and it has been expanded. Earliest development took place in the NE $\frac{1}{4}$  NW $\frac{1}{4}$  NE $\frac{1}{4}$  of section 25 with expansion to the southwest in the SW $\frac{1}{4}$  NW $\frac{1}{4}$  NE $\frac{1}{4}$  area. During the past few years deepening of the eastern part of the quarry was suspended while the westward expansion was developed into the NE $\frac{1}{4}$  NW $\frac{1}{4}$  of the section. Quarry operations concentrated on the exploitation of the Platteville and Galena carbonates. The south wall of the quarry was formed along the Kentland Quarry Fault with St. Peter Sandstone on the footwall and the north wall was stopped short into the upper part of the Galena Dolomite in order to support the north dipping Maquoketa Shale. To the west fault geometry cut off the St. Peter Sandstone and carbonates of the Shakopee Fm. and the Silurian units were encountered south of the fault. These were quarried southwestward into the corner of the property where the top of the Maquoketa Group was encountered. Deepening in this part of the quarry was curtailed because the quality of the rock is not as good as the Mid-Ordovician carbonates. The latter make up the west wall of the quarry north of the Kentland Quarry Fault and these will continue to be exploited into the adjoining Means property.

The structure in the quarries is dominated by folding and faulting. The major structure is that of a steeply plunging synclinal fold with some suggestion of anticlinal continuation on either end. The western portion indicates change in strike of the beds and the Means quarry has rocks which dip to the northwest. Rocks in the abandoned McKee Quarry to the east dip eastward, Fig. 14. Other evidence of folding is present in the southwest corner of the quarry where the Maquoketa and Silurian rocks are tilted into a broad openly plunging anticline with faulted limbs. Along the north wall of the northeast part of the quarry, there is a plunging anticline but this may be due to drag related to complex faulting, Fig. 18.

Faulting is present throughout the quarry on a grand scale. The major fault structure which dominates the geometry is the Kentland Quarry Fault. This zone extends throughout the quarry and is folded along with the beds. It dips steeply to the north, northeast, and northwest. Thickness of the Platteville-Galena carbonates increases considerably in two places by fault duplication. In the central part of the quarry close to the axis of the plunging fold, there is a double section of Mid-Ordovician carbonates. This is probably due to a nested fault which drops a block of Platteville-Galena to the north along the axis of the fold. The structure in the northeast part of the quarry is complicated by faulting which duplicates the Platteville Group, Fig. 18.

East of the Kentland Quarry Fault zone along the east wall of the quarry there is faulting which puts Mid-Ordovician rocks along this wall. These seem to be structurally compatible with the same rocks in the McKee Quarry to the southeast. Unfortunately the reentrant to the southeast in the large quarry which at one time exposed the Platteville-Galena section is now backfilled and covers these rocks.

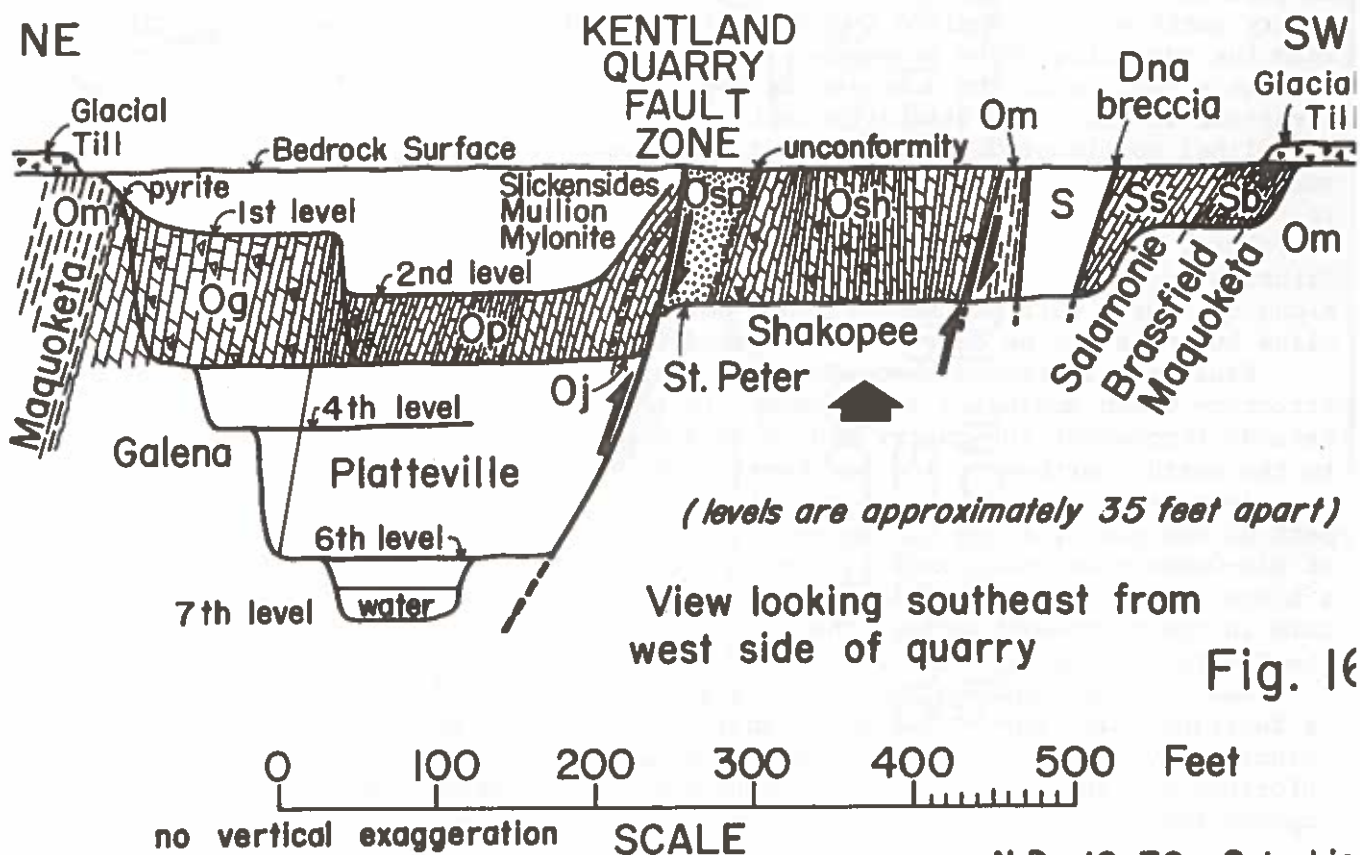
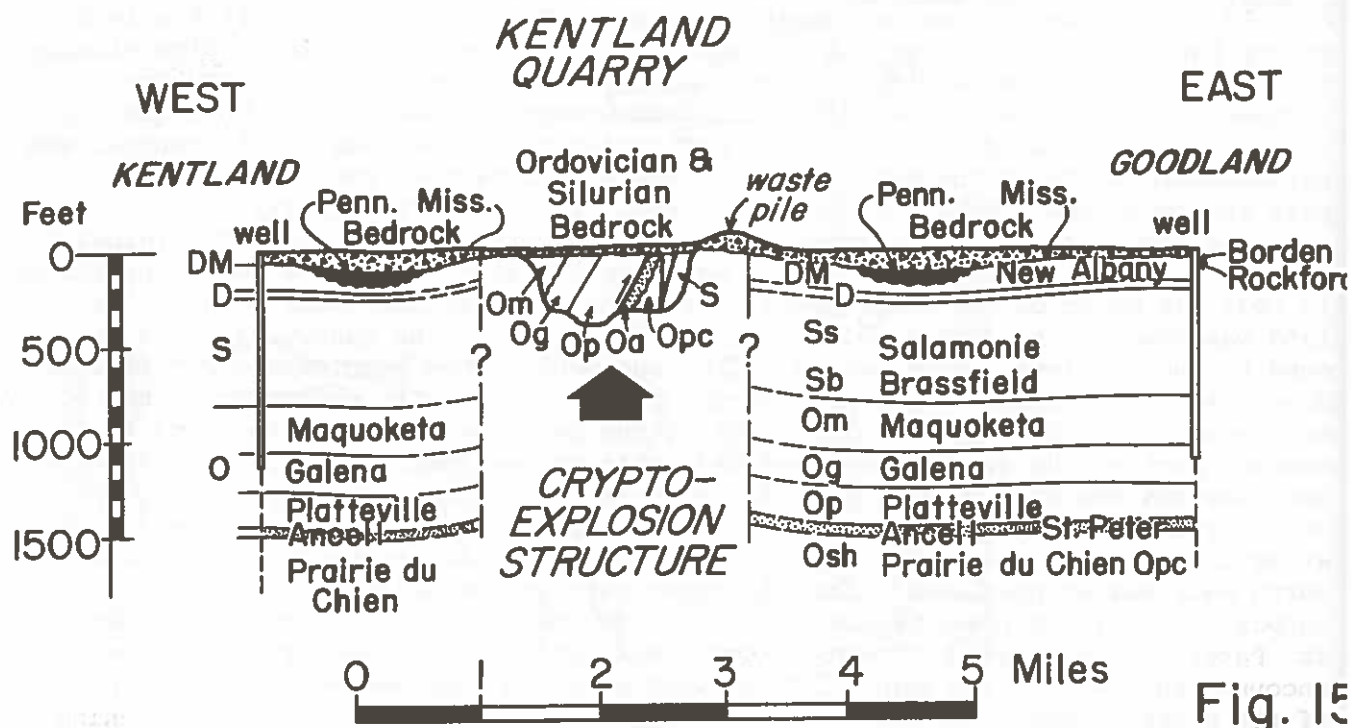


Fig. 16



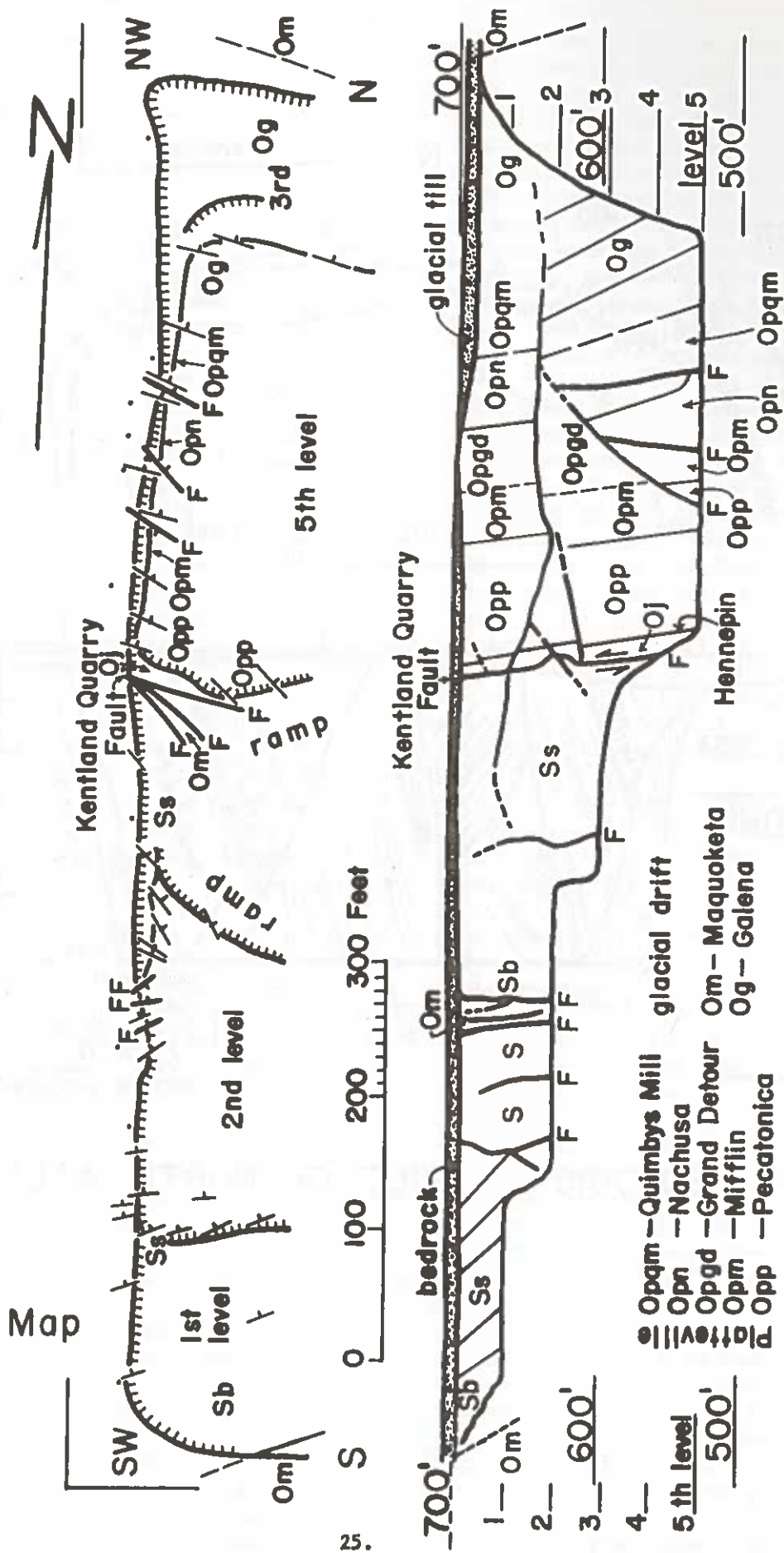


Fig. 17



In the central one-third of the quarry which includes the axial portion of the main syncline, there is a symmetry on both sides of this axis with respect to the stratigraphy and structure. Along the NNW plunging axis, the Shakopee is exposed high on the south wall and the Joachim, Platteville and Galena succession is repeated by a peculiar crescentic, nested fault mentioned above. Both flanks of this fault are transverse to the stratigraphy while the central axial portion is parallel to the strike of the beds. The fault surface is in the form of a plunging syncline somewhat parallel to the major syncline. One interpretation of this structure is that the fault is a normal dip-slip fault with the north hanging wall block down with respect to the south foot wall. Based on the geometry of the strata and the faults, this requires a large amount of throw and especially net slip. High on the south wall, there is an overhanging cornice of hanging wall which is transversely faulted close to the axis of the fold. This remnant contains upper Joachim and lower Platteville strata.

The southwest part of the quarry is a complexly interesting one. It exposes the oldest rocks in the quarry along with the youngest rocks, Shakopee Dolomite and Silurian Salamonie Dolomite respectively. The footwall of the Kentland Quarry Fault consists of the Shakopee-St. Peter sequence. This is separated on the south from the Silurian block by a narrow linear wedge or sliver of dark Maquoketa Shale. The plunging anticline of Maquoketa-Silurian rocks south of this shale wedge has faulted limbs which have been rotated towards the axis of the fold. As a result, there are three blocks to this structure. Breccias at the intersection of the bounding faults of these blocks contain chunks of dark gray Upper Devonian New Albany Shale with Tasmanites. This is the youngest Paleozoic lithology recognized in the quarry.

Kentland Quarry Fault- The Kentland Quarry Fault which winds its way throughout the quarry is really a fault zone. The main shear is crisp and sharp within parts of the brittle, granular upper St. Peter Sandstone and the tenaciously tough, brittle, aphanitic lower Joachim Dolomite. The fault surface is smooth, undulating, slickensided, chattered, and has mullion structure well developed. The surface is generally in the form of a broad open plunging syncline; however there is a pronounced anticlinal bulge to the east of the axis of the syncline and a more gentle reverse curvature to the west. The fault is a steep reverse fault which dips around 75° northwards.

Perhaps the most impressive sight in the Kentland quarry is the magnificent continuous exposure of the smooth fault surface. The east wall displays a smooth undulating fault surface generally in the Joachim Dolomite. Quarry extraction is bounded on the east by this surface. Mullion and slickensides are strikingly evident on the anticlinal surface in the SE part of the quarry and also in the western part. The rusty white St. Peter Sandstone makes up a large surface immediately east of the main synclinal axis, and the west limb has a remarkable display of the surface accessible for detailed examination.

Movement of the hanging wall was dip-slip along the axis of the fold and oblique slip on the flanks. The obliqueness increases progressively westwards on the west flank of the structure indicating greater movement of the hanging wall inward towards the axis of the syncline. The east flank also has oblique slip towards the axis. Although the main movement of the fault was reverse with hanging wall up with respect to the footwall, apparently late relaxation of compression caused normal fault slippage. Slickensides indicate this last imprint on the fault surface. Mortar-like breccias are present along the entire length of the fault.

Another important feature of the Kentland Quarry Fault is the nature of the hanging wall adjacent to the fault, that is, where it is preserved and can be observed. The rocks within about 50 feet from the fault have been broken up by faulting. Oblique slip along the flanks of the synclinal fold has caused these parts to be jostled around with their strike oblique to the main fault. Remnants of the hanging wall high on the east side of the quarry exhibit this very well. The easily recognized Hennepin key beds of rusty limonite-dripped bedding surfaces are duplicated 3 or 4 times in small blocks oblique to the main fault surface. Another block along

the ramp in the west portion of the quarry has a slickensided, mullion surface oblique to the main structure as part of the hanging wall.

It is difficult to calculate the total amount of movement along the Kentland Quarry Fault. The fault has very low obliquity with the bedding and it comes between stratigraphically adjacent or superposed strata--the St. Peter Sandstone and the Joachim Dolomite. Faulting within the quarry has cut out the upper part of the St. Peter Sandstone and the lower part of the Joachim Dolomite so that nowhere in the quarry can the thicknesses of these formations be measured. This relationship is illustrated in Fig. 16. Because of the near parallelism of the fault surface with the bedding especially in hanging wall carbonate beds and the variation in observed attitudes of these surfaces, it is even difficult to approximate the amount of displacement. Even though the stratigraphic throw is very small, the net slip must be reasonably large and significant.

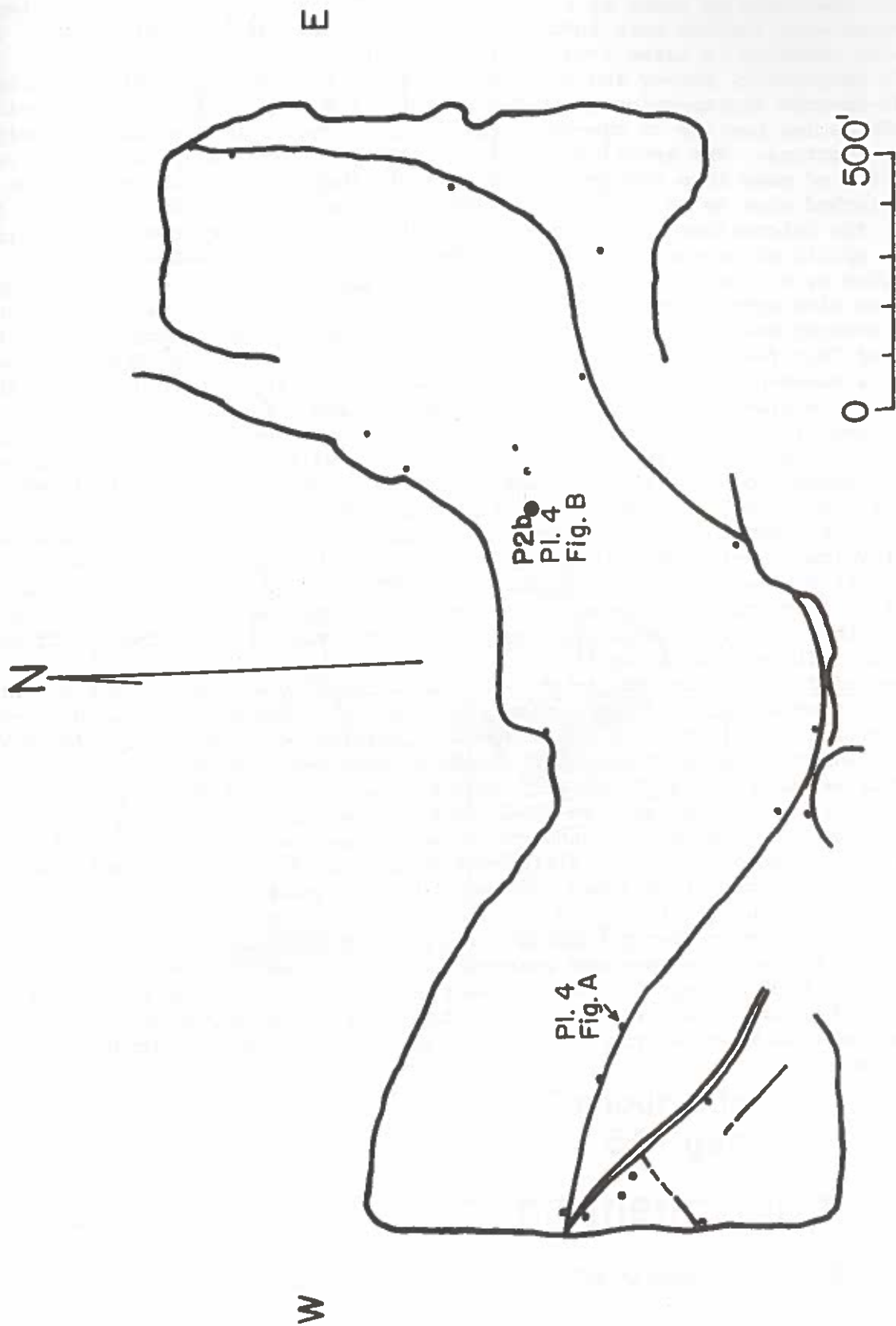
Other Structures- There is one exposure of a low angle thrust fault along an old abandoned ramp on the south side of the quarry west of the fold axis. Shakopee Dolomite and St. Peter Sandstone in normal succession is moved northwards along a south-dipping fault surface. Stratigraphic displacement is less than 50 feet.

Slices and patches of dark Maquoketa Shale crop out in scattered places in the quarry east and southwest of the Kentland Quarry Fault. This refers to structurally displaced masses rather than the normal sequence along the north wall of the quarry. The small patches are wedged between faults or caught up between blocks along the fault surface so that their distribution is somewhat random.

Kentland Breccias- Throughout the quarry, faults, fractures, and fissures are filled with mortar-like breccias. The matrix is light gray to gray, fine-grained material and the clasts range in size from sand size to pieces greater than two feet in diameter. Larger blocks may be present. Fragments consist of limestone, dolomite, chert, dark-gray and light-green shale, fossil chunks (e.g. stromatoporoid heads 6" diameter of Silurian affinity), quartz grains, sulphides and other materials. The clasts seem to be obviously derived from strata exposed in the quarry rocks. The nature of the breccias and their distribution, Fig. 19 gives one the intuitive impression that there was extensive pulverization of rock and dilation of volume accompanying catastrophic disruption of strata to grout the material into openings prior to and during collapse and settling of the blocks. Perhaps fluids may have also played some role. The similarity of the breccias throughout the quarry suggests that they had some common source.

Shatter Cones- The Kentland quarry is perhaps the type "shatter-cone" locality in this country. It was here on the basis of shatter cones that Dietz in 1947 noticed their preferred upward orientation and suggested meteorite impact. These structures are present in many places throughout the main quarry and also in the abandoned McKee quarry. Throughout quarry operations, examples have been found and reported only to be removed. They occur in just about every lithology and formation in the quarry although they are not found everywhere. Striking examples have been seen and photographed in the Joachim Dolomite, Platteville Group, and Maquoketa Shale. Generally the finer and denser the rock, the better the chance for shatter cones. Most commonly they are small, only a few inches in height; however very large ones have been observed, up to several meters. Examples are scattered in the quarry but swarms of small ones are present in Silurian carbonates in the southwest part of the quarry. Observations over the years indicate that most of the shatter cones point upward stratigraphically; yet there are some that point in both directions. Preferred orientation data has not been systematically plotted yet.





BRECCIA LOCATIONS IN KENTLAND QUARRY

Fig. 19

Geophysics- A detailed geophysical study of the Kentland disturbed area has recently been made by Tudor et al, 1972. Many shot holes were drilled to bedrock which will furnish more information on the nature of bedrock geology. The following abstract is taken from their 1972 presentation.

"A geophysical survey and drilling program in the Kentland disturbed area, a drift-covered cryptoexplosion structure in northwestern Indiana, has provided new information bearing on the areal extent, form, geologic age, and the origin of the structure. The areal extent is interpreted from a detailed gravity survey consisting of more than 2600 closely spaced stations which shows the outline of the disturbed area to be subcircular with a maximum radius of approximately four miles. The deformation is interpreted as being typically cryptoexplosive with a central uplift of intensely fractured older rocks raised more than 1500 feet surrounded by at least one ring syncline at a radius of two miles, and a ring anticline with approximately 50 feet of structural relief at a radius of four miles.

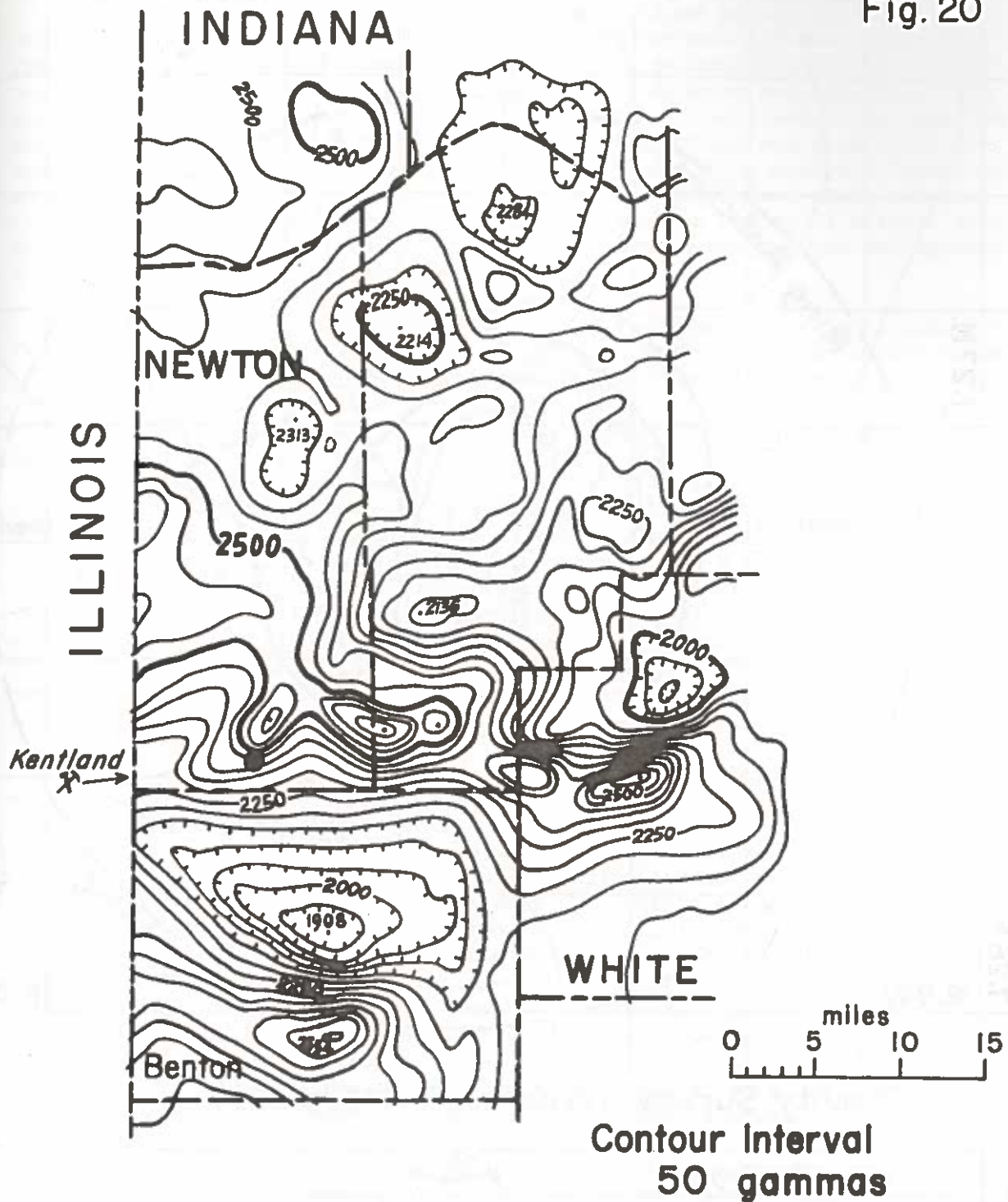
A gravity positive anomaly of 3.5 to 4.0 milligals has a maximum depth to source of 7800 feet, and shows a mass excess. Three-dimensional gravity modeling suggests a basement uplift of 2000 to 3000 feet. The ring syncline is best displayed on the gravity residual from the sixth degree polynomial surface which shows a negative anomaly of 1.0 milligals. The interpretation of the negative anomaly is supported by two dimensional gravity modeling. An encircling outer positive anomaly of less than 0.5 milligals and a coincident low relief, structural high are the basis for interpreting the ring anticline.

The disturbance is interpreted as a cryptoexplosion structure because neither a cryptovolcanic nor a meteoritic impact origin can be demonstrated unequivocally.

Uplift of the sedimentary Paleozoic rocks in the quarry of 1800 feet and the indication from gravity information of an uplifted basement 2000 to 3000 feet suggests that the disturbance is deep seated. The magnitude of the uplift does not seem to diminish with depth.

Simple-minded Explanation of Dynamics of Disturbance- The oldest rocks are brought up in the central uplifted area where the dilation becomes greatest. High energy concentration in a short time span causes pulverization, brecciation, fracturing, faulting and centripetal transfer followed by ring collapse of the central area and synclinal depression of the surrounding area. Kentland quarry is the south part of this central collapse in which rocks are rotated vertically, e.g., the oldest Shakopee Dolomite and younger beds are brought up and tilted to the north. During this rotation, there is differential gliding of the rock layers one over the other as the mass is pitched northward. Shear failure takes place in the mechanically granulated rocks and the dense brittle beds. Juxtaposition of such lithologies in the St. Peter Sandstone and Joachim Dolomite is the logical zone of weakness to produce the Kentland Quarry Fault zone. Rotation of the block to the north causes younger beds to ride up older ones. Shearing takes place along the St. Peter-Joachim contact with curved surface dipping north concave side up. Reverse faulting results from this pattern and final relaxation produces some gravity movement.

Fig. 20



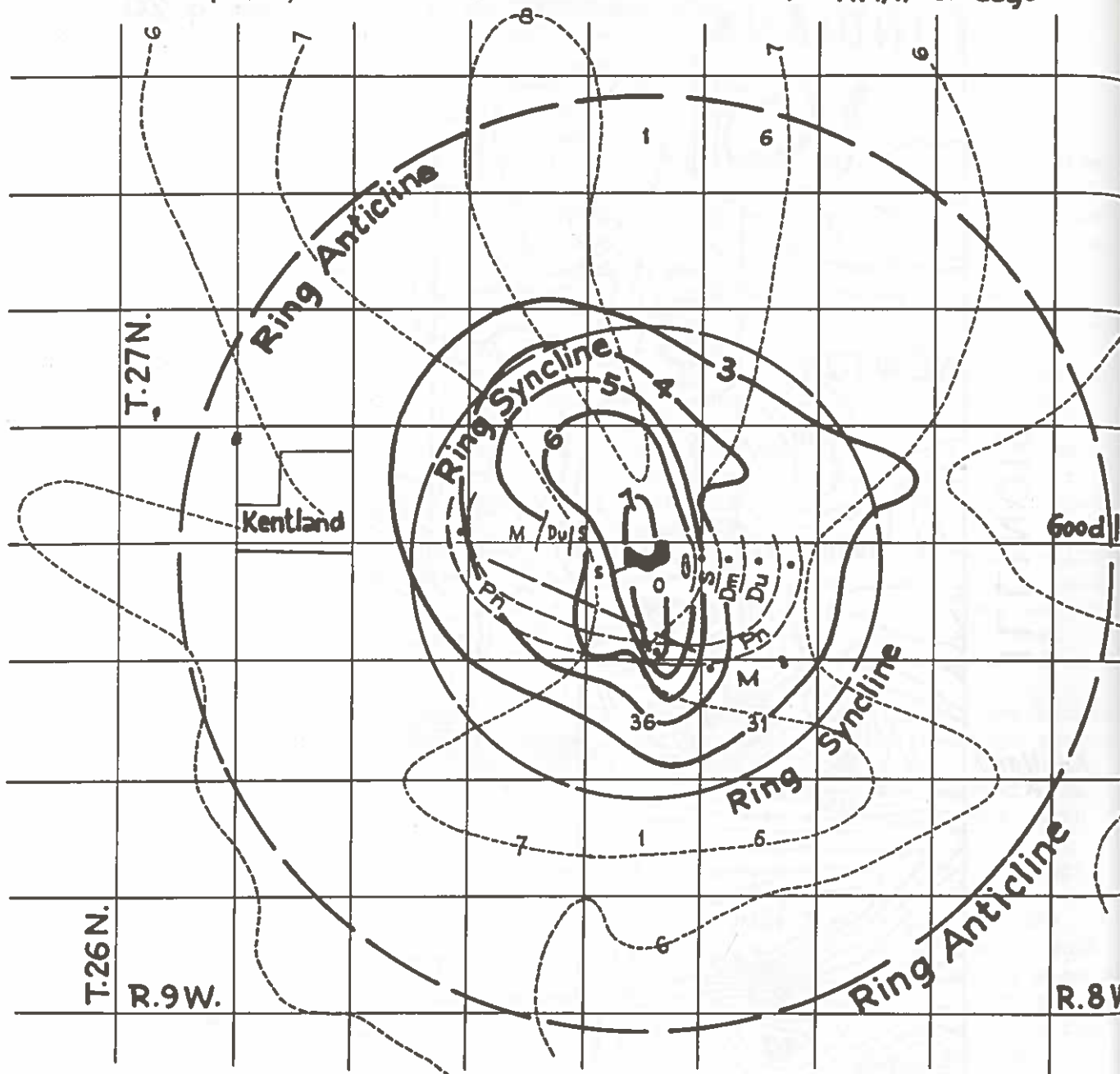
## Total Intensity Aeromagnetic Map

Henderson & Zietz, 1958, USGS. P.P. 316-B

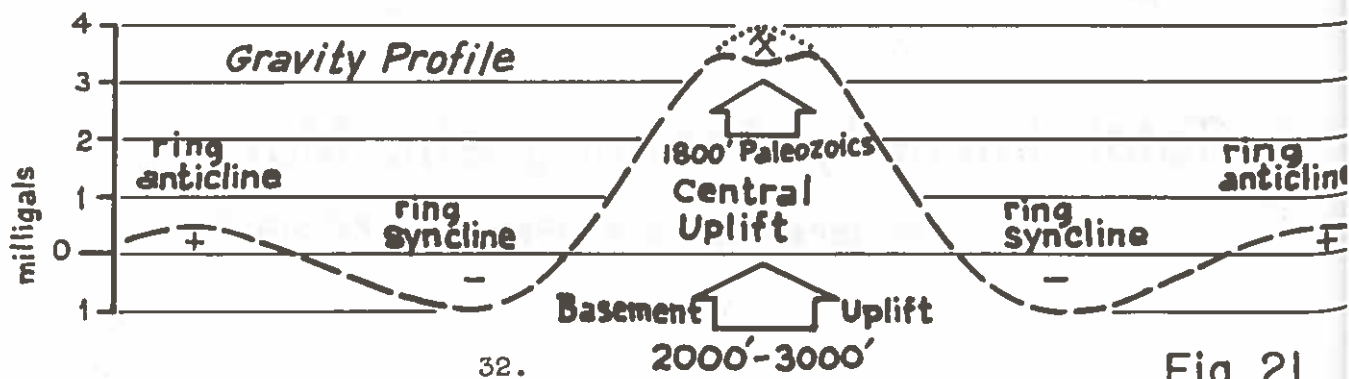


**Radio Field Intensity Contour**  
(Pullen, 1953, p.48, Fig.29; p.50, Fig.30)

—— 4 WIND Chicago  
----- 7 WAAF Chicago



**Gravity Survey** (Tudor et al, 1972, p.353)



**Fig. 21**

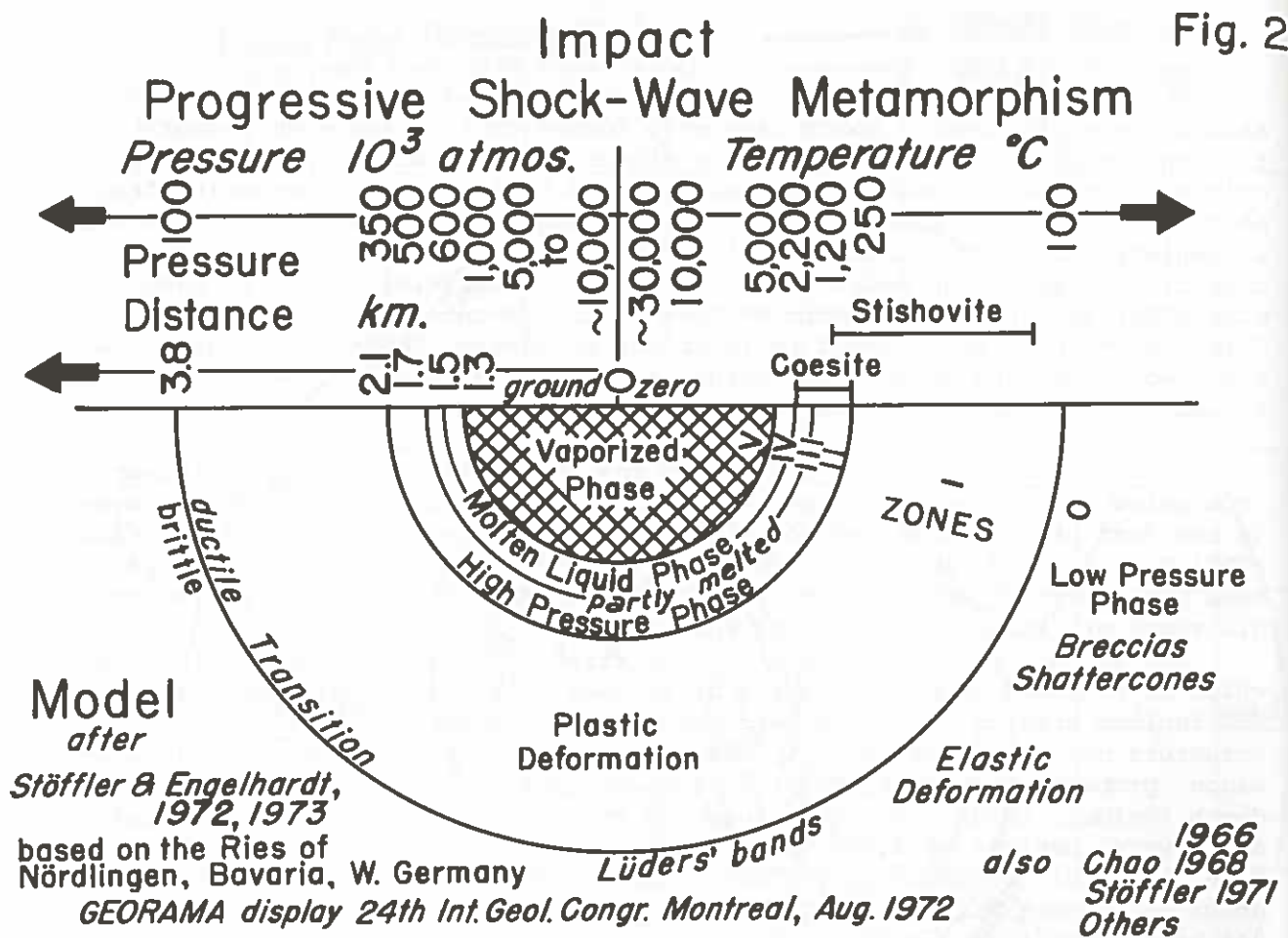
There are many small to large, complex localized structural anomalies around the world some of which have well formed craters and even meteorite fragments associated with them. Many others are astroblemes in which their original surface expression has been modified by erosion and meteorite fragments or evidence of igneous activity is missing. A vast amount of data has accumulated for these structures including on the ground and from space recognition, high energy model studies, computer simulation analysis, chemical, mineralogical, and petrographic studies to try to understand their origins. Criteria has been established to favor one or another theory of origin; however geological and geophysical evidence does not always provide the answers. A summary of theories is given as follows.

Cryptovolcanic theory- The energy for structural disruption originates from below due to explosive release of confined volcanic gases, mostly steam, in the form of a blowout upwards without igneous injection (Branca and Fraas, 1905; Bucher, 1933, 1936, and others). This may include the basement and does not always or necessarily have to be accompanied by igneous extrusion. Diatremes are thought to have had this origin.

The Serpent Mound structure in Ohio first described by Bucher, 1933, in which he proposed a cryptovolcanic origin has a centrally uplifted, folded and faulted area in which shatter cones occur. Recent re-study of this structure has concluded that it owes its character to a series of gas explosions probably resulting from resurgent boiling of a crystallizing melt at depth (Reidel, 1975). The structure was activated along pre-existing faults and several periods of disturbance, brecciation, mylonization, and mineralization occurred. Clear to yellow to purple sphalerite and related zinc minerals occur as breccia fill and replacement but impact metamorphic indicators have not been identified.

Meteorite impact theory- Energy originates from above in the form of a meteorite or comet head travelling at hypersonic velocity which impacts the earth. The energy is dissipated by penetration of the extra-terrestrial body, compression, explosion, and ejection of the shocked, dilated rock. Meteorite craters and ancient geologic impact scars, astroblemes, are manifestations of impact (Dietz, 1961, 1972). Such catastrophic collision and accompanying shock mechanics produces impact metamorphism which is modelled in Fig. 22 (Chao, 1966; Engelhardt, Stöffler, and Schneider, 1960; Engelhardt, 1972; Stöffler, 1973; and others). High pressure polymorph minerals may be formed such as maskelynite, coesite, stishovite, and lechatelierite. Solid state diaplectic and melted fused quartz glasses and other minerals may be formed as well as planar deformation lamellae in quartz, and mono- and polymictic breccias. The above petrographic shock metamorphic effects are often accompanied by shatter cones regarded as conical shock fractures formed along the boundary between an elastic and plastic shock wave (Dietz, 1972). The compressional shock wave produces shatter cones whose apexes converge towards ground zero (point of impact); thereby etching the shock wave vector field into the geologic record. Reflected waves may give inverted cones with their apexes pointing downwards. There are a score or

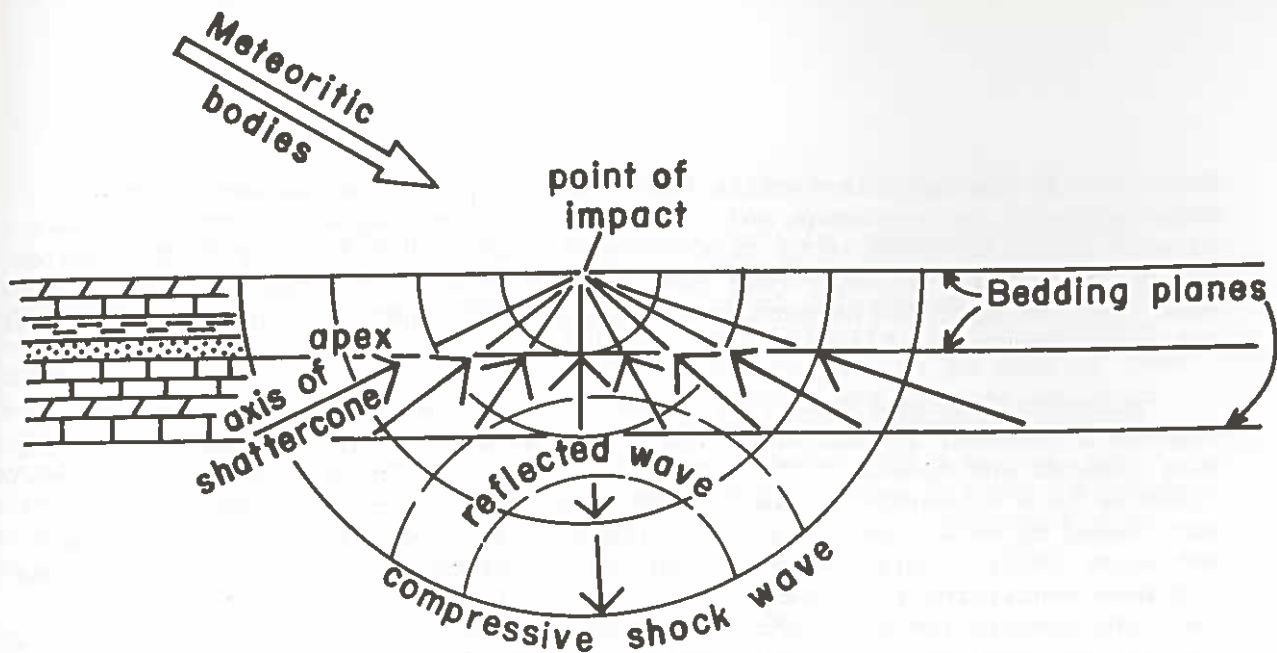
Fig. 22



STAGES		PRODUCTS	EXAMPLES	
			Peak Pres (kb.)	Post-shock T. $^{\circ}\text{C}$
5	Vapor phase <i>Silicate</i>	Boiling point of the rock melt	> 800	> 3000 $^{\circ}$
4	Liquid phase <i>Total Melt</i>	flowable Rock melts with <i>Lechatellierite</i> (fused quartz)	600	1500 $^{\circ}$
3	High Pressure phases <i>a Partial Melt</i>	<i>Coesite</i> ( $\text{SiO}_2$ ) in glassy quartz and fused-feldspar <i>vesicular</i>	550	1300 $^{\circ}$
2	High Pressure phases <i>diaplectic glass</i>	Unfused quartz and feldspar ( <i>Maskelynite</i> ) glasses ( <i>solid state</i> )	450	900 $^{\circ}$
1	High and Low Pressure phases <i>diaplectic crystals</i>	Quartz and feldspar with planar elements <i>lamellae</i>	300	350 $^{\circ}$
0	Low Pressure phases	Breccias, Shattercones, kinked micas	100	100 $^{\circ}$

density within shock front → post shock density →

↑ PRESSURE ↑ TEMPERATURE ↑



more of cryptoexplosion structures, presumed to be astroblemes, which have shatter cones according to Dietz, 1972.

Fault theory- Energy from below responsible for major faulting has been suggested as the origin of these complex localized faulted structures. Solid evidence is lacking to account for all phenomena present in the structures. In some cases the cryptoexplosion structures are associated with surface faults of major extent but this may be fortuitous. Possibly a triple junction type of fault pattern might develop anomalous confining pressures which result in explosive relief and release of the energy. It was suggested by Jamieson, 1963, that pressures as high as 200 kilobars might develop locally and persist for a short time in the earth's crust. His speculation was based on high pressure experiments whose geometries have direct analogues in nature; however uniformitarianism has not been demonstrated with actual natural examples. Sliding friction experiments have been made by Friedman, Logan, and Rigert, 1974, on sandstone which yielded glass-indurated quartz gouge. The sandstone was deformed under confining pressures up to 5 kb. and temperatures to  $410^{\circ}\text{C}$ . Occurrence of glass along natural faults (Scott and Drever, 1954) and in the experiments indicates that local silica-fusion temperatures occur during fractional sliding. However, the experiments were done on dry sandstone and the effects of fluid pressures has not been determined as far as I know.

Diapiric theory- Origin of the energy is from below due to very high fluid pressures, strong inward horizontal confining stresses, formation of a diapiric core, and explosive hydrostatic upward extrusion of the rock column (Nicolaysen, 1972). Elastic energy stored in compressed rock and compressed pore fluid is thought to be the massive energy source needed to form such cryptoexplosion structures. If sufficient compressive strain energy is stored in the upward-moving rock column, Lüders' band phenomena are expected where the compressed column approaches the earth's surface and encounters a zone of sudden, marked relief from the horizontal confining stresses. The Lüders shock fronts account for shock deformation textures characteristic of the central uplift. Shatter cones develop through the penetration of tensile joints into the plastic zone where Lüders' bands form (Nicolaysen, 1972), the latter represent



fractures at the brittle-ductile transition. Lüders' bands were produced experimentally on sandstone and limestone and were compared with a possible natural occurring example by Friedman and Logan, 1973; however no discussion was given to their relationship with shatter cones. The experiments of Jamieson, 1963, should also be mentioned although their application is uncertain in natural situations.

Solution Collapse Evaporite Dome- At least one disturbance, the Des Plaines structure, is attributed to a leached and partly collapsed evaporite dome (Langan and Speed, 1973). The Des Plaines disturbance in northeastern Illinois is a subsurface anomaly with a central core raised about 0.3 km. surrounded by an annular depression (Emerich and Bergstrom, 1962; Buschbach and Heim, 1972). This complexly faulted structure is interpreted to be over a graben containing pre-Upper Cambrian evaporites down-faulted into pre-Cambrian crystalline basement. Anhydrite is present in a single deep well in central Michigan and it is regarded as of Cambrian age (Catacosis, 1973, A.A.P.G. 57(12):2408). The structural interpretation is based on a localized gravity low coincident with a negative magnetic anomaly. The mechanics to produce the configuration and stratigraphic displacement of the structure are not clear. Access is limited to subsurface information and indirect observations so that little is known concerning presence or absence of shatter cones, breccias, metamorphic petrographic indicators and other factors.

Cryptoexplosion structures- Since cryptovolcanism and meteorite impact designations are genetic and imply an origin which is not substantiated for many structures, the noncommittal term cryptoexplosion is used (Dietz, 1959). Shatter coning appears to be a valid criterion according to Dietz, 1972, for relating geologic structure to intense shock and that orientation of cones is central in the structure thereby implying an astrobleme cosmic impact origin. However positive proof in the form of solid evidence of the missile is most often lacking. Geologic strategy (scientific method including the multiple working hypothesis) allows for some reasonable doubt (Nicolaysen, 1972; Dietz, 1972). Of course, a low density impacting body, such as a comet, would generate a shock wave at the surface but would volatilize upon impact with little or no penetration or direct evidence of its visit (Roddy, 1968; Milton and Roddy, 1972). Cryptoexplosion should continue to be used if there is insufficient proof of the structures origin.

## Conclusions

To evaluate the origin of this structure, one is impressed with the major anomalous structural disruption in an otherwise undisturbed area, the geometrical pattern, and the rock mechanics of deformation. The structure is that of a faulted dome with the Shakopee Dolomite, oldest bedrock formation, raised from its normal stratigraphic position by as much as 1800 feet vertically, Figs. 4 and 15. The quarry exposes the central uplifted part of the dome; however the structure is somewhat a semi-circular plunging syncline. Perhaps the quarry represents the south half of a central collapsed structural depression. There is some evidence that a linear feature south of the quarry represents a fault which separates the disturbed area on the north from the undisturbed area south of it.

Folding and shearing are impressive in the central part of the disturbance exposed in the quarry. Fault surfaces are sharp and bold with extensive slickensides and mullion structure. Dense carbonates and granular quartz sandstone rocks are fractured and shattered along the shear zone. Dense brittle rocks have shatter cones which are developed throughout the quarry and they also occur in shales and sandstones. Most commonly their apexes point upwards stratigraphically but some point to the bottom of the bed. Quartz grains are highly fractured and contain omega lamellae and cleavage produced by high strain rate deformation (Friedman, pers. comm. 6/20/73). Some quartz grains from Shakopee Dolomite acid residues are offset in step fashion and recemented. Asterism in the X-ray pattern has been reported by Simon and Dacheille, 1965. Coesite has been reported in very low concentration by Cohen, Bunch, and Reid, 1961, from the St. Peter Sandstone found in the southeast part of the quarry. However, as far as I know, no one has been able to confirm the presence of coesite in the quarry. Closely spaced fractures (joints) are common especially in the St. Peter Sandstone adjacent to the faults, Pl. 5C. Breccias are found throughout the quarry as injections (?) along the faults and fissure fill out from the fractures. Clasts in the polymictic breccias are related to rocks in the quarry exposure, e.g. limestone and dolomite fragments, sandstone, green and black shale, white chert, and other pieces with angular shape in a mortar-like groundmass. The composition and textures of the breccias throughout the quarry are very similar. Neither volcanic materials nor metallic meteorite fragments have been found but there is no strong reason to expect to find these.

There are many interesting facets to the geology of Kentland and these include sedimentation, stratigraphy, paleontology, structural geology, mineralogy, petrology, petrography, rock mechanics, geophysics, geochemistry, and others. There are many problems and interesting projects which require perceptive observation, field and laboratory investigation, scientific judgment, and articulate exposition. There are many enigmatic and frustrating problems waiting for answers. Clearly Kentland structure and quarry exposures serve as a challenge and study for students.

The array of rock deformation structures and transformations runs from shatter cones and breccias through quartz lamellae to coesite (?) yet no one has recognized either diaplectic or fused (melt) glasses. Shatter cone orientations suggest convergence of

apexes upwards towards a center. Geophysical evidence by Tudor, 1971, and Tudor, Mead, Rudman, and Blakely, 1972, suggests a 2000 to 3000 foot uplift involving the basement which does not indicate decrease of energy with depth.

In summary, it is significant that geological and geophysical data has not proven the origin of this structure unequivocally. More information is needed.



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Geological Map of Indiana

Glacial Map of Indiana

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Kentland, Indiana, 1962	1:24,000	5' C.I.
Wadena, Indiana, 1962	1:24,000	5' C.I.
Goodland, Indiana, 1962	1:24,000	5' C.I.
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Figure 23

An interpretation of the bedrock geology of the Kentland dome disturbed area. Source of the data is from Tudor's (1971) geophysical bedrock drill program, Indiana Geological Survey drill holes-cuttings and cores, and geological mapping in the quarries. Stratigraphic identifications of subsurface data was done by the staff geologists of the Indiana Geological Survey. Cores and cuttings were examined in the storage files of the Survey at Bloomington, Indiana.

Grateful acknowledgement is made to Dr. Daniel Tudor and members of the Indiana Geological Survey for their generous cooperation and wealth of data related to this structure made available to the public. The Northern Indiana Public Service Company in part subsidized Tudor's research and are to be thanked for releasing the drilling information.

Note that Lower Ordovician rocks are brought up in the central core of the truncated dome (faulted) which is surrounded by the Lower Mississippian Borden Group which would normally constitute the bedrock of this area. The oldest rocks represent a vertical displacement of at least 1800 feet. The few isolated occurrences of Pennsylvanian strata encountered in several drill holes are interpreted as stream channel-fill outliers similar to the one exposed in Fountain Park about 1 mile north of Remington, Indiana, and others found to the south adjacent to the Pennsylvanian margin (east side) of the Illinois Basin.

Fig. 23

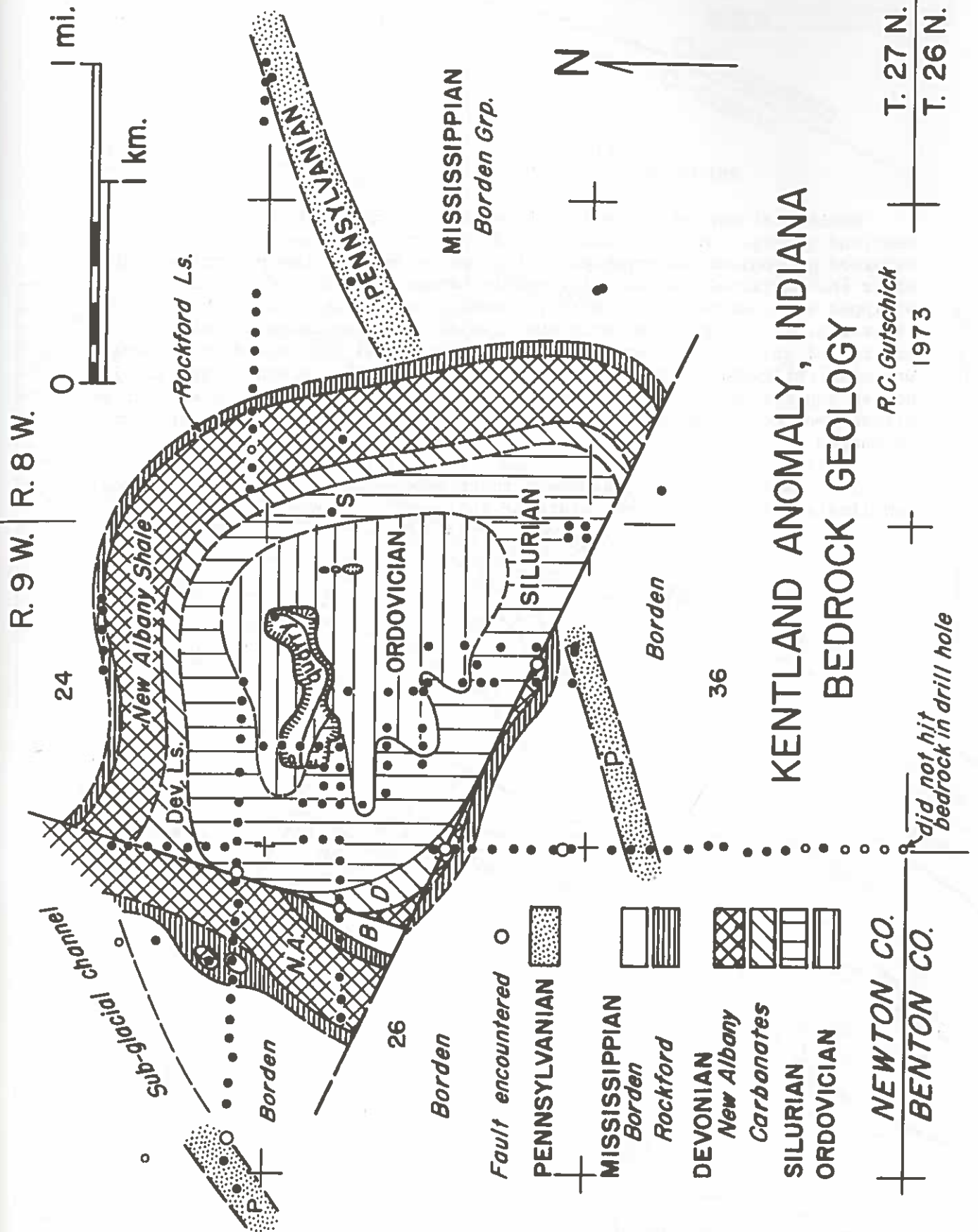


Figure 24

Geological map of the Means property and western part of the Kentland quarry. Of particular significance is the great amount of detailed geological observations which can be made on the bedrock surface after the surficial glacial till mantle beneath the farm field is stripped and removed by bulldozer, shovel, and trucks. Bedrock exposures, lithologies, stratigraphic units from groups to members, tracing of units, structure (bedding, faulting and folding, drag of beds, breccias, slickensides and directional properties), paleontology, glacial polish and striations were identified, located, and mapped by plane table-alidade method. Glacial drift thickness and bedrock topography can also be mapped.

This small area has the oldest rocks exposed and is probably the most complicated structure in the state of Indiana.

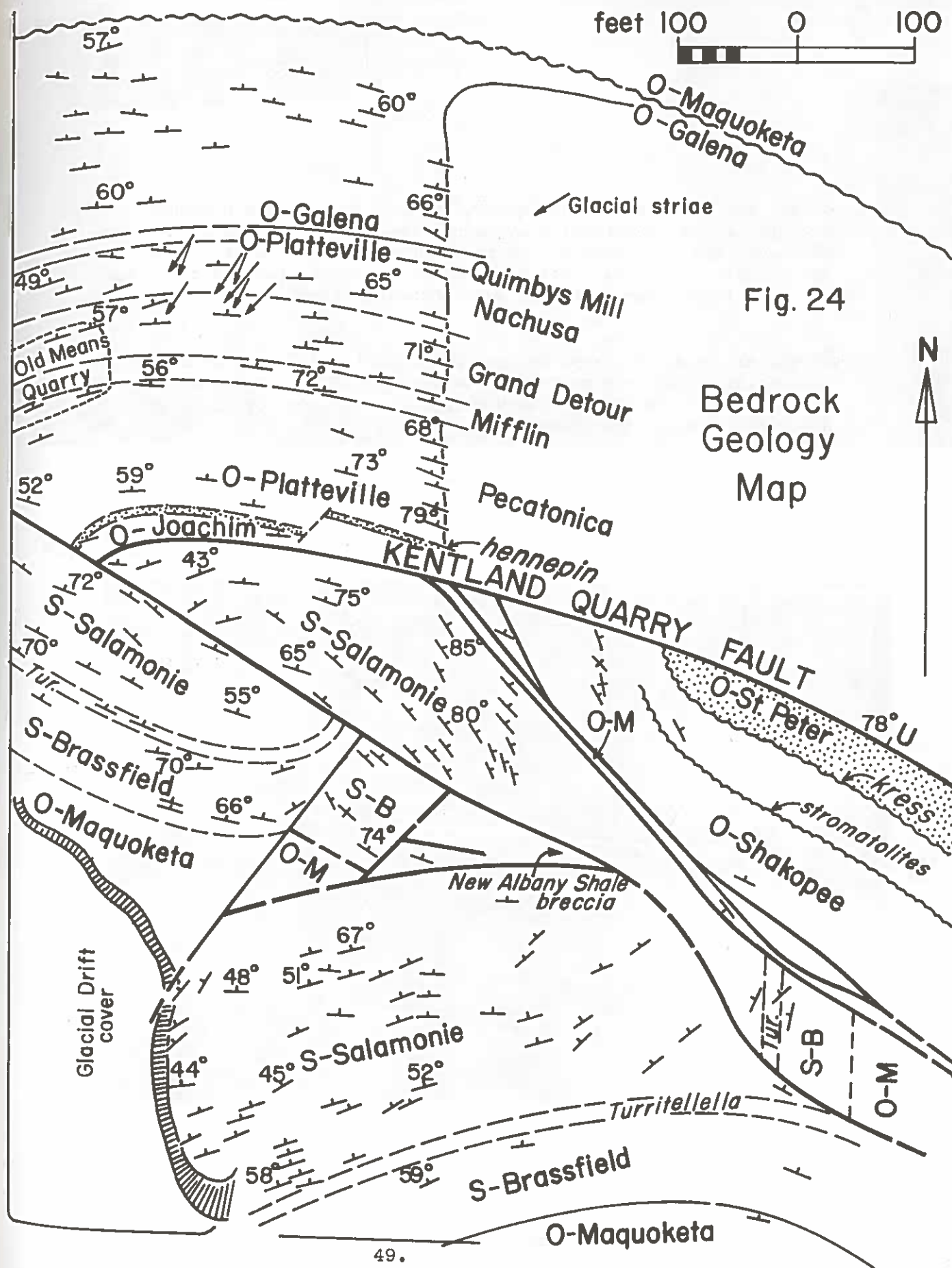
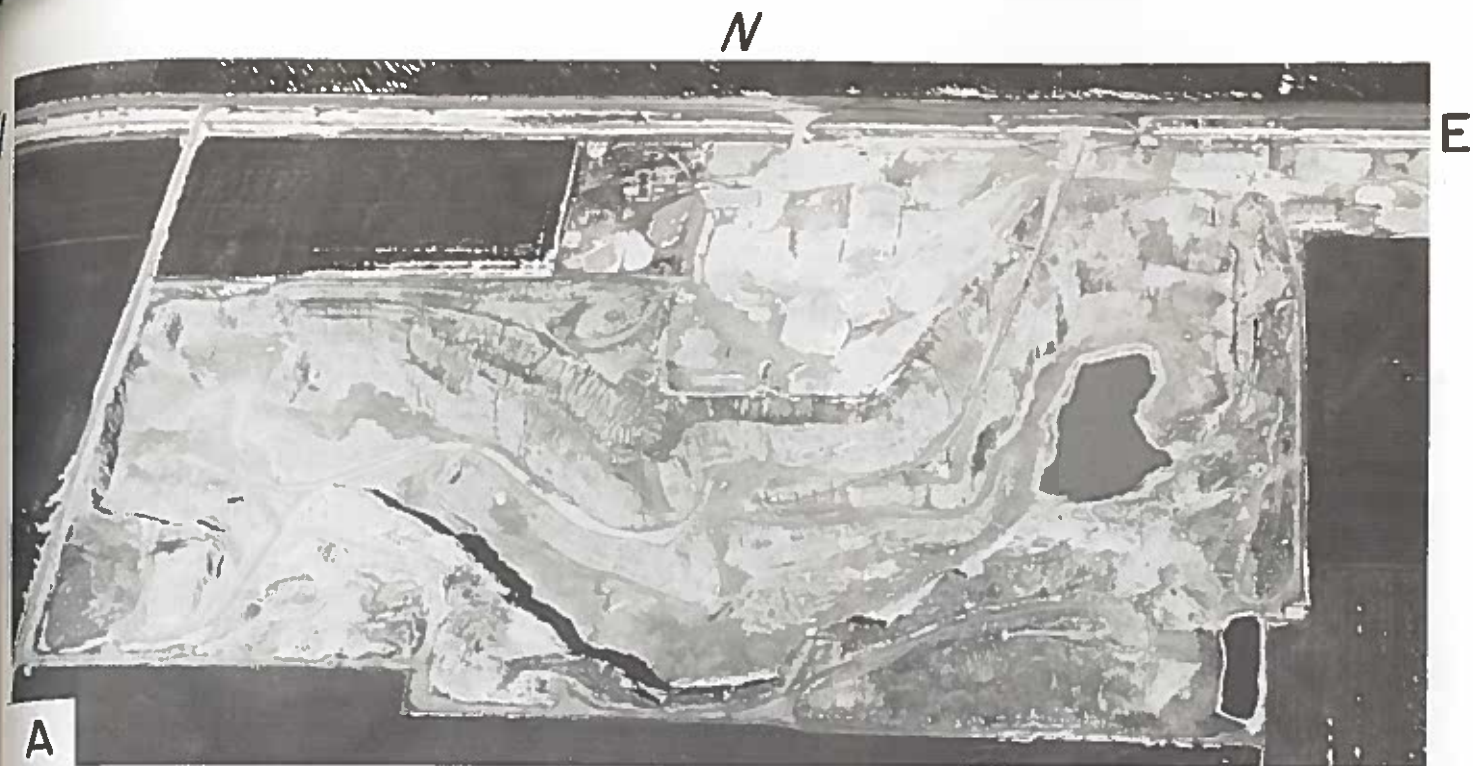


Plate 1

- A. Oblique air view of Kentland quarry looking north shows U-shaped pattern of faulted plunging syncline viewed down dip and down plunge of fold. The west side of the photo shows that the west limb of the plunging syncline is also the east limb of a plunging anticline and both folds plunge steeply NNW. Compare with Figs. 13 and 24.
- B. Oblique air view of sharp, narrow, diagonal linear strip which runs diagonally across the south half of section 25, T. 27 N., R. 9 W. Photo is view towards the south with the south edge of the quarry along the bottom edge of the photo.





*Linear  
feature*

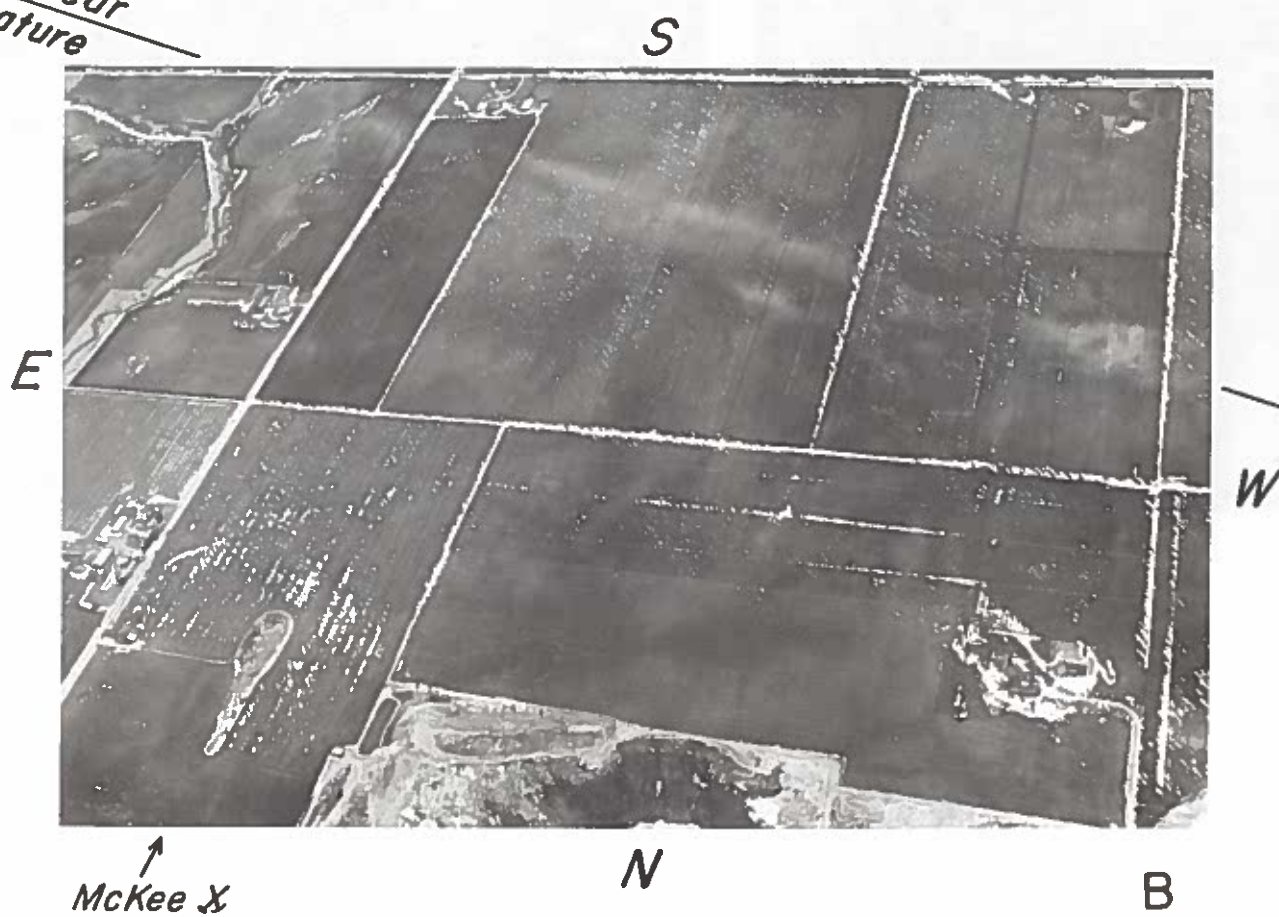




Plate 2

- A. Oblique air view of the Kentland quarry looking almost directly to the east. Steep south wall to the right is the Kentland Quarry Fault along the footwall contact. Quarry pit outlines the extent of Middle Ordovician Platteville-Galena carbonate rocks. High on the north wall in the foreground, glacial till overlies the dark steeply northward dipping Maquoketa Shale which is propped in place by the top few beds of the Galena Group. The Means property is in the lower part of the photo. The picture was taken from a helicopter, April 4, 1964.
- B. Oblique air view of linear surface feature looking ESE from point south of quarry. Land surface is till plain. The light colored linear pattern is a southeast continuation of that shown in Plate 1, Figure B.



Plate 3

- A. Complexly faulted north wall in the northeast part of the quarry. Middle Ordovician carbonate rocks of the Platteville-Galena Groups are partly duplicated by faulting. Structure and stratigraphy is graphically shown in Figure 18.
  
- B. Kentland Quarry Fault displacing brittle, granular St. Peter Sandstone of the footwall sharply against light colored, fine-grained, hard, brittle Joachim Dolomite of the footwall. Structure is a steep reverse fault. Location of view is shown in Figure 14.

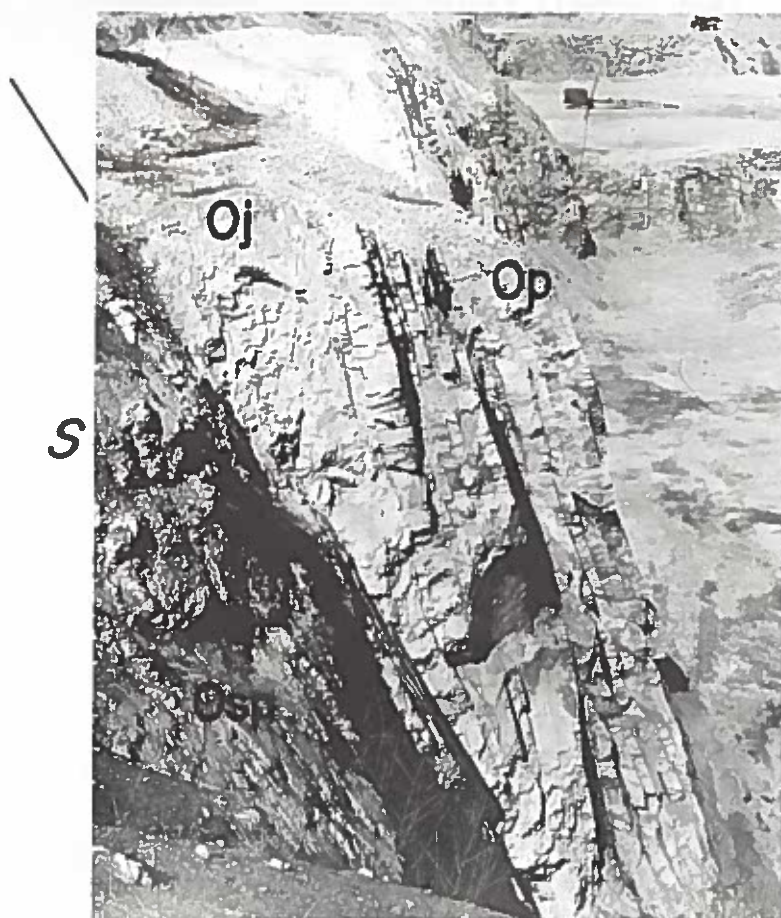
W



E

A

*See Fig. 18*



S

N

B

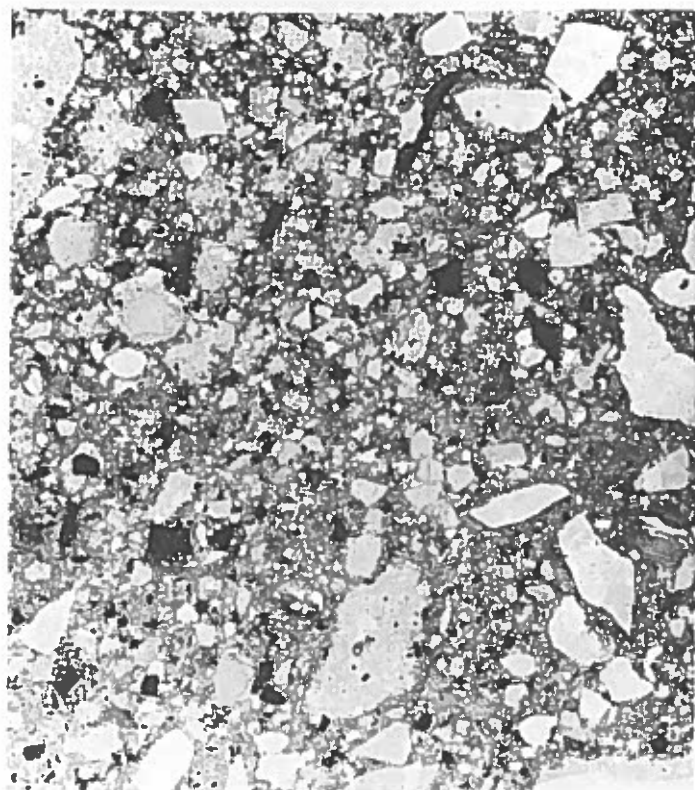
Plate 4

- A. Fault breccia along footwall surface of Kentland Quarry Fault where wall has been stripped back and exposed by quarry operations. 6" black scale is shown below center of photo. Note rectangular slab clast of dark shale left of center. See Figure 19 for location.
- B. Polymictic breccia with angular which chert, dark shale, and carbonate clasts in a cataclastic mortar-like groundmass. Sample P2b was found along a narrow 2" fracture fill and location is shown in Figure 19. Photo was made from thin-section.
- C. Slickenslided footwall fault surface with mullion structure along the Kentland Quarry Fault. Exposure is about 25 feet or more wide and its location is shown in Figure 14.





A



0 5 10 mm. 20

B



C

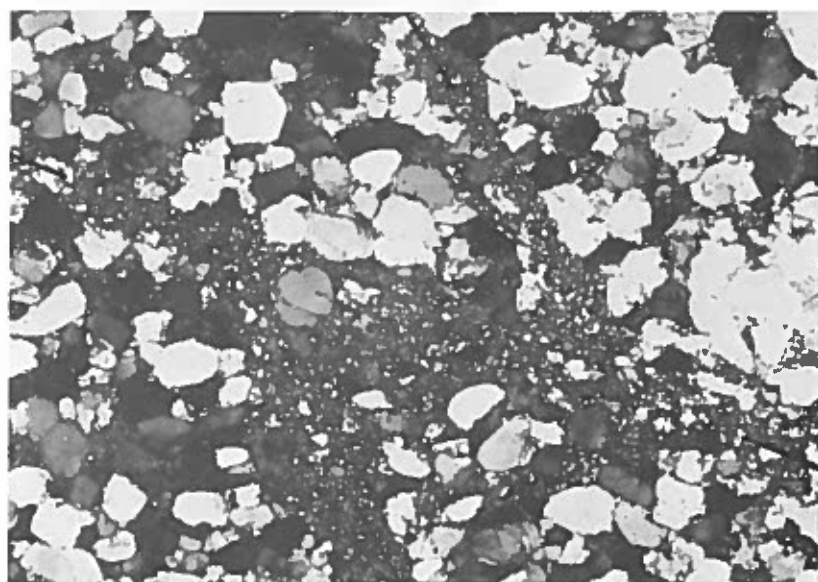


Plate 5

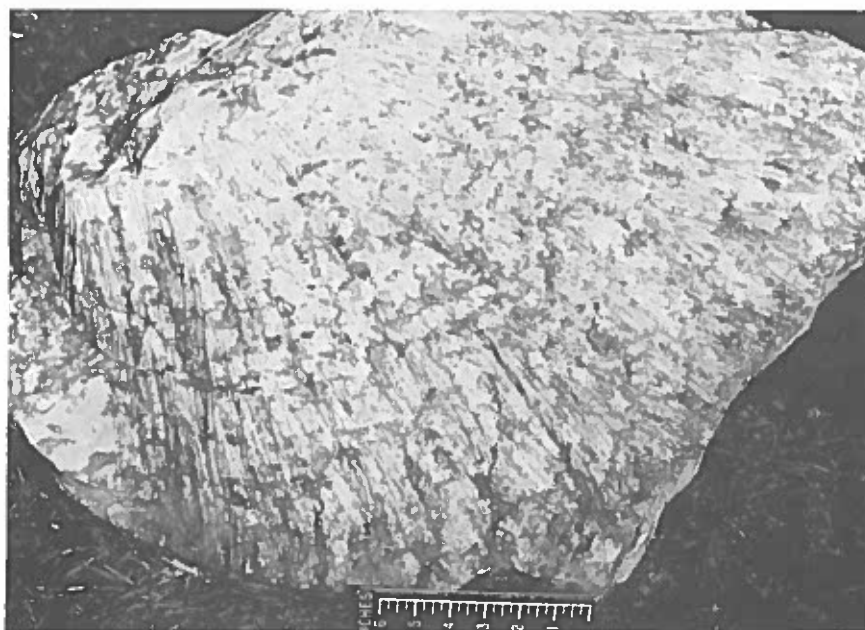
- A. Large shatter cone in the Maquoketa Shale with prominent rounded ridges and sharp intervening striae. Trace of the bedding is indicated by the light colored bands which cross the ridges. The apex of this large cone points down stratigraphically towards the top of the Galena dolomite. Shatter cone occurred along the west side of the overhead belt ramp. Photo taken November 7, 1959.
- B. Shatter cone in Place in Platteville Pecatonica Member with apex pointing down stratigraphically. Occurs below and south-west of silo. Photo taken March 3, 1972.
- C. St. Peter quartz sandstone showing cataclastic shear fracture granulated gouge along diagonal shears marked along margin of photo. The sandstone is medium- to coarse-grained in contrast to the finer crushed quartz. Photo of thin-section Kdt<sub>2</sub> prepared by Dr. Mel Friedman of Texas A. & M. University.
- D. Large well-formed single shatter cone in mottled limestone showing the intricate pattern of peripheral conelet clusters with horsetail-like ridges.



A



C



D



67 (200)  
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1982  
no. 4

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*Field Trip No. 4*

# Geology of the Kentland Structural Anomaly, Northwestern Indiana – Update

Raymond C. Gutschick



16th Annual Meeting, North-Central Section  
Geological Society of America  
Field Guidebook                      May 1, 1982

Edward J. Cray, Jr.  
Field Trip Chairman

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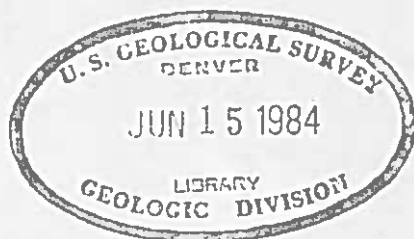
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**GEOLOGY OF THE KENTLAND STRUCTURAL ANOMALY,**

**NORTHWESTERN INDIANA — UPDATE**

**Study for Earth Science Students**

**FIELD GUIDE**



**Raymond C. Gutschick, Research Geologist  
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Notre Dame, Indiana 46556**

**16th Annual Meeting, North Central Section, Geological Society of America  
Sponsored by the Department of Geosciences, Purdue University, West Lafayette,  
Indiana 47907, April 29-30, 1982. Field trip Saturday, May 1, 1982.**

**MAR 12 1991  
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The photo of Samuel Means is from framed portrait that Mr. M. Ford kindly allowed the author to photograph when the picture was being removed from the farmhouse before the latter's destruction. The photo of John McKee is from a family group picture taken in Kentland, Indiana, in 1897, which was kindly loaned to me for this guidebook by Mr. and Mrs. Ross McKee, owners of the McKee farm and quarry.

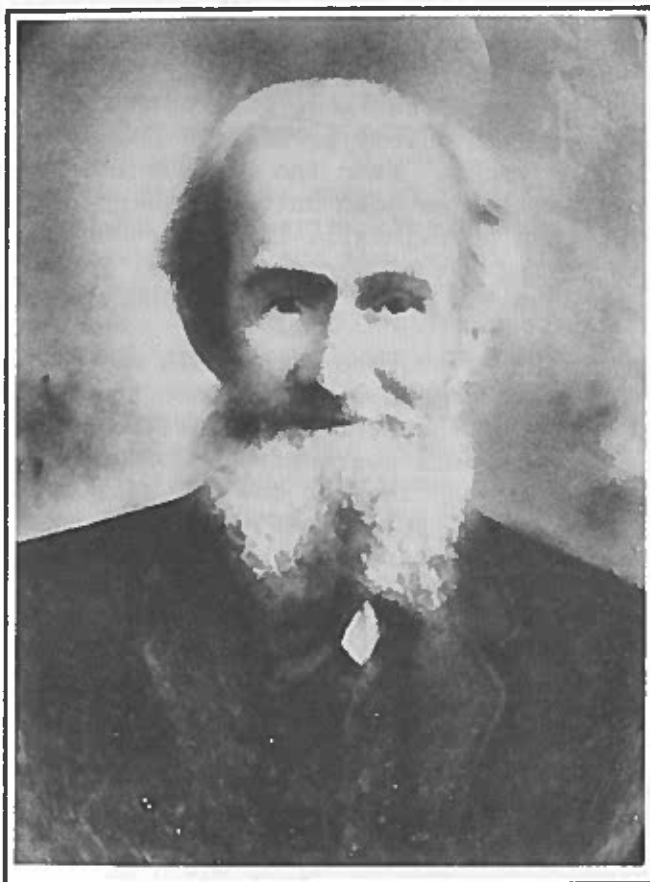
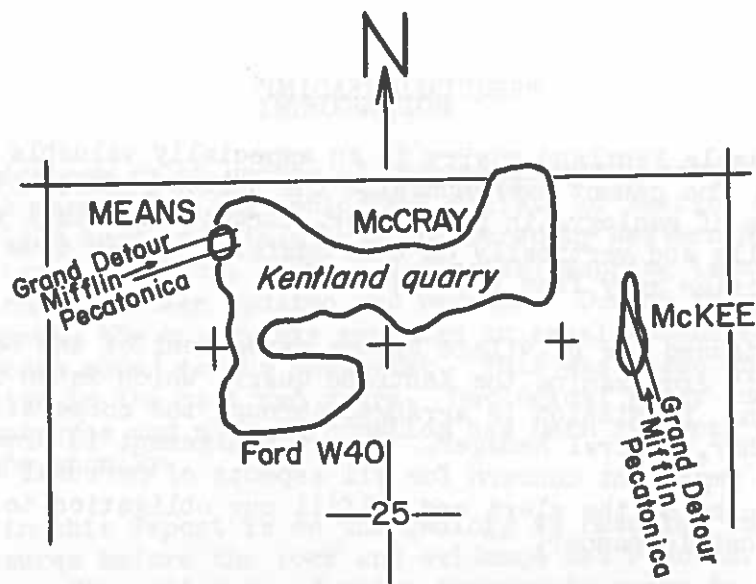
The guidebook is also dedicated to George K. Greene, paleontologist from New Albany, Indiana, who collected fossils from the McKee quarry in 1881 and correctly identified them as Lower Silurian (Ordovician of current usage). Greene assisted Prof. John Collett, Indiana State Geologist at the time. Greene recognized the disrupted upturned strata, the unusual early age of the fossils, and cone-in-cone (shattercones) structure which caused him to speculate on the origin of this anomalous local rock exposure.



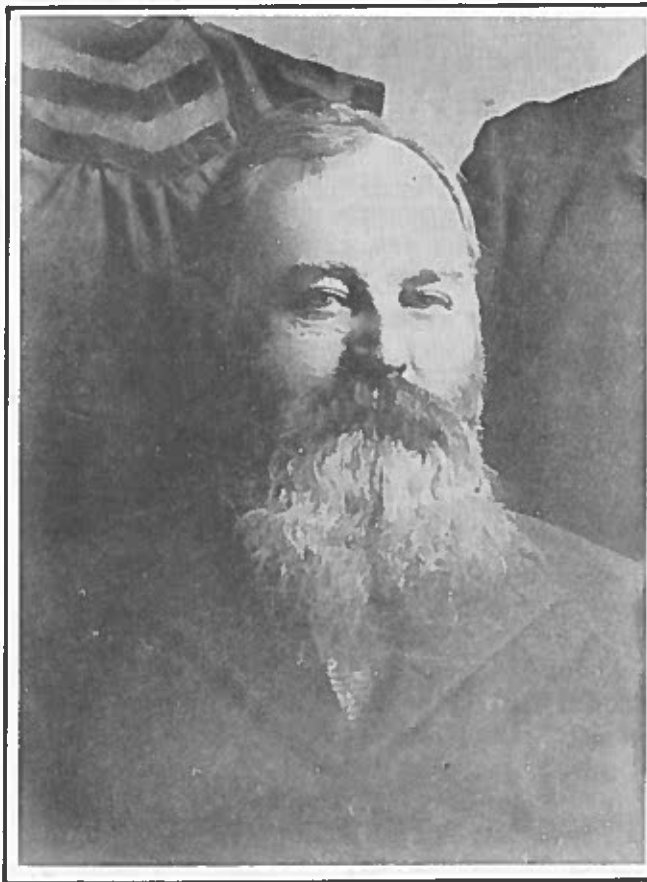
George K. Greene's photograph was given to me by N. Gary Lane, Department of Geology, Indiana University, Bloomington, who obtained a copy of the photo from Ruth Ann Kramer of the New Albany-Floyd County Public Library while researching materials for Greene's biography. The original photo came from Miss Emma Carleton's Scrapbook #1, p. 11, in this library. This all came about through inquiry to Dr. John B. Patton, State Geologist of Indiana, who is interested in Greene's role in the Survey's history.

To all of the above people, I express my gratitude and enjoyment of this historical record.





Samuel Means



John McKee

This guidebook is dedicated to two pioneers, John McKee and Samuel Means, who migrated from Pennsylvania and settled in Newton County, Indiana. Land was purchased in February, 1865, and the tract was eventually divided into the McKee and Means farms. Both men established quarries on their farms coincidentally in the same rock sequence (see diagram above). The McKee quarry was in existence in 1881 referred to by George K. Greene who visited it to collect fossils twice in 1881. Gorby, 1886, referred to surface rock exposures on both the McKee and Means farms and spoke about quarries but only mentioned the McKee quarry. Both quarries must have been in existence in the 1880's.

## "REQUIRED READING"

The remarkable Kentland quarry is an especially valuable field laboratory for student study. One cannot overemphasize the unique opportunity available to observe various aspects of geology, in particular, structural detail which is seldom freshly exposed laterally and vertically on this scale. This is true in the midwestern plains and prairies away from the mountains.

We are extended the privilege by the management of the Newton County Stone Company to visit and examine the Kentland quarry which is an interesting large and deep excavation. Permission is arranged through the cooperation and courtesy of Mr. Carl Fletcher, General Manager. Quarry management is proud of their efficient production and important concern for all aspects of personal safety; therefore we are required to be on the alert and fulfill our obligation to use good judgment and act in a responsible manner.

Each visitor is required to register with his or her signatures on a liability release form provided by the company. It is imperative that we stay together as a group and avoid interference with regular quarry operations. Production has top priority which means that trucks have steady uninterrupted flow and roadway from the source to the crusher. Watch out for the trucks and keep well out of their paths. Hard hats are required of each person while on the quarry premises. Quarry walls are high and steep with the danger of falling rocks. Even the birds which perch along the quarry walls push loose rock off the ledges down onto the quarry floor. Rock falls are especially possible after a thaw or rainfall. It is prudent to stay away from the walls. Be sure to take everything out of the quarry that you bring into it. Do not litter. Collecting is permissible as is geological photography.

Quarry operations go back to the early 1880's started from small natural outcroppings. The present quarry has been in continuous operation since about 1900 during which time many geologists and students of the earth have visited and examined its progressive exposures. Quarry management is well aware of the uniqueness and importance of this site to science and education and they go out of their way to cooperate with our interest to see this structure. Let's keep this healthy relationship for future groups for the quarry should be in operation for some time to come.

Quarry personnel and students have been helpful in geological study of the quarry. Don Fritz of the quarry staff has helped me in many ways to expedite the work. Don Sprague and Bill Ehmann, University of Notre Dame geology students have helped in plane table mapping and study of the rocks.

For those of you who may wish to arrange field trips to the Kentland quarry, contact can be made through communication with:

Mr. Carl S. Fletcher, General Manager  
Newton County Stone Co., Inc.  
P. O. Box 147  
Kentland, Indiana 47951

Office phone: 219 474-5125

Keep in mind that the quarry is not available when explosives are being placed and during shooting. Normal quarry operations are from 7:00 A.M. to 4:00 P.M., Monday through Friday; 7:00 A.M. to 12:00 noon on Saturdays. The quarry is otherwise closed during holidays and is not available for obvious insurance and liability reasons. During the summer, the quarry operates on daylight savings time.

## INTRODUCTION

This field guidebook is an update of and supplements, rather than supersedes, the guidebook which served for the Geological Society of America North Central Section Kalamazoo 1976 Kentland field trip sponsored by Western Michigan University Department of Geology (Gutschick, 1976). Geological mapping is current and all graphic illustrations have been updated and redrawn. During the past six years since the above report, the quarry has expanded in areal extent and deepened. A new extension has been added to the southwest. This was based on core drill operations and exploration in the past two years. Geological study and mapping continues with new quarry exposures and more information has been gathered on the stratigraphy and structure of the anomaly.

The emphasis in this report is on the geology as revealed in the present quarry and from past exposures before the rock and evidence was removed. Geologic mapping and the structural configuration is of prime concern in order to document observational data. This phase will continue as long as there is a quarry expansion and explorational activities. It forms the basis for dynamic deformational interpretation. The logic is that the pattern has been established in all of its details. Therefore, everything must fit this pattern- spatially, sequentially, and genetically. Is the anomaly conventional or catastrophic?

No attempt is made at this time to expand on the origin of this cryptoexplosion structure. The various theories have been reviewed (Shrock, 1937; Tudor, 1971; Gutschick, 1976) and the latest explanation (Laney and Van Schmus, 1978) attributes the structure to be the result of a large natural impact event. Study of Ordovician conodonts (Votaw, 1980) gives resolution in dating some of these rocks and observations of the color alteration index (CAI) indicates an anomalously low thermal effect (50°-90° range, CAI 1½, Epstein, Epstein, and Harris, 1977) for an impact site. Except for the revised geologic map, no new evidence has been revealed which might throw additional light on the structure's origin. Breccias, shattercones, and crushed quartz petrofabric specimens can be found in and near the fault zones. Coesite has been reported from the St. Peter Sandstone along the Kentland Quarry Fault.

A reasonably complete geologic-structural map of the quarry is presented in this report. The map represents a synthesis of all available information and the best interpretation of these data. It serves to document the research of two or more decades during which time I have observed, measured, mapped, photographed, collected, and recorded information in the field on numerous occasions along with laboratory study of the Kentland structure. Quarry exposures are continually available but just as fast, they are lost forever. Fortunately in this program there is a photographic record which includes air photos, public and private, black and white and color, and many ground level kodachrome slides and black and white photographs. Progress plane table maps and field notes are also available. The series of published reports and theses continues to be a good source of information (Shrock, 1937; Boyer, 1953; Gutschick, 1961, 1976; Tudor, 1971; and Laney and Van Schmus, 1978).

The geological and structural pattern of the Kentland structure is unique. In the progress of mapping the quarry, it has not always been possible to identify stratigraphic units nor to trace their contacts. Often the solution was elusive and enigmatic. It was therefore an exhilarating experience to brainstorm all of the above resources for the clues which enabled construction of the geologic-structural interpretation of the quarry with high confidence.





Several examples are given to illustrate the process. The east wall of the quarry has always been an enigma partly because of its complexity and also because it is not now readily accessible. Rock units were mis-identified and out of context. A high resolution air photo of the quarry (Indiana Highway Department stereo-photos furnished by James Flew) revealed a possible structural trend of one of the fault blocks. Kodachrome slides taken from a helicopter at the proper angle in 1970 helped to resolve the identity of the rocks and the structure of the block. The block has a sequence of brown Pecatonica Dolomite overlain by gray Mifflin Limestone with almost vertical strata. This becomes the key to structural mapping in this part of the quarry since it forms the hangingwall for the Kentland Quarry Fault and the footwall for the newly designated McCray Fault. It is also bounded on the east by the newly designated McKee Fault which offsets the Kentland Quarry Fault.

Another case in point deals with the southwest extension. Geologic mapping of the bedrock surface after it had been stripped of glacial drift on the Means quarry tract (Gutschick, 1976, p. 49, fig. 24) revealed the truncation and offset of the Kentland Quarry Fault by the newly designated Means Fault. It also suggested the presence of the detached Galena and Platteville carbonates to the south in normal sequence south of the Salamonie, Brassfield, and Maquoketa map units. Core drill exploration confirmed this to be true resulting in the new southwest quarry extension.

Location of the Kentland structural anomaly in the context of the geology of Indiana is shown on the geologic map of the state (Fig. 1). Most rock formations in Indiana at the bedrock surface are dipping only a fraction of one degree either into the Michigan or Illinois Basins and the oldest rocks present are Upper Ordovician on the Cincinnati Arch. Yet, in the Kentland quarry Lower Ordovician is exposed at bedrock level and the rocks have very steep dip. Quarry operations are in sharp contrast to the simple, flat-lying "layer-cake" strata in most midwestern stone quarries. The geology of the area and anomaly becomes an important practical science recognized by quarry management. The geometry of Kentland's four-dimensional (rock masses in 3-D space and time) jigsaw puzzle is more than an academic exercise.

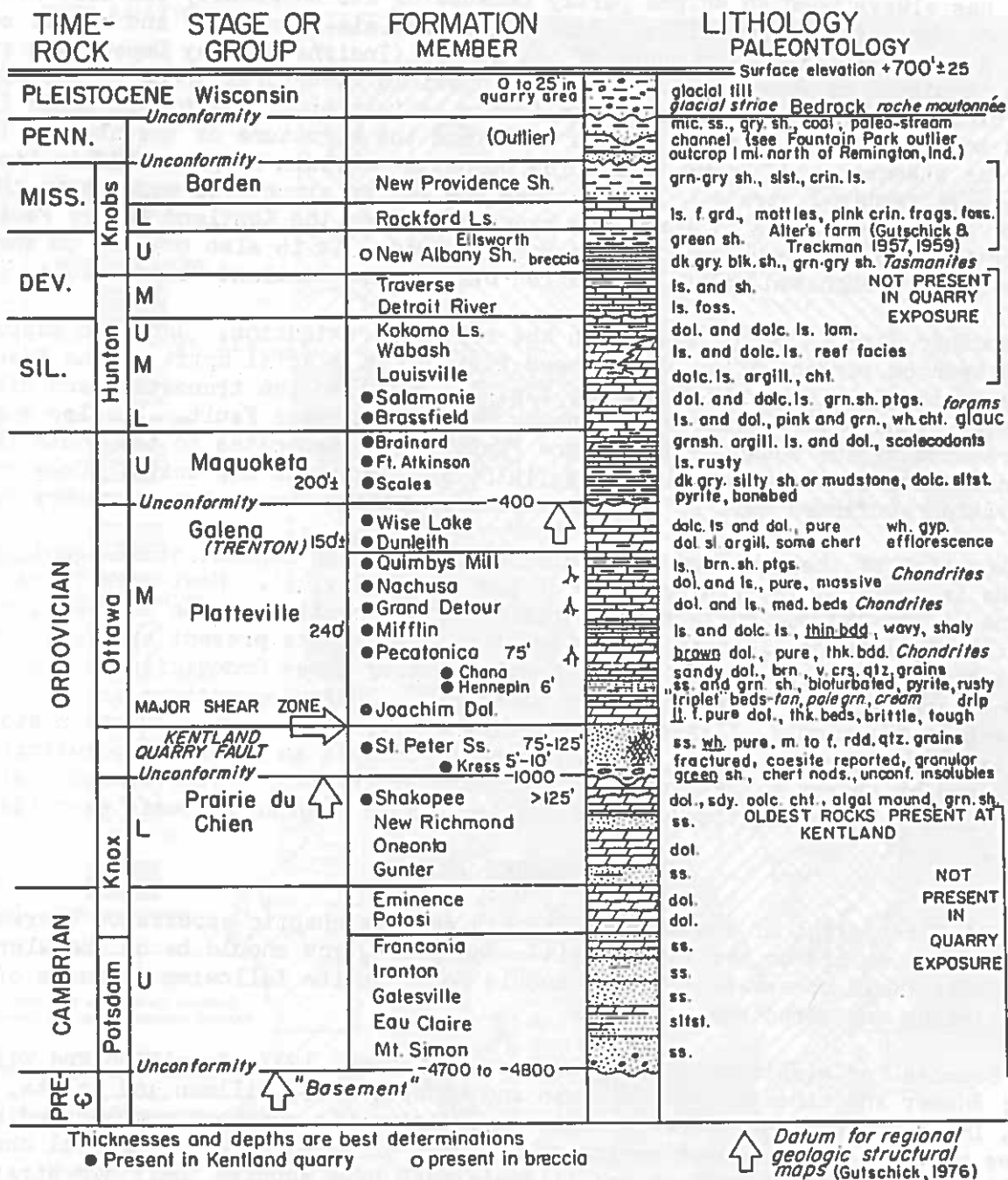
#### KENTLAND QUARRY GEOLOGY

The first sight of the quarry with its complex chaotic appearance overwhelms the observer on his or her first visit. Therefore, you should be on the alert with perceptive field observations which should focus on the following features of stratigraphy and structure.

Sources for stratigraphic resolution are Shrock, 1937; Templeton and Willman, 1963; Shaver and others, 1970; Willman and others, 1975; Willman and Kolata, 1978; Gray, 1972; and others. Stratigraphic nomenclature is somewhat complicated since facies patterns fall between sedimentary basins or areas of environmental changes in which the states of Indiana and Illinois each have adopted their own stratigraphic policies and nomenclatural standards. Thus a combination of the names used by each state has been applied depending upon the rocks and their facies to the most typical areas, e.g., Joachim Dolomite- Ozarks; Platteville Group- SW. Wisconsin and N. Illinois; Galena Group- NW. Illinois; Brassfield Limestone- S. Indiana; Salamonie Dolomite- EC. Indiana, etc.

#### STRATIGRAPHY AND THE STRATIGRAPHIC KEY

More than 1000 feet (305 m) of stratigraphic section or succession is exposed in fault blocks in the quarry whose maximum depth is 330 feet (100 m)! The sequence



STRATIGRAPHIC KEY IN KENTLAND QUARRY STRATEGY  
PROJECTION TO BASEMENT

Fig. 2



is continuous from the Lower Ordovician Shakopee Dolomite to the Middle Silurian Salamonie Dolomite. Key beds within the sequence, based on lithology, succession, color, textures, bedding detail, weathering characteristics, fossils, and other subtle differences, enable resolution of the structural details.

The following is a summary of the stratigraphic succession with some of the most useful characteristics for recognition of groups, formations, members, and key beds. Compare with Fig. 2:

(youngest)		Glacial drift- till .....	oxidized- rusty unoxidized- gray
		***** unconformity *****	BEDROCK *****
DEVONIAN			
Upper-		New Albany Shale Group- black and dk grn-gry sh, <u>Tasmanites</u> (occurs in fault breccia)	
SILURIAN (250'±)			
Middle-		Salamonie Dolomite- lss, dolc lss, lt grn-gry, hrn sh ptgs, non-reefy, fossils	
Lower-		Brassfield Limestone- lss, dolc lss, lt grn-gry and pink beds, white tripolitic chert, pyrite, glauc, agglut forams- <u>Turritella</u> tiny brachs- <u>Pentamerella</u>	
		----- gradational -----	(Pl. 1, fig. C)
ORDOVICIAN			
Upper-		Maquoketa Shale Group (200'±) Brainard Shale- shale and dolc ls, grn-gry, thin even-bdd, foss trilobites, brachs, pyrite replacement, scolecodonts Ft. Atkinson Limestone (10'-15')- ls, rusty weathering color resembles Galena but within sh, thin unit, thk beds, squeezed Scales Shale (65'-70')- sh, dk gry, silty, sltst interbeds, thin planar bdg ribs, unfoss.	
		***** unconformity *****	
		Conspicuous pyrite-marcasite layer, bonebed, fish and conodonts, frag, blk shiny bored phosph pebbles, heavy rusty weathering stain; on top of	
Rock quarried for crushed stone and agricultural lime	Middle-		Galena Group (undifferentiated) (150'±)- dols, dolc lss, lss, ubiquitous rusty weathering of Fe <sup>++</sup> in dolomite, wh gyp efflorescence, some chert nods, monolithic breccia, foss few
			Platteville Group (240'±) Quimbys Mill Fm.- dolc lss and lss, gry, brn-gry, micritic, <u>Chondrites</u> Nachusa Fm.- dolc lss and lss, brown and gray, fine grd, <u>Chondrites</u> some chert nods, colonial corals Grand Detour Fm.- dolc lss, lss, variable, red-brn sh ptgs (Forreston Mbr.), some chert nods, <u>Chondrites</u> common Mifflin Fm. (15'-20')- very distinctive gray and tan ls and dolc ls thin wavy bdd, micritic, sh ptgs, calcarenite beds, foss Pecatonica Fm. (75')- dol, brn, f to m grd, pure, med-bdd, some chert, mottled rock <u>Chondrites</u> common, crs qtz grains in Chana Mbr. near base of fm Hennepin Member (6')- important key bed- green sh and wh ss, shly weak layers, bioturbated, wh ss burrow-fill in disturbed grn-gry sh, pyrite nods oxidize to give conspicuous spots and rusty drip stain on bedding surfaces well exhibited on south fault wall Joachim Dolomite (15'-20'±)- distinctive unit, dol, very lt gry, f grd, med-bdd, tough, brittle; contains beds of three subtle alternating colors (triplet)- tan or lt brn, very pale grn-gry, cream colors; "tile mosaic" pattern along bdg surface near top of fm, bottom unknown fault contact
	hangingwall		DENSE, BRITTLE, FRACTURED
	XX		
	KENTLAND QUARRY FAULT ZONE		
	XX		



XXXXXXXXXXXXXXXXXXXX KENTLAND QUARRY FAULT ZONE XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX  
FOOTWALL GRANULATION, PULVERIZATION, FRACTURED, CATACLASIS

St. Peter Sandstone (100'±)- most recognizable unit- wh qtz rdd  
frosted f to crs-grd, fractured, friable, rust stained along fault  
in breccia zone; top unknown fault contact; thickness depends upon  
abrasion, granulation, pulverization between fault blocks and amount  
of stress (thinnest or absent in synclinal trough, thickest on flanks  
of syncline or crest of anticline); coesite reported  
Kress Member (5'-10'±)- good key unit- bright green sh, wh nod chert  
rust coated, reworked unconformity insoluble residuals

\*\*\*\*\* unconformity \*\*\*\*\*

Lower

Shakopee Dolomite (125'±)- dol, green sh ptgs, wh chert nods some  
oolc chert, algal mounds, limited exposure at present

(oldest)

### GEOLOGICAL STRUCTURE

#### REGIONAL

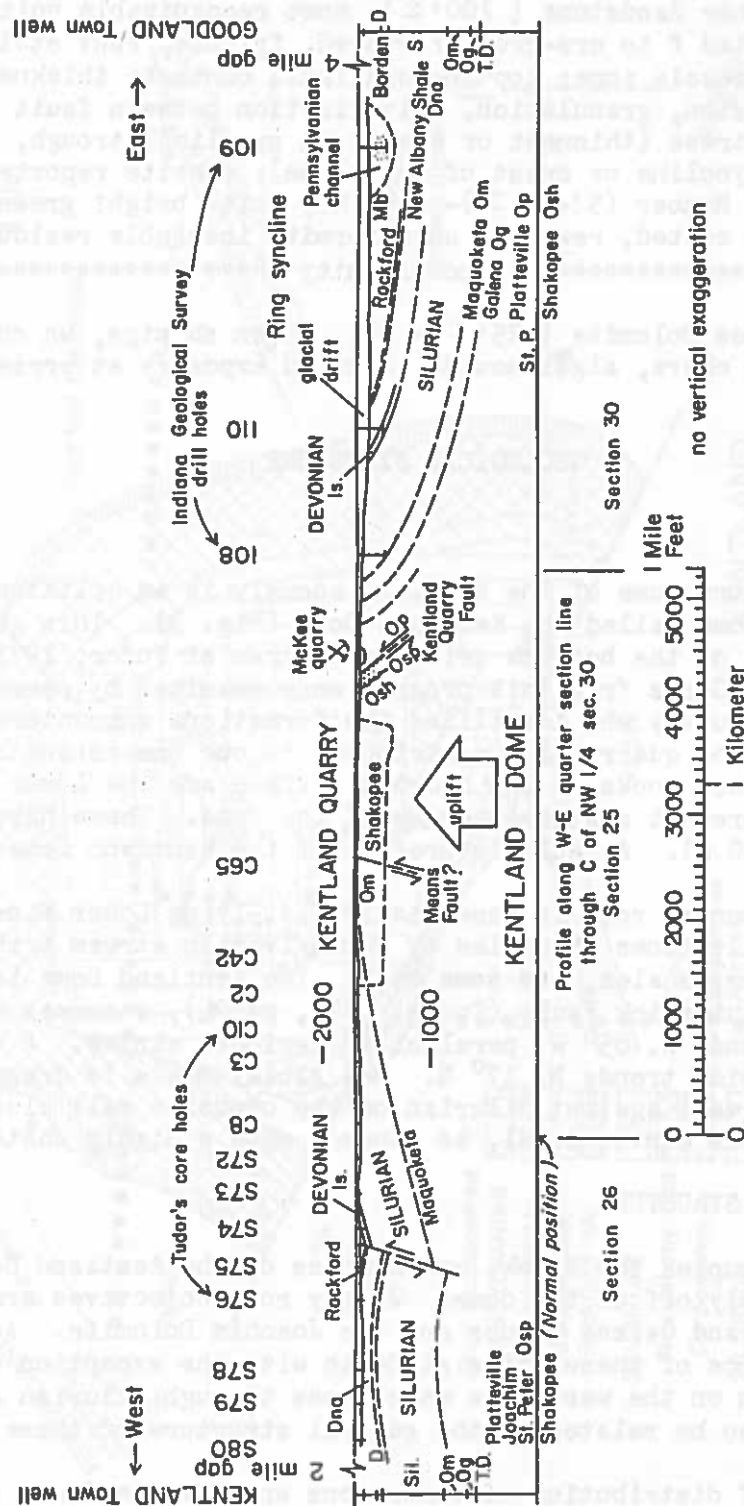
The regional structure of the Kentland anomaly is an uplifted complexly faulted truncated dome called the Kentland Dome (Fig. 3). This geologic map is based in large part on the bedrock drilling program of Tudor, 1971, used for his geophysical study. Cores from this program were examined by personnel of the Indiana Geological Survey who identified the formations encountered in each hole. Geology exposed in the quarry also contributes to our understanding of this domal structure. The oldest rocks at the bedrock surface are the Lower Ordovician Shakopee Dolomite present near the center of the dome. These have been uplifted about 2000 feet (610 m). A geologic profile of the Kentland Dome is shown in Fig. 4.

Undisturbed country rock is essentially flat-lying Lower Mississippian Borden Group shales and siltstones channelled by Pennsylvanian stream tributaries which deposited sandstones, shales, and some coal. The Kentland Dome is faulted on the south side by the Gutschick Fault (Tudor, 1971, p. 94), a normal south-dipping structure which trends N. 65° W. parallel to regional strike. A second normal fault on the west side trends N. 17° E. New Albany Shale is dragged up on the hanging downthrown wall against Silurian on the opposite wall along both faults. Otherwise the dome is conventional, as mapped, with a highly shattered core.

#### QUARRY GEOLOGY AND STRUCTURE

The quarry occupies the N, NW, and W sides of the Kentland Dome so that rocks generally dip steeply off of the dome. Quarry rock objectives are the carbonates of the Platteville and Galena Groups and the Joachim Dolomite. As a result the pit outlines the presence of these units at depth with the exception of the cross-cut to the SW extension on the west side which goes through Silurian and Maquoketa rocks. Excavations can also be related to the general structure of these carbonate rocks.

The pattern of distribution of formations and members found at the bedrock surface, along the quarry walls and floor is shown on the geologic map, Fig. 5. The west half of the map depicts bedrock geology mapped shortly after the glacial drift was stripped off. The east half of the map is a combination of bedrock, quarry wall and floor exposures so that some contacts are drawn continuously from



GEOLOGIC PROFILE W-E OF KENTLAND DOME

Fig. 4

the bedrock surface to the deep floor of the quarry. Therefore, care should be taken to visualize the geometry of the rocks and structures shown on this part of the map.

In general the oldest rocks in the main quarry are to the south and the youngest rocks to the north. The beds are right side up so their dips are to the north. The basic structure is folded with a steep NW plunging syncline flanked on both sides by anticlines which are cut transversely by faults on their distal limbs. The major Kentland Quarry Fault parallels the fold structure and forms the south wall of the main quarry. Faulting is between the St. Peter Sandstone and the Joachim Dolomite.

There is a single sequence of Platteville-Galena on the west limb of the syncline and in the SW extension. The quarry on the east half of the map is much more complex as evidenced by the duplicate patterns of Platteville and Galena rocks. This repetition of carbonates accounts for the enlargement of the east half of the main quarry except for the "narrows".

The combination of doming, folding, and faulting are represented in the Kentland area and quarry. Folding obviously preceded faulting. The carbonates were more competent than the sandstones and shales and since they are the commercial product, the carbonates dominate the quarry. The synclinal-anticlinal folds drape the dome but continuity is severed by transverse faulting, Fig. 6. The anticline-syncline scallop around the flank of the dome is interrupted by offset and duplication of stratigraphic units. Again the pattern must indicate the sequence of events but such orderliness is not obvious nor predictable.

**FOLDING-** The main quarry from west to east follows the plunging anticline-syncline-anticline structural trend which is continuous. It is cut off on the west end and re-appears in the SW quarry extension as a plunging anticline. Coincidentally two other small fault blocks have similar plunging anticline structure involving Joachim-Pecatonica beds. One occurs in the west wall, Fig. 7, between the Kentland Quarry Fault and the Means Fault. This small block plunges steeply to the NW. The other structure is in the north wall, Fig. 8, of the NE part of the main quarry. In this latter case, it is apparent the footwall anticlinal part of an anticline-syncline separated by faulting along the limb in common. It also is plunging to the NW. The hangingwall of this same fault is the syncline which continues along the floor of the deep NE part of the quarry.

**FAULTING-** The Kentland quarry displays localized catastrophic disruption of strata in an area of otherwise structural simplicity. Faulting is conspicuous on the structural map, Fig. 6, recognized by abrupt changes in lithology, changes in the structural trends, duplication of rock units, and the patchy mosaic of structural blocks. Four important faults have been named, Kentland Quarry Fault, Means Fault, McKee Fault, and McCray Fault, the latter three are newly named.

**Kentland Quarry Fault-** Apparently the weakest bond in the stratigraphic section during deformation was the St. Peter Sandstone-Joachim Dolomite juxtaposition combination couplet. Brittle fracture and granulation caused by mechanical stress during folding resulted in the Kentland Quarry Fault (KQF), Pl. 2, fig. F. The KQF, fault zone, and all of its manifestations are magnificently exposed and worthy of your close attention and concentrated observation. Seldom does the geologist have the opportunity to see and feel such freshly exposed structure on this large scale.





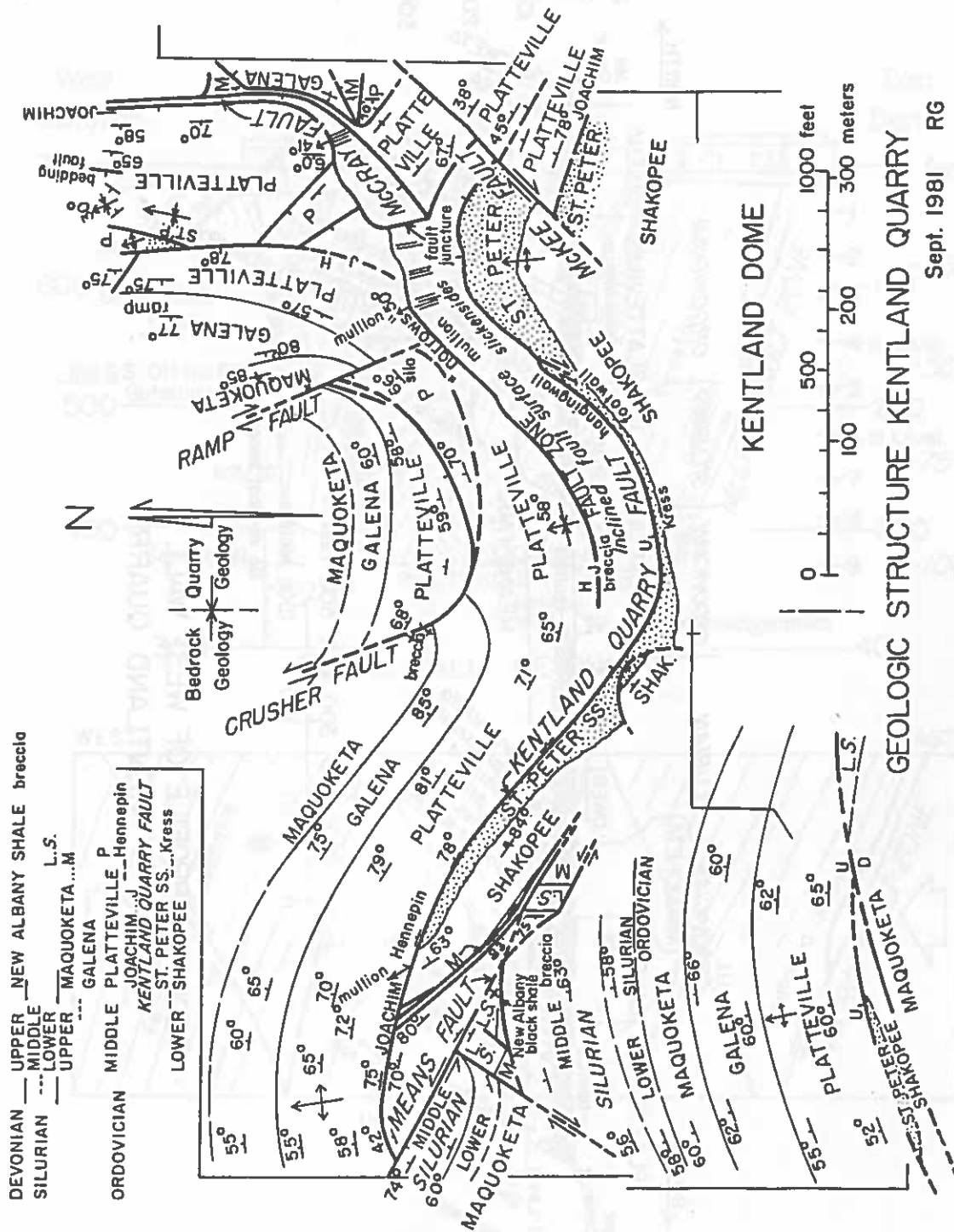


Fig. 6

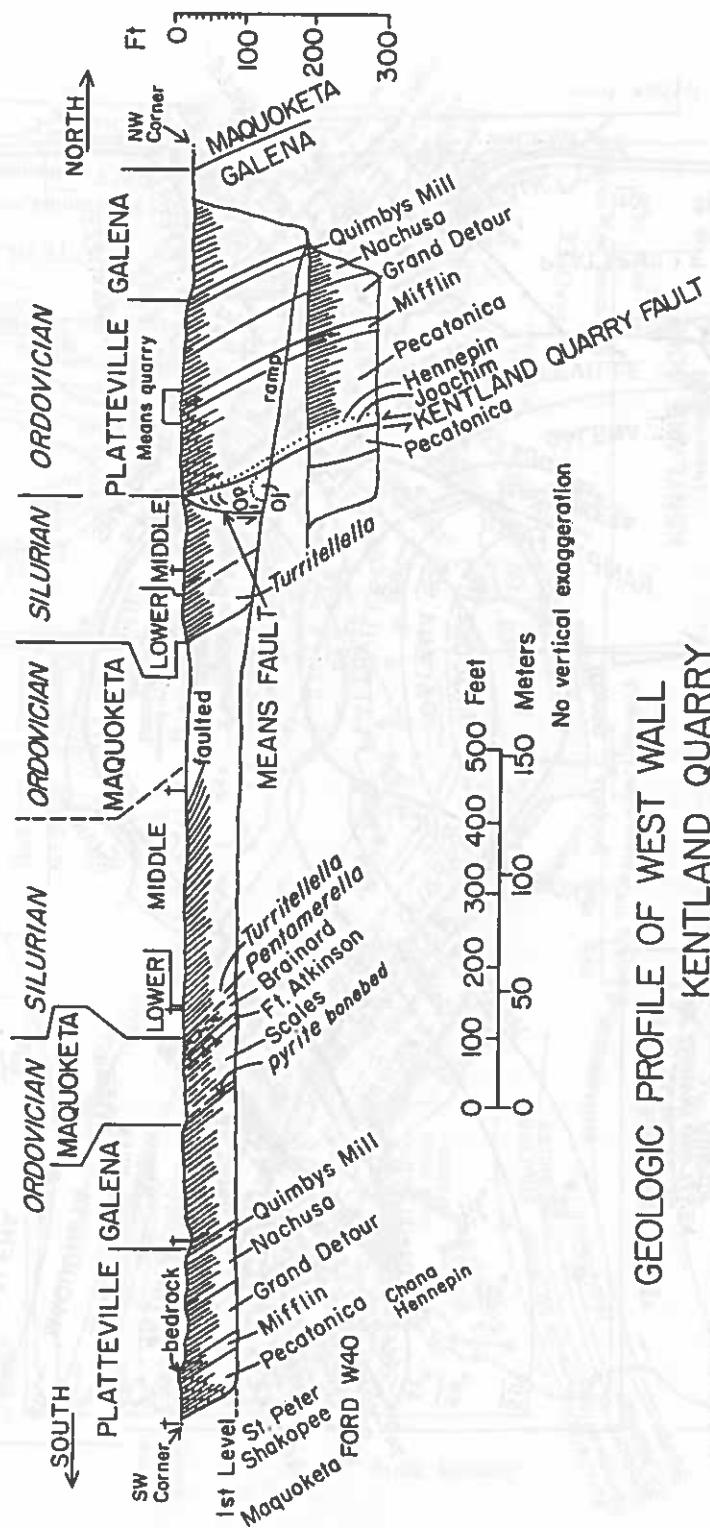


Fig. 7

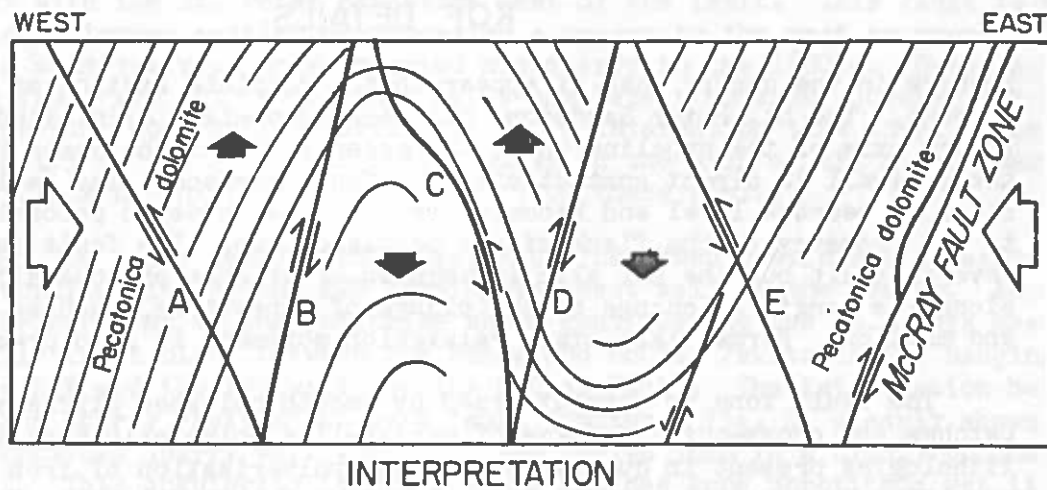
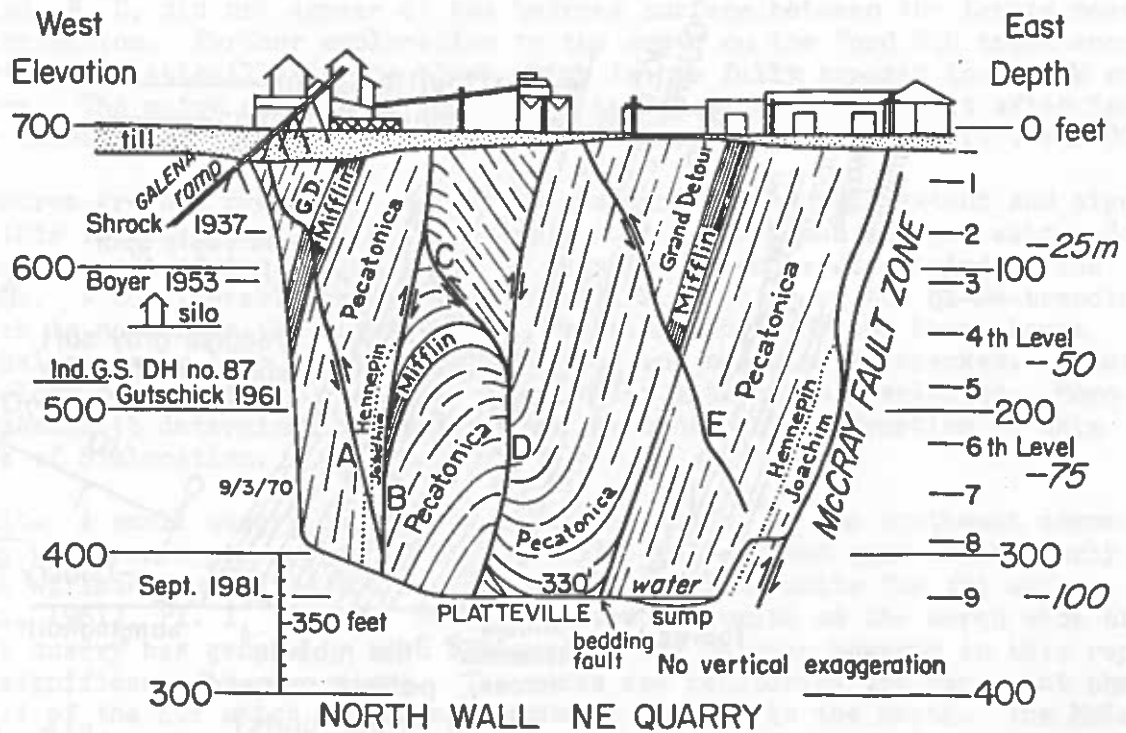


Fig. 8

The KQF is probably a bedding fault, or almost so, dipping steeply to the north possibly slightly more than the north-dipping beds, Fig. 9. The upper part of the St. Peter Sandstone is cut into or abraded by grinding and granulation and the lower part of the Joachim Dolomite is affected by fracture shearing.

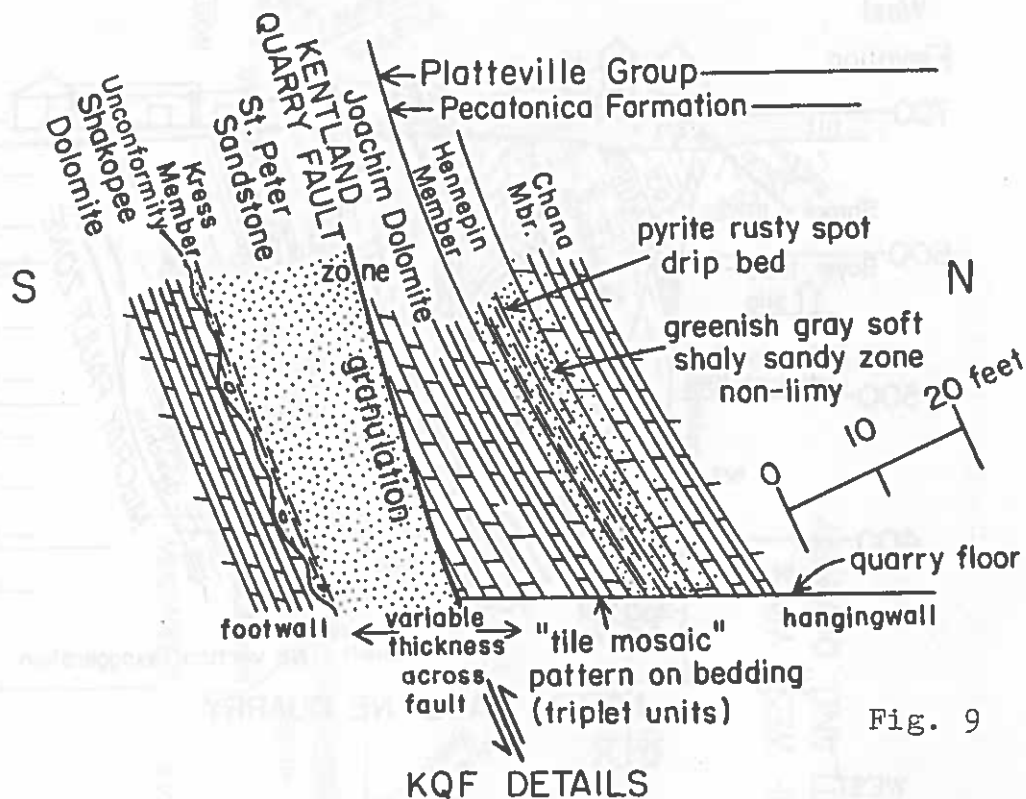


Fig. 9

Nowhere in the quarry does it appear that a complete section of either unit is present. The St. Peter Sandstone has been completely eliminated along the trough axis of the syncline where the green shale of the Kress Member makes up the footwall in direct contact with the fault surface. The fault surface is steep at bedrock level and becomes less steep with depth probably conforming to the geometry of the flank of the Kentland Dome. The fault is logically a reverse fault but the net slip is unknown. Variable oblique slip is indicated along its length by change of the plunge of lineations, such as slickensides and mullion. Normal late-stage relaxation movement is also present.

The fault zone is characterized by smooth polished slickensided surfaces, patches and cross-cutting dikes of mortar-like polymictic breccia involving lithologies present in quarry rock types, pulverization of iron sulphides resulting in pervasive oxide stain along the fault walls, St. Peter Sandstone on the footwall and Joachim Dolomite on the hangingwall. The latter has been faulted zigzag fashion for 5-15 meters away from the fault as is evident by disposition of the key Hennepin Member unit which is easy to recognize and trace. Two recent pertinent references related to the St. Peter Sandstone are Hoholick, 1978; and Pittman, 1981.

Means Fault- During westward expansion of the quarry onto the Means tract, it became apparent from bedrock mapping that the KQF was cut by a younger WNW-trending fault with left lateral slip (Gutschick, 1976, p. 49, fig. 24). Note that the small folded Pecatonica-Joachim block which shows up in the west wall, Fig. 7; Pl. 1, figs. B, D, did not appear at the bedrock surface between the faults near their intersection. Further exploration to the south on the Ford W40 tract encountered the detached Platteville-Galena block which is now fully exposed in the SW extension quarry. The major surface of separation is named the Means Fault after Samuel Means who homesteaded the property in 1875 and opened a small quarry in the 1880's.

Exposures are not presently available to determine the full extent and significance of this fault. The fault has steep dip to the south and oblique slip. Not all of the movement of the blocks south of this fault can be attributed to the Means Fault. A considerable amount of movement is taken up by the NE-SW-trending fault which is normal to the Means Fault. The block north of the Means Fault labelled Salamonie in 1976 may be mis-identified and needs to be checked. Details of the geology between the KQF and the Means Fault also needs resolution. More study is needed to determine the geometry and mechanics of deformation in this major area of dislocation.

McKee Fault- A small quarry projection to the southeast in the southeast corner of the quarry was opened and mapped by Boyer, 1953. It remained open in the early 1960's when H. B. Willman identified the Joachim and Platteville units for the author (Gutschick, 1961), Pl. 1, fig. F. Rusty weathered dolomite on the north side of this small quarry has generally been assigned to the Galena; however in this report its true significance is recognized. The rocks are Pecatonica and represent the hangingwall of the KQF which continues to the SE and not to the north. The McKee Fault accounts for the offset of Platteville rocks east of the fault which are in fault contact with the St. Peter Sandstone west of the fault. This fault is named for John McKee, pioneer settler who operated a quarry to the east on property adjacent to the main quarry. McKee started his quarry in the 1880's. Details concerning this fault are not known since it is completely covered; however the right lateral strike-slip component is obvious. It is interesting that there is an apparent symmetry of the Means and McKee Faults to the axis of the major quarry syncline and flanking anticlines both cut off by these faults.

McCray Fault- The newly designated McCray Fault has been previously thought of as a northward continuation of the KQF forming the east wall of the quarry. As stated above, the KQF conforms to the anticline which continues to the SE. This means that the Platteville fault block between the McKee and McCray Faults is the hangingwall block for the KQF and the footwall for the McCray Fault. The intersection between the KQF and the McCray Fault shown as a fault juncture, Fig. 6, clearly shows on the present slickensided quarry wall where the two faults join in a highly obtuse angle, Pl. 1, fig. F. This angularity is not obvious and has gone unnoticed; yet it can be recognized once the significance is known. Perhaps the main distinction between the two faults is the fact that the KQF is essentially a bedding fault; whereas the McCray Fault cuts across the bedding of the footwall. Another difference is the nature of the footwall which is the St. Peter Sandstone for the KQF, and Platteville, Galena, and Maquoketa Groups for the McCray Fault.

Shrock, 1937, referred to the McCray quarry which was the NE part of the main quarry two levels deep, about 75 feet, at that time. The fault is named after Warren T. McCray who owned the quarry in the 1920's and became Governor of Indiana in 1928. The McCray Fault is a steep westward-dipping fault. The hangingwall along its east side is much like the hangingwall of the KQF with Joachim-Platteville sub-parallel to the fault zone and smooth slickensided walls. Due to folding and faulting, the hangingwall swings north to where the bedding is almost normal to the strike of the same Pecatonica Formation in the footwall block. The footwall in the NE corner of the quarry is inaccessible and has not been determined.

Other Faults- Duplication of the Platteville in the north wall of the NE part of the quarry, Pl. 1, fig. E, and along the ramp is interpreted as a faulted anticline-syncline, Fig. 8. This folded structure is believed to be the result of compression of the hangingwall block of the KQF and McCray Fault; however the structural block has been twisted and rotated clockwise with break-away shear along the Crusher Fault, Figs. 5, 6; Pl. 2, fig. E. The synclinal structure is cut transversely by the Ramp Fault with right lateral slip component. The Crusher Fault is curved and U-shaped with a forked split both cut by the Ramp Fault. It is probable that the curved fault in the Platteville east of the Ramp Fault is the east limb continuation of the Crusher Fault. This suggests that the limb common to the anticline-syncline, Fig. 8, has been overridden and is beneath the synclinal hangingwall block of the Crusher Fault northwest of the "narrows", Pl. 2, figs. E, F. It is also logical that the two NW-SE trending faults between the Crusher Fault (east limb) and the McCray Fault are normally faulted.

High on the east wall of the quarry is a steeply inclined smooth curved slickensided surface. This is the hangingwall of an east-dipping fault and the block is regarded as Galena Dolomite. Between this fault and the McCray Fault is vertical N-S striking Maquoketa dark shale and siltstone ribs of the Scales Formation.

There are two other interesting fault structures in the west half of the map. One is a very narrow graben, 10-15 feet wide, between the KQF and the Means Fault. This tensional feature runs diagonally NW-SE and drops Maquoketa dark gray shale of the Scales Formation against Shakopee at the bedrock surface cutting out rocks from the St. Peter Sandstone to the Galena Dolomite inclusively. The south fault wall dips 82° N and is slickensided with vertical striae. The second fault feature is a small low-angle thrust of Shakopee Dolomite over St. Peter Sandstone involving the footwall of the KQF along the west side of the central syncline. This can be found on the south side of a long abandoned quarry road south of the prominent white St. Peter Sandstone exposure.

Small triangular fault blocks on the south side of the Means Fault are worthy of note. These involve easily identified Maquoketa Shale and Lower Silurian rocks but most notable is a brecciated wad of dark brownish-gray and alternating dark green-gray shale with Tasmanites remains characteristic of the Late Devonian New Albany Shale. This is the single spot which represents the youngest Paleozoic stratum found in the quarry.



## GLACIAL EROSION AND DEPOSITION

Glacial Till- Glacial deposits from the Wisconsin drift sheet covers the bedrock in the Kentland area. Deposits belong to the Cartersburg Till Member of the Trafalgar Formation (Wayne, 1966; Bleuer, 1974). Glacial drift over the Kentland Dome is generally thin ranging from 1-30± feet thick, Figs. 10, 11. The drift is thinnest over the durable resistant Mifflin Formation of the Platteville Group which consists of thin-bedded micritic limestone; and it is the thickest over the Maquoketa Shale and weathered Galena Group especially the lower Dunleith Formation. The bouldery-cobblestone-pebbly clay till is weathered (oxidized) down to about 8 ± feet in depth. There is a fairly sharp contact between the rust-colored oxidized till and the gray unoxidized till. Sand and gravel lenses, probably meltwater stream deposits, are found within the till out from the quarry (Tudor, 1971). These serve as aquifers in the area.

Bedrock- Topographic expression of the bedrock surface is related to its resistance to glacial scour and erosion, Pl. 2, figs A, B. Glacial striae are present everywhere the bedrock is exposed. They generally trend S. 20°-30° W., Pl. 2, fig. C, which suggest identification with the distal margin of the Lake Huron Saginaw Lobe, Fig. 5. Differential ice scour has produced as much as 15-20 feet of relief on the truncated upturned strata bedrock surface, Figs. 12, 13. There is a direct correlation between rock types and glacial erosion so that glacial abrasion furnishes an excellent index to the hardness and durability of particular rock units in the quarry.

The Platteville Group is the most resistant to erosion by the ice and forms a prominent bedrock platform. Surprising is the fact that the thin-bedded micritic limestone Mifflin Formation forms a buttress roche moutonnée in frontal defiance of the glacier in the main quarry, Fig. 12, and especially in the Ford W40 SW extension, Fig. 13. Upturned bedding surfaces of the Mifflin are polished and striated horizontally where the ice moved sideways before it was able to go up and over the strike roche moutonnée on this rock unit. Glaciers moved S. 30° W. and encountered Mifflin Limestone beds which strike E-W to WSW with steep dip, 60°, to the north. The oblique angle between the directional vector of the ice movement and the strike of the rocks deflected the ice to shift laterally and horizontally with westward component to abrade, polish and scratch the durable micritic limestone on the bedding surface facing the ice. This is well exhibited on the exhumed bedrock surface in the southwest extension quarry, Fig. 13. The Pecatonica Dolomite forms a high glacial pavement platform on the leeward side of the Mifflin ridge.

Glacial scour was most effective in weathered carbonates of the Galena Group and the Maquoketa Shale, Figs. 12, 13. Some of this scour may be due to ice gouge movement parallel to the strike of the rocks directed by the Mifflin buttress. The top of the Galena is case hardened by a pyrite-marcasite unconformity crust which made it more ice-resistant and the Ft. Atkinson Limestone Member of the Maquoketa withstood erosion while the shales on either side of it were being removed. Silurian carbonates also maintained a high stand adjacent to weak Maquoketa Shale.

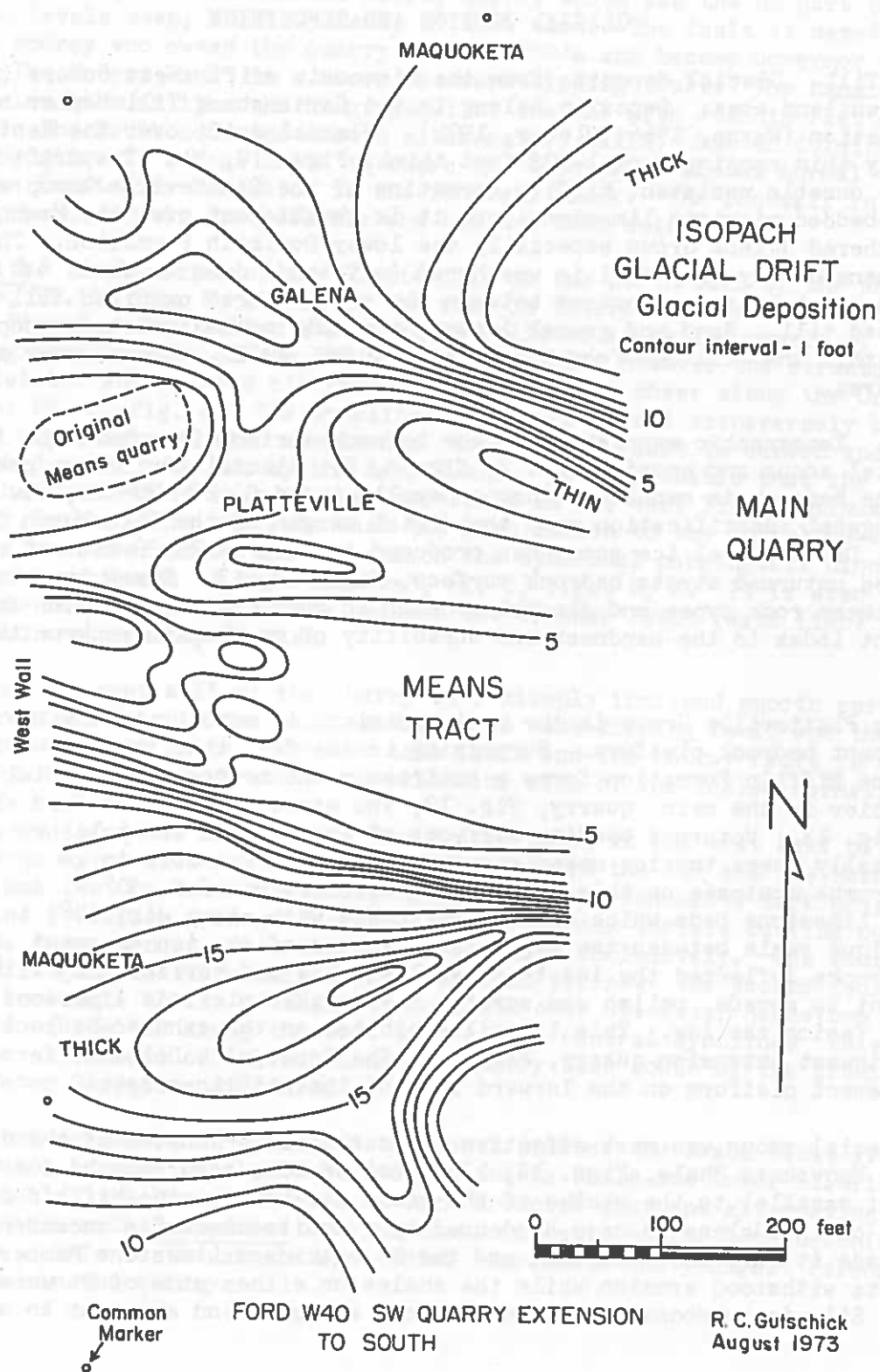


Fig. 10

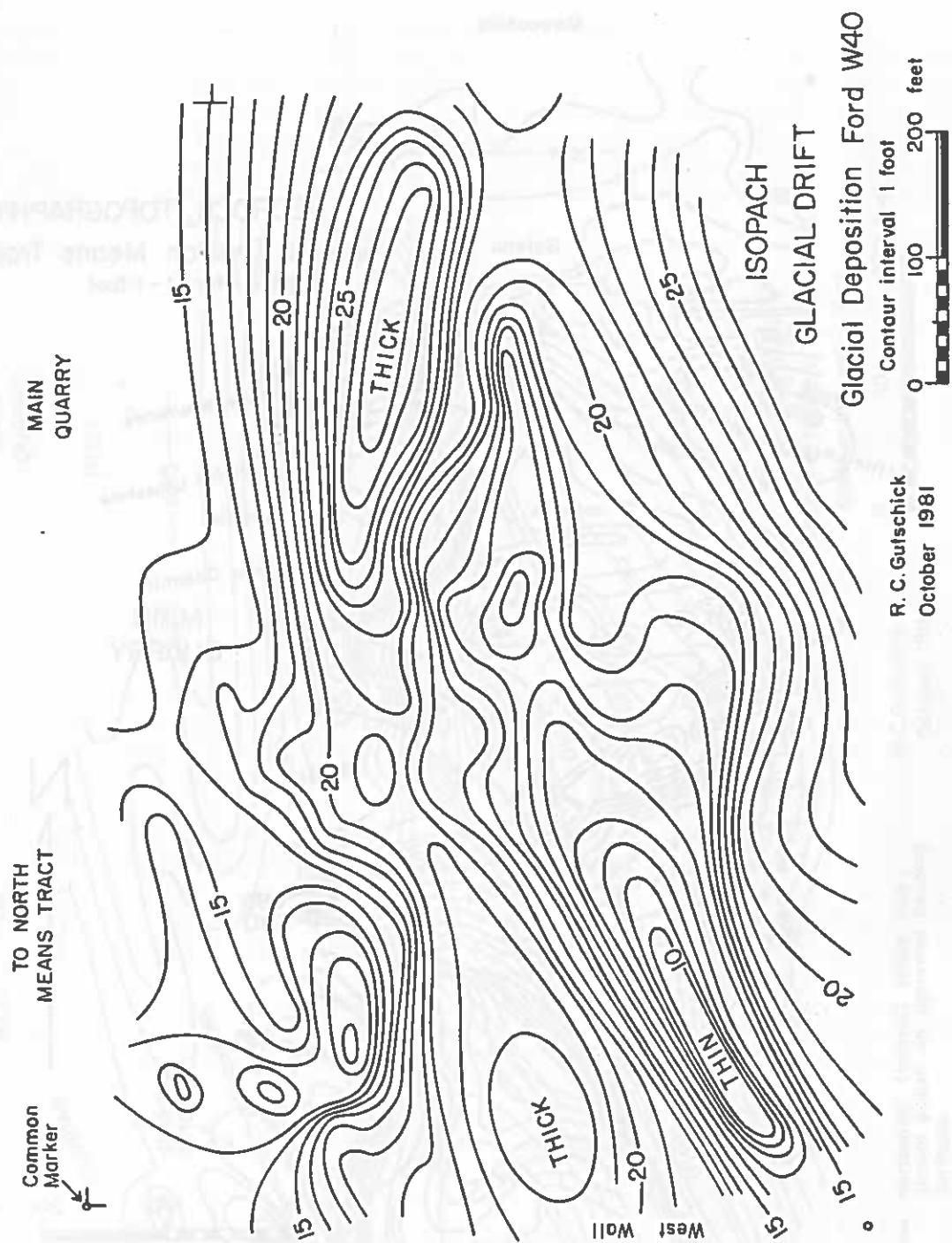


Fig. 11

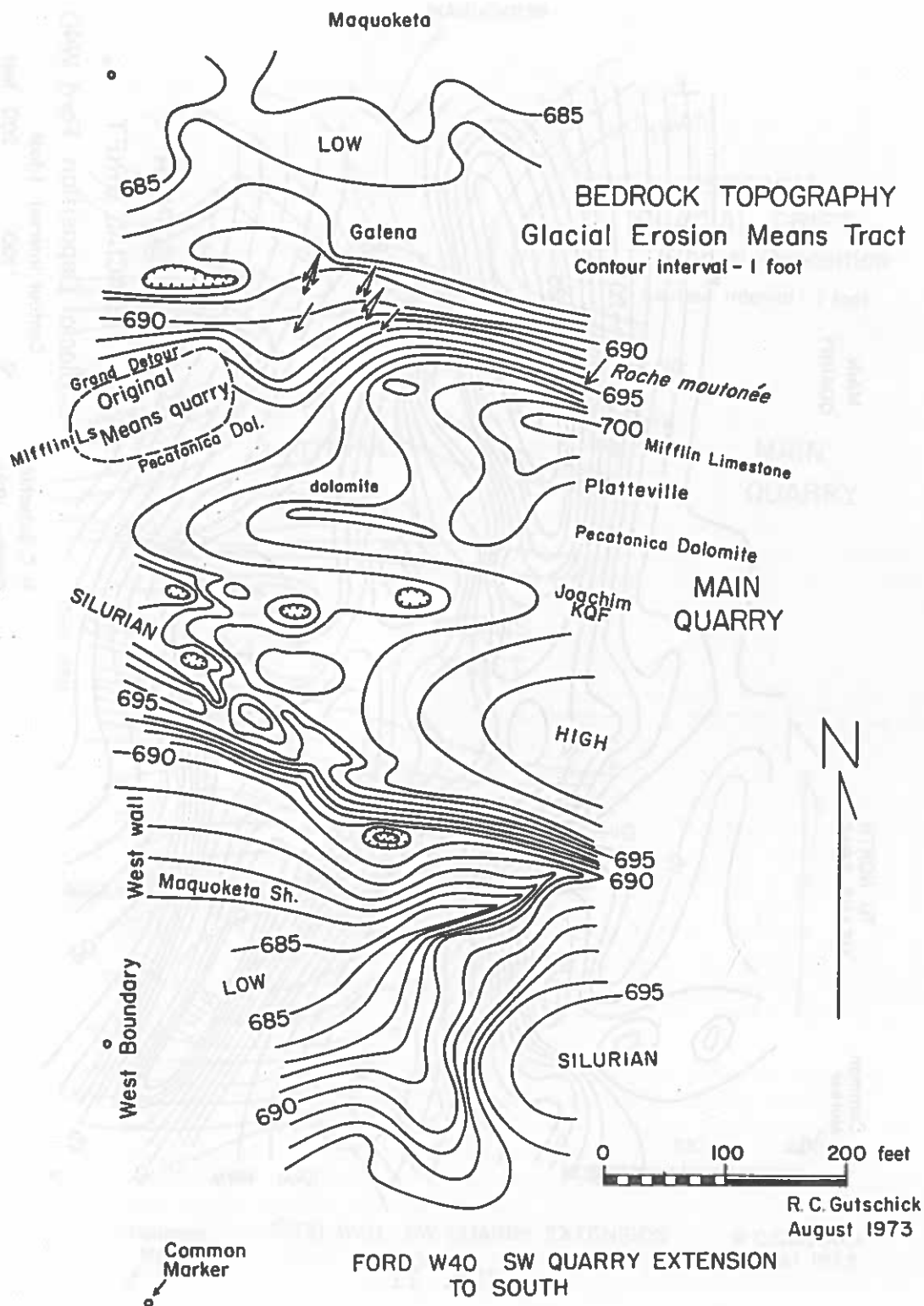


Fig. 12



In view of the bedrock surface topography-geological maps, it does not seem to be coincidental that the two quarries started in the 1880-1890's, the Means and McKee quarries about 3000 feet apart, quarried the identical sequence of rock namely upper Pecatonica, Mifflin, and lower Grand Detour. These rock units represent the topographic high roche moutonnée which either must have cropped out or they were shallow enough to impede plowing of the field. These formations are also the best quality lithologies in the carbonate sequence.

Another interesting ice feature is the exhumation of a large granite erratic which was in place and completely surrounded by till except for the top surface, Pl. 2, fig. D. This surface has a flat polished surface with S. 30° W. striations. Apparently the boulder was deposited as an ice contact emplacement and then was subsequently overridden by the ice to record the direction and glacial thrust on the till surface of which the boulder was a part.



## ECONOMIC CONSIDERATIONS

The potential uses and economic value of mundane bulky, non-metallic resources such as limestone, dolomite, sand and gravel, gypsum, and similar products are often overlooked. In the case of limestone and dolomite, their value lies in the physical and chemical character of the rocks (Lamar, 1967; Rooney and Carr, 1971). Physical properties include hardness, soundness, toughness, durability, abrasion resistance, porosity and permeability, and inertness. Chemical properties are percentage of effective lime (calcium carbonate equivalent, CCE), percentage of inert ingredients, and trace elements.

Deleterious undesirable, harmful material in stone can be listed as follows:  
(see Fig. 14)

Clays, shale, clay seams, clay lumps- soft, non-lime, MgO (> 3-4%)  
Sands, sandstone- crumbly, granular, non-lime, silica  
Chert (porous) weathered- non-lime, alkali-silica reaction  
Pyrite → Limonite- rusty discoloration, non-lime, crumbly (poisons other stone)  
Weathered rock, surface water leaching- soft  
Organic matter

Crushed carbonate stone can be used for aggregate in concrete and bituminous mixes for highways, drives, sidewalks, and building construction; for fill as base courses for roads and road metal, and ballast on railroad beds. The other important use of the carbonates is for agricultural lime in which it must contain at least 80% calcium carbonate equivalent. Benefits of Ag lime can be summarized as soil and acid rain neutralization, supplies Ca and Mg and trace elements to the soil, aids in nitrogen fixation, furnishes more efficient soil base for fertilizers, improves the physical structure of the soil, and increases crop yield. Other uses of limestone are for cement, flux stone, chemical lime, and riprap.

Basic information pertinent to make reserves calculations is included in this guide. Surprising is the weight in tonnage per unit volume for the carbonates, e.g., 300 acre-feet encompasses more than one million tons of carbonate rock. Tables are also given for the kinds of stone produced in the Kentland quarry, recommended uses for the products, and the current prices of the grades.

In conclusion, the geologist has the responsibility for exploration of our natural resources, the evaluation of their economic worth, and the feasibility of exploitation of the natural resource(s). Geologic mapping is fundamental to such investigation.

### CONVERSION FACTORS (For production and reserves calculations and estimates)

1 ft <sup>3</sup> = 7.481 gallons	1 acre = 43,560 ft <sup>2</sup>
1 gallon = 8.337 lbs. (water)	1 acre foot of water = 1358.42 tons
1 ft <sup>3</sup> = 62.37 lbs (water)	

Mineral	Rock	sp. gr.	lbs/ft <sup>3</sup>	ft <sup>3</sup> /ton	ton/acre ft
Calcite	Limestone	2.71	169.02	11.83	3681.32
Quartz	Sandstone	2.65	165.28	12.10	3599.80
Dolomite	Dolostone	2.86	178.38	11.21	3857.91
"	"	2.84	177.13	11.29	3885.08
		2.672	166.67	12.0	some adjustment for porosity and water content
		2.565	160.0	12.5	

# NATURE'S MIX OF CLAY, SILT, SAND, LIME AND CHERT (Qualitative estimates)

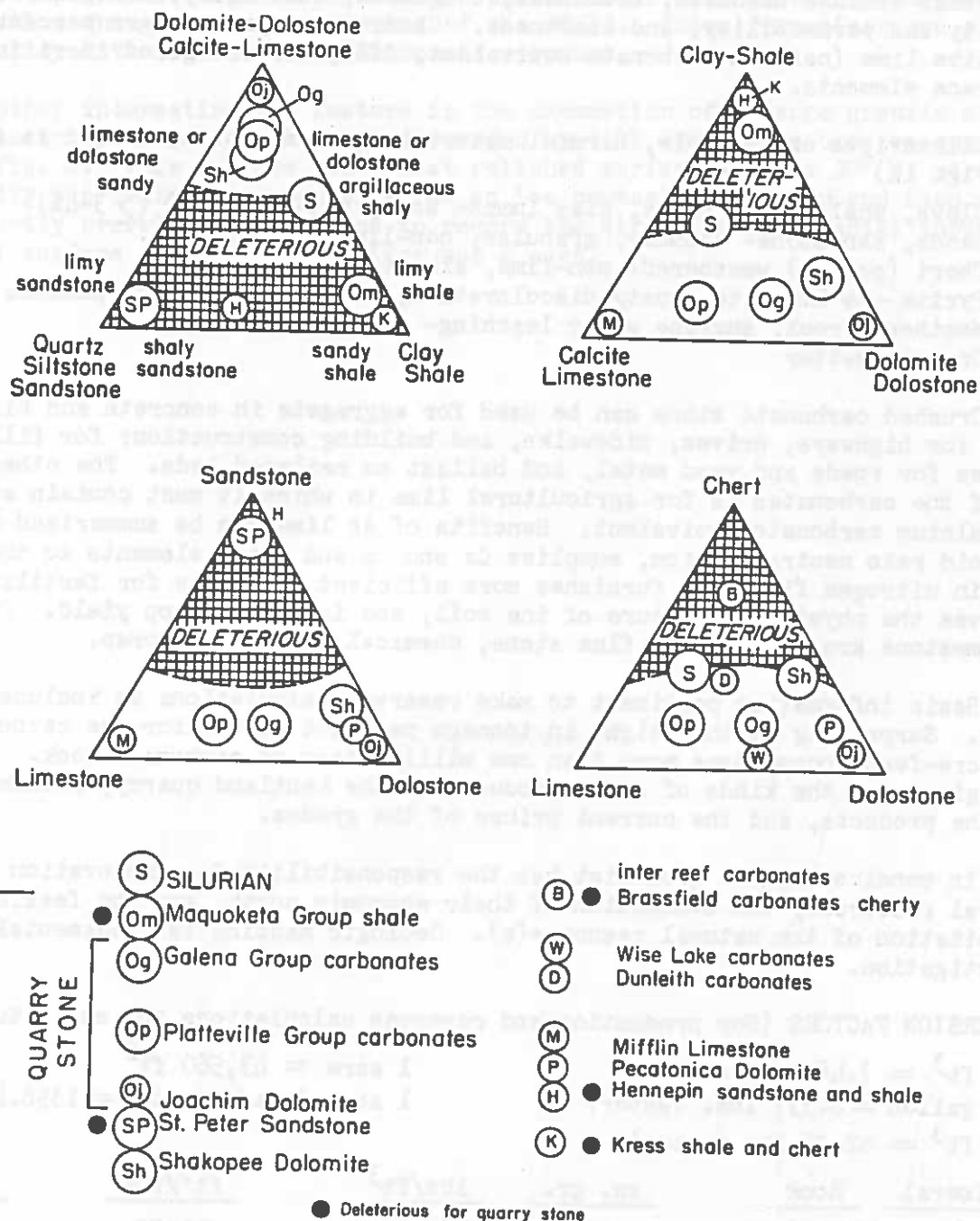


Fig. 14

RESERVES CALCULATIONS (carbonate rocks- limestones, dolomites, dolomitic limestones, calcitic dolomites)

1 acre/ft = 3500 tons (sp. gr. 2.5765; 1 ton = 12.446 ft<sup>3</sup>)

111 ft x 111 ft = 1000 tons/ft (sp. gr. 2.60; 1 ton = 12.33 ft<sup>3</sup>)

(111 ft = 33.833 meters)

Kentland quarry products- Crushed stone and agricultural lime

Type of stone	Basic Size Range
#2	2" to 1"
Ballast	1 1/2" to 1/2"
#5 or Ca7-2	1 1/2" to 3/8"
#8	1" to 3/8"
#9	3/4" to 3/8"
5/8" or Ca-14	5/8" to 1/4"
#11, 1/2, and Ca-15	1/2" to 1/4"
Indiana 3/8	3/8" to 1/4"
Ca-16	3/8" to 1/4" (with 1/2")
#12	3/8" to 1/8"
Ca-13	1/2", 3/8" and 1/4"
#73 or Ca-10	1" to dust
#53 or Ca-6	1 1/2" to dust
Agricultural Limestone *	through 1/8" screen to dust

\* Government specification for standard agricultural ground limestone:

80% must pass No. 8 screen and 25% must pass No. 60 screen

Minimum calcium carbonate equivalent... 80%

Uses of stone products

Fill for large holes	#2, Ballast
Base material for drives and roads	#2, #53, or Ca-6
Railroad track beds	Ballast
Concrete and asphalt mixes	#5 or Ca7-2
Concrete mixes	#8
Descriptive fill around shrubs and trees, driveways	#8
Asphalt binder mixes	#9
Temporary seal coat on asphalt roads	5/8" or Ca-14, #12
Asphalt binder and surface mixes	#11, 1/2, and Ca-15, Indiana 3/8 Ca-16
No skid asphalt surfaces	Ca-13
Road maintenance, driveways and parking lots	#73 or Ca-10
Neutralizer, increases crop yield and legume growth, enhances fertilizer	Agricultural Limestone

ATMOSPHERE → PRECIPITATION → SOILS → CROPS → SOIL DEPLETION → FERTILIZATION  
 AGRICULTURAL LIME → NEUTRALIZATION → CATION EXCHANGE

POLLUTANTS

SO<sub>2</sub>

SO<sub>3</sub>

CO

CO<sub>2</sub>

NO

NO<sub>2</sub>

ATMOSPHERE COMPOSITION

molecular N<sub>2</sub>....78% volume

O<sub>2</sub>....20.95%

Ar.....0.934%

H<sub>2</sub>O.....0.004 to 4%

CO<sub>2</sub>.....0.032%

acids

HCl hydrochloric

H<sub>2</sub>SO<sub>4</sub> sulphuric

H<sub>2</sub>CO<sub>3</sub> carbonic

H<sub>2</sub>NO<sub>3</sub> nitric

RAIN WATER

mean composition  
cyclic constituents

Na<sup>+</sup>.....1.98 p.p.m.

K<sup>+</sup>.....0.30

Mg<sup>2+</sup>.....0.27

Ca<sup>2+</sup>.....0.09

Cl<sup>-</sup>...3.79

SO<sub>4</sub><sup>2-</sup>...0.58

HCO<sub>3</sub><sup>-</sup>...0.12

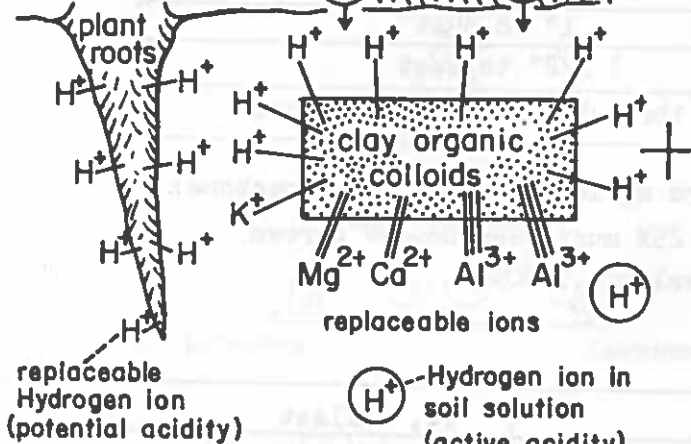
H<sup>+</sup> + CO<sub>3</sub><sup>2-</sup> ⇌ HCO<sub>3</sub><sup>-</sup>

OXIDATION  
SOLUTION  
HYDROLYSIS

PLANTS  
SOILS

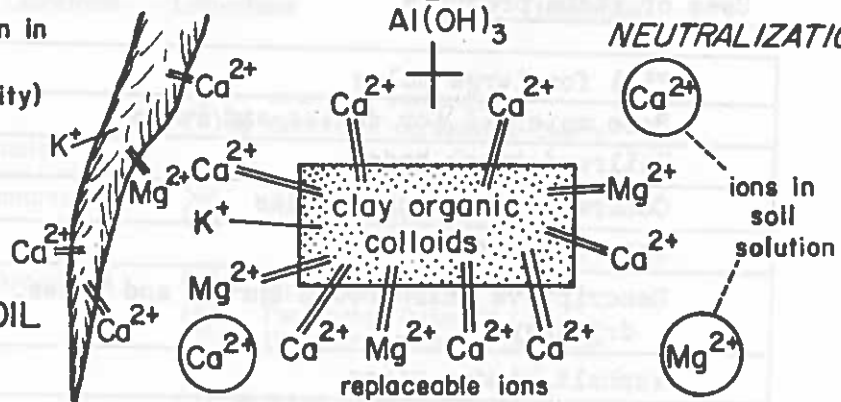
ACID RAIN pH... <4...5...7...  
PRECIPITATION

NEUTRALIZATION



CaCO<sub>3</sub>.....limestone  
magnesium limestone  
AG LIME calcitic dolomite  
Ca, Mg (CO<sub>3</sub>)<sub>2</sub> dolomite  
trace elements

exchangeable H<sub>2</sub>O cations  
Al(OH)<sub>3</sub> NEUTRALIZATION



ACID SOIL + AG LIME → NEUTRAL SOIL

STABILITY SERIES:

Ca > Mg > Na > K > Si > Fe > Al  
High.....Low Solubility

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# Quarry stone prices

<u>Sizes</u>	<u>Charge</u>
Ca-6 (1 1/2" to dust), Ca-10 (1" to dust), #53 (1 1/2" to dust), #73 (1" to dust)	\$ 4.50/ton
#1, #2 (2" to 1"), #4, #5 (1 1/2" to 3/8"), Ballast (1 1/2" to 1/2")	4.50/ton
#8 (1" to 3/8"), #9 (3/4" to 3/8")	4.65/ton
#11 (1/2" to 1/4"), #12 (3/8" to 1/8") Indiana 3/8 (3/8" to 1/4")	4.70/ton
Ca-5, Ca-7, Ca7-2 (1 1/2" to 3/8")	4.70/ton
Agricultural Limestone (through 1/8" screen to dust)	5.25/ton
Ca-13 (1/2" to 3/8", and 1/4"), Ca-14 (5/8" to 1/4") Ca-15 (1/2" to 1/4"), Ca-16 (3/8" to 1/2" with 1/2")	5.50/ton
Pugging charge	Add .50/ton

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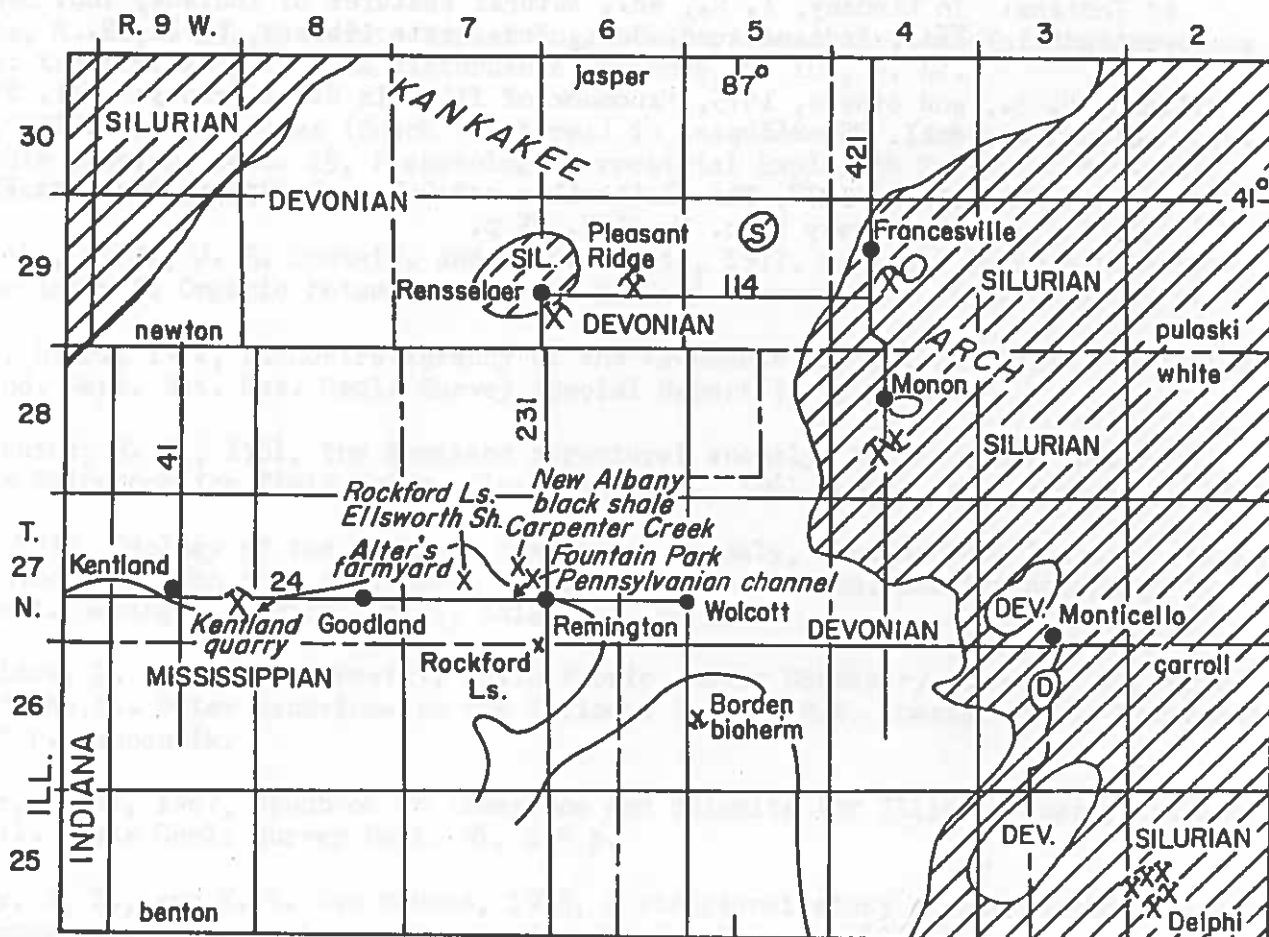


Fig. 15

## REGIONAL GEOLOGY OUTCROPS- The Kentland Structural Anomaly in Context

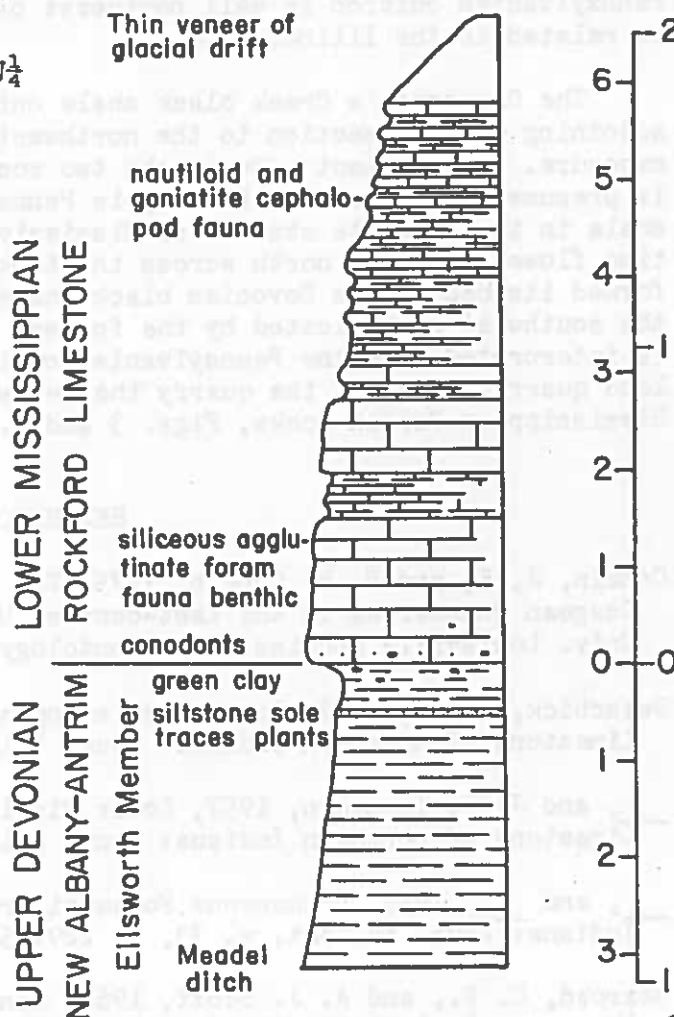
There are exposures of Devonian, Mississippian, and Pennsylvanian rocks that are reasonably close to the Kentland quarry which gives some perspective to the structural anomaly in the normal geologic framework. These supplementary field stops reveal the flat-lying black and green shales of the Ellsworth Member of the Antrim-New Albany Shales, Mississippian Rockford Limestone, and Pennsylvanian sandstone channel eroded apparently into Devonian black shales. Three additional field stops where these can be seen are 10-12 miles east of the Kentland quarry and 1 mile north of U. S. highway 24, Fig. 15.

Feet Meters

### Chris Alter farmyard exposure-

This locality is near the center of NW $\frac{1}{4}$  section 21, T. 27 N., R. 7 W., Jasper County, Indiana. This small but important exposure was called to attention by Shrock and Malott, 1929, and subsequently has received much study. Scientific papers based upon fossils found here include Gutschick and Treckman, 1957, 1959; Gutschick, 1957; Rexroad and Scott, 1964; and Conkin and Conkin, 1975. Mississippian and Late Devonian rocks form the bedrock which is essentially horizontal. The section consists of the Rockford Limestone which overlies the Ellsworth Shale, Fig. 16. A thin sequence between the two units is regarded as a condensed section with a paracontinuity contact at its base which represents the Devonian-Mississippian boundary (Conkin and Conkin, 1975). The green plastic clay above this surface contains an abundance of conodonts, small bright shiny black bored and smoothly rounded phosphatic pebbles, and fish fragments which collectively suggests a slow rate of sedimentation.

Note that the Rockford Limestone and Late Devonian shale have been domed up and truncated around the Kentland Dome, Figs. 3 and 4. Otherwise their outcrop pattern is related to the Kankakee Arch and beveling along its south flank.



Alter farmyard section

Fig. 16

Carpenter's Creek black shale outcrop- There are two interesting rock exposures about 1-1 $\frac{1}{2}$  miles NNW of Remington, Indiana along Carpenter's Creek. The northern one immediately northwest of Chautauqua (Fountain) Park has Late Devonian black shale cropping out along the west bank of the stream. The exposure consists of several meters of black bituminous fissile well-jointed shale from water level upwards to where it is covered with glacial drift. Tasmanites are common in the

shale. Rocks at this locality must be directly beneath the section exposed on the Alter farm, Fig. 16.

Chautauqua or Fountain Park exposures- This small park area consists of a wooded hillside of oak trees growing on sandstone which crops out in bold exposures along Carpenter's Creek. The sandstone is coarse-grained with well rounded quartz granules and it has cross-stratification sets which dip towards the southwest into the Illinois Basin. The rock is regarded as Pennsylvanian and the sandstone body as the outlier remnants of a stream channel of the Michigan River system. This Pennsylvanian outcrop is well northeast of the main system bedrock pattern which is related to the Illinois Basin.

The Carpenter's Creek black shale outcrop of the previous location is in the adjoining quarter section to the northwest of the Pennsylvanian channel sandstone exposure. The contact between the two rock units or bodies is not exposed but it is presumed that the unconformity is Pennsylvanian sandstone on Late Devonian black shale in the complete absence of Mississippian rocks. The stream in Pennsylvanian time flowed from the north across the Kankakee Arch into the Illinois Basin. It formed its bed on the Devonian black shale at this place and continued to flow to the southwest as indicated by the foreset bedding. A similar stream from this system is interpreted from the Pennsylvanian outlier patches in the vicinity of the Kentland quarry. East of the quarry the Pennsylvanian channel is unconformable on Mississippian Borden rocks, Figs. 3 and 4.

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Plates 1 & 2

# Plate 1

- Figure A- West quarry wall, light colored block of Silurian rocks on south side of Means Fault in sharp contrast to darker brown dolomite of the Pecatonica Formation north side of the fault. Note the fault dislocations within the Silurian block. Photo taken April 4, 1975.
- B- West quarry wall continuation of Figure A to the north showing Means and Kentland Quarry Faults with folded Joachim-Pecatonica strata in block between the faults. Hangingwall of KQF has light colored Joachim Dolomite (Oj), thin shaly Hennepin Member (h) and Pecatonica Dolomite in sequence.
- C- West quarry wall showing continuous sequence of rocks across the Ordovician-Silurian boundary. The Ft. Atkinson Limestone and Brainard Shale Formations of the Maquoketa Shale Group grade upwards into the Brassfield Limestone of Lower Silurian age. Photo taken August 12, 1981.
- D- West quarry wall showing structural relations which continue to lower levels of the quarry. The scale is apparent from the Euclid truck on the ramp and the shot-hole drill rig on the lower level. Photo taken July 9, 1980.
- E- North wall of NE part of the main quarry showing faulted duplicated section (see Fig. 8 for structural interpretation). Ramp road is in upper left-hand corner and shops are on top to right. This wall represents the north edge of the original quarry mapped by Shrock in the early thirties and Boyer, 1953.
- F- Intersection of Kentland Quarry Fault (KQF) and McCray Fault in southeast part of the main quarry. Picture was taken April 28, 1965, when the Platteville was exposed in the small cul-de-sac quarry before it was back-filled. The block between the fault juncture and the pump standpipe along the quarry wall is lower Platteville hangingwall of the KQF and footwall for the McCray Fault.





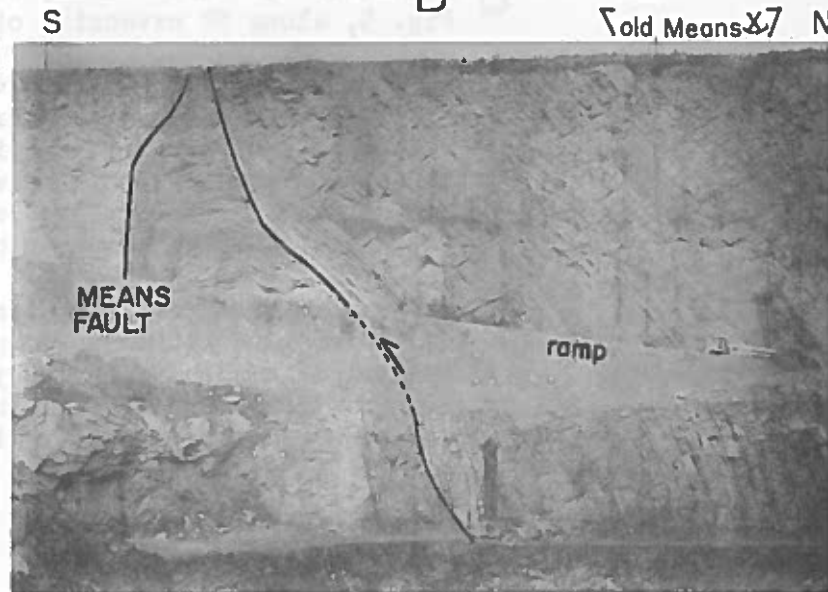
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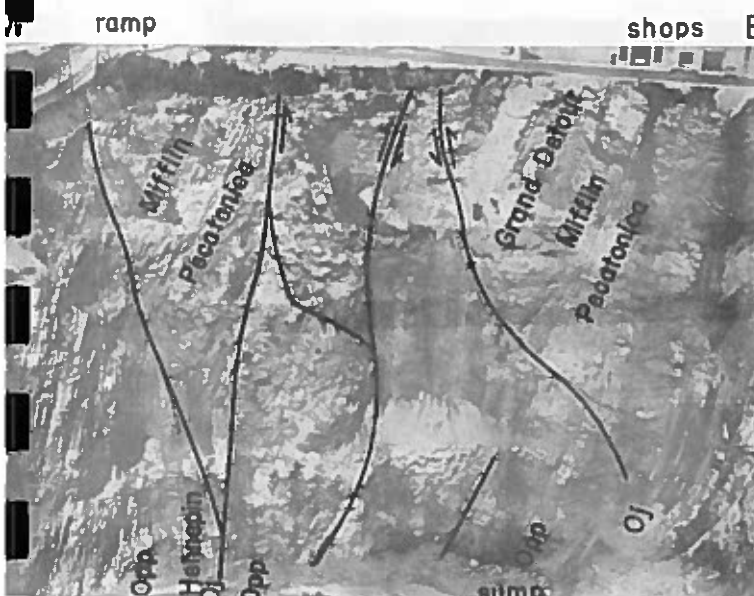
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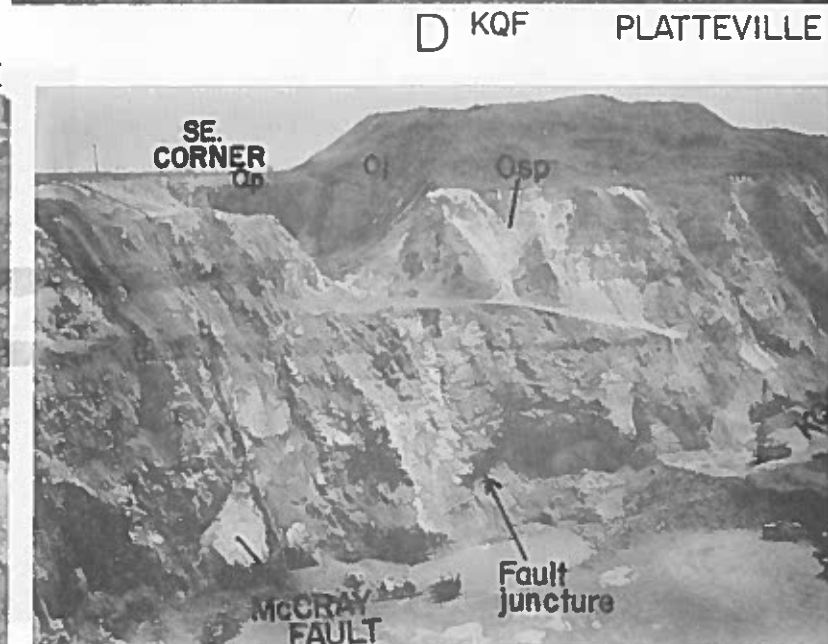
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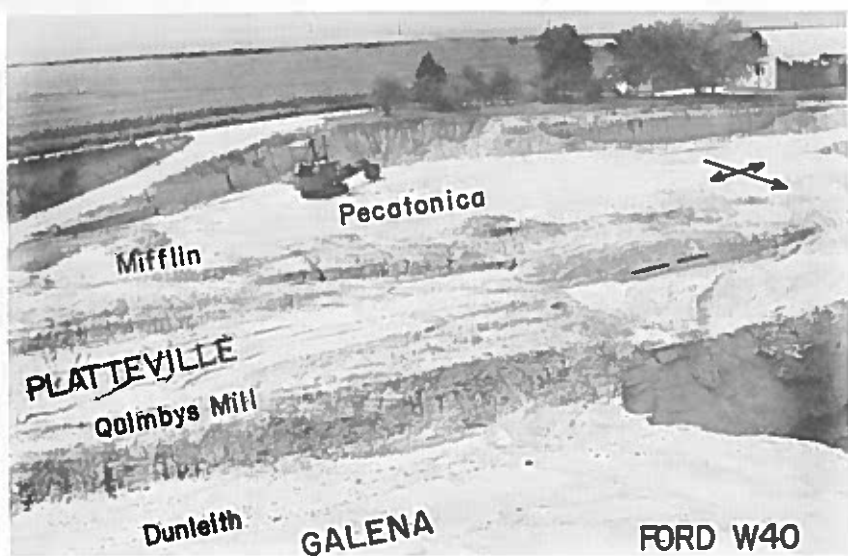


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PLATE 2

- Figure A, B- Bedrock glacial pavement, Ford W40 SW quarry extension, view looking southwest in direction of glacier movement. Bedrock surface shows differential ice erosion related to rock formations and structure. The highest bedrock elevations are along the Mifflin Formation *roche moutonnée*. The lowest is the Dunleith Formation, lower Galena Group. Photo taken August 12, 1981.
- C- Glacial striations on hard micritic limestone of Mifflin Formation showing direction of ice movement, Ford W40. Photo taken February, 1981.
- D- Granite erratic embedded in till. Boulder surface is polished and striated. Striations have same vector as striae on glacial polished and striated bedrock surface. Location is shown on geologic map, Fig. 5, along SE extension of Means Fault. Photo taken in May, 1969.
- E- Geology in area of crusher, view looking to NE. Crusher Fault cuts Maquoketa and Galena transversely to give duplication of Platteville-Galena in central part of main quarry. The Pecatonica and Mifflin Formations are beneath the overhead conveyor belt between the crusher and silo. The Platteville-Galena contact is exposed north of the road to the left of the conveyor belt.
- F- Footwall of the Kentland Quarry Fault along the south side of the main quarry showing attitude and polished, slickensided fault surface. Removal of carbonate rocks by quarrying has eliminated the hangingwall down to the quarry floor. The east wall of the quarry is seen in the background. Photo was taken in November, 1967.



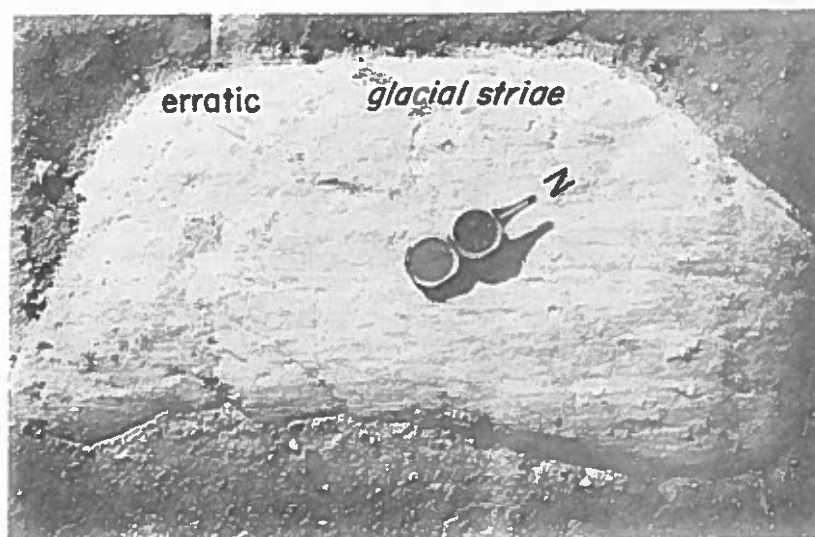
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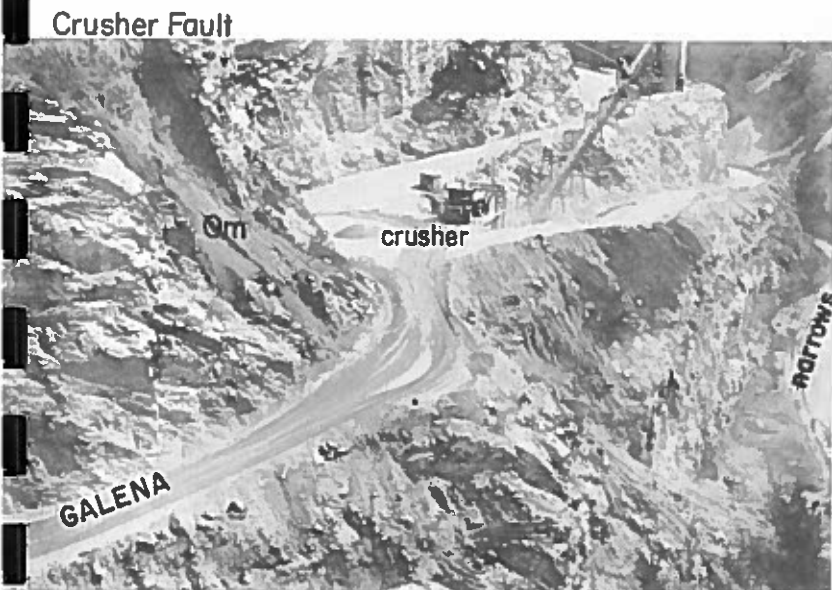
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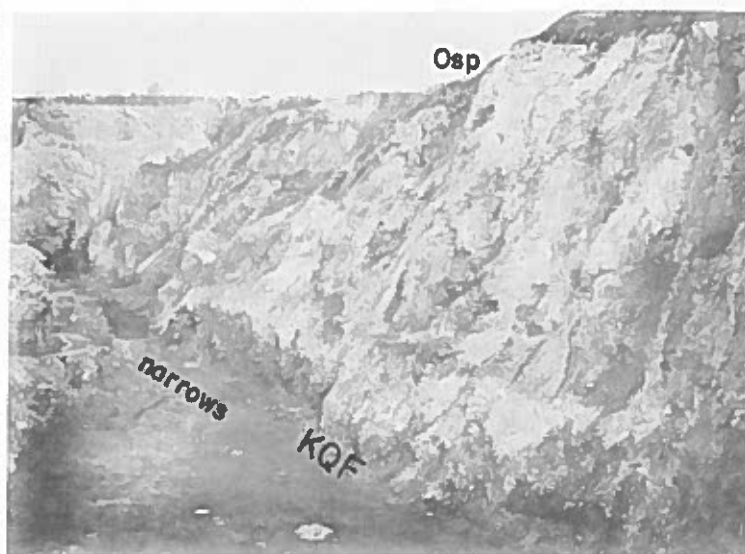
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*To Bill - the latest update of this interesting unusual structure  
with best regards*

Field Trips in

Midwestern Geology

*Ray Gutschick*

FIELD TRIP #5

GEOLOGY OF THE KENTLAND DOME STRUCTURALLY COMPLEX  
ANOMALY, NORTHWESTERN INDIANA

Raymond C. Gutschick  
University of Notre Dame,  
Notre Dame, Indiana

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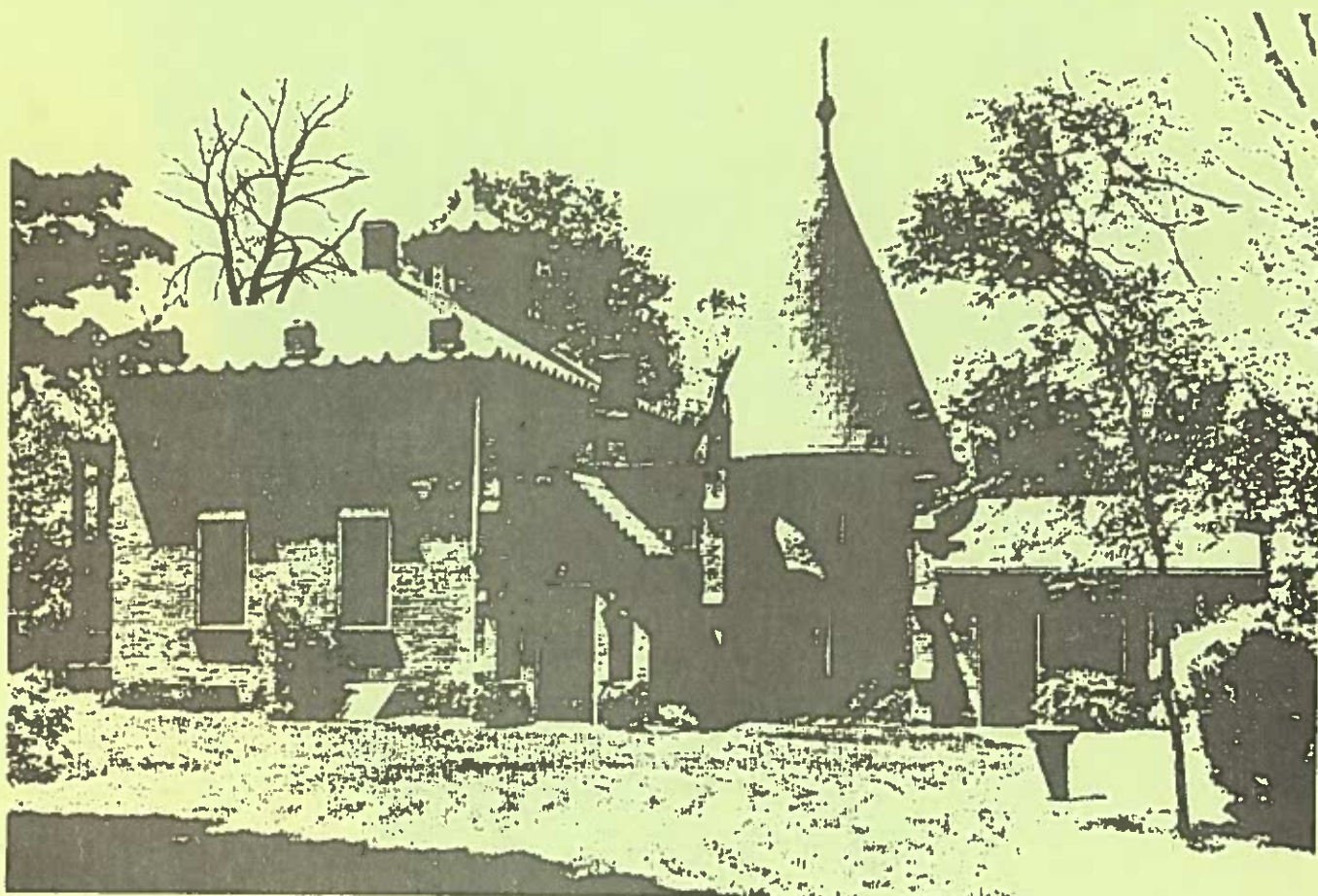
THE GEOLOGICAL SOCIETY OF AMERICA

THE INDIANA GEOLOGICAL SURVEY *and*

THE DEPARTMENT OF GEOLOGY, INDIANA UNIVERSITY

*On the Occasion of*

THE 1983 ANNUAL MEETING OF THE GEOLOGICAL SOCIETY  
OF AMERICA AND AFFILIATED SOCIETIES AT INDIANAPOLIS



Volume 1



# Field Trips in Midwestern Geology

Volume 1

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# GEOLOGY OF THE KENTLAND DOME STRUCTURALLY COMPLEX ANOMALY, NORTHWESTERN INDIANA (FIELD TRIP 5)

RAYMOND C. GUTSCHICK

University of Notre Dame, Notre Dame, Indiana

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## ITINERARY

Sunday, October 30, 1983--One-day field trip to the Kentland quarry, 100 miles from Indianapolis, and return.

The field trip group leaves from the east side of the Convention Center on Capitol Avenue, Indianapolis, at 7:45 a.m. Our route leads northward over Indianapolis city streets to I 65, following it beyond Lebanon through Lafayette and West Lafayette to U.S. 24. We continue west on U.S. 24 to the Newton County Stone Company quarry, about 3 miles east of Kentland Indiana; total, 100 miles; 10:00 a.m.

The route is over the Cartersville Till Member of the Trafalgar Forma-

tion drift sheet of the Wisconsinan glaciation, beneath which is the preglacial east-west trending Teays Valley and some of its tributaries (fig. 1). The route also follows the strike of Late Devonian and Early Mississippian bedrock formations that dip to the southwest off the Kankakee and Cincinnati Arches into the Illinois Basin (fig. 2).

At stop 1, time allocated to examination of exposures in the Newton County Stone Company quarry is 3 hours, 20 minutes: 1:20 p.m. Sign liability release, hard hats required, stay together. The group travels 3 miles west to Kentland for lunch at the Nu-Joy Restaurant; 1:30 p.m.



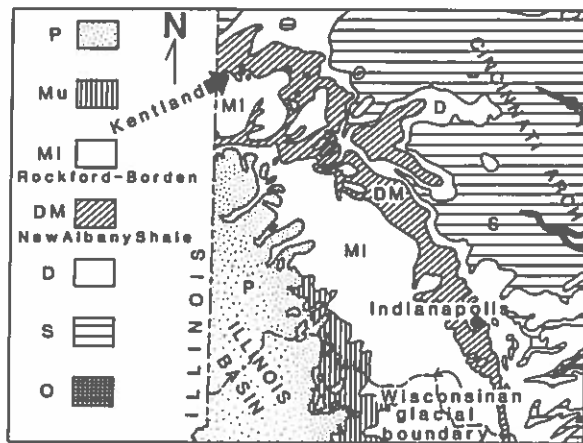


Fig. 2. Generalized geologic map of west-central Indiana along field-trip route from Indianapolis to Kentland (adapted from Indiana Geological Survey Regional Geologic Map series, 1970).

## INTRODUCTION

### THE QUARRY

The remarkable Kentland Quarry is an especially valuable field laboratory for study. One cannot overemphasize the unique opportunity available to observe various aspects of geology, in particular, structural detail which is seldom freshly exposed laterally and vertically on this scale. It is an exhilarating experience to view and study the extensively exhumed exposures of this spectacular geologic feature.

The quarry of the Newton County Stone Company, Inc., is owned by Ralph Rogers & Company, Inc., Bloomington, Indiana. Richard Rechter is President of the Rogers Group. Max Scott is Vice-President, Norman Greenberg is General Manager, and William Davidson is Quarry Superintendent of the Newton County Stone Company, Inc.

The Kentland Quarry has received much attention from geologists and student groups over the years. The quarry management is well aware of the uniqueness and importance of this site to science and education

and they go out of their way to cooperate with geological visitors. They also are very concerned about personal safety. Each quarry visitor is required to sign a release form, and each person must wear a hard hat inside the quarry. It is imperative that we stay together as a group and that we avoid the steep quarry walls. Rock falls are especially likely after a rainfall or thaw. Rock collecting and geological photography are permitted. Please do not litter.

### STATE OF KNOWLEDGE

This guidebook is one of a series of progress reports on an extended geologic study of the Kentland Quarry. The study evolved from my first visit to the quarry as a student in 1939 shortly after R. R. Shrock's geologic report of the structural anomaly in 1937. In 1947, as an academician, it became easy to accept the challenge to keep pace with developments by retrieving geological information during continued quarry expansion and deepening. This has been done for more than three decades, and this fascinating pursuit has produced the results described herein. Geological mapping has followed quarry developments and has been supplemented with exploration core-drill information.

Quarry operations in the Kentland structure are unique. Normally, exploration for carbonate stone and exploitation of it in the Midwest are uncomplicated processes, since the strata generally are nearly flat lying and facies changes are not as abrupt as is fault disruption. However, in the complexly folded and faulted Kentland structure, where all strata are upended and chaotic, an understanding of the geology is of primary practical importance. The quarry operators recognize this value and appreciate the interdependence of geology and quarry management.

This field guidebook is an update

enigmatic. It was therefore an exhilarating experience to brainstorm all of the above resources for the clues which enabled construction of the present geologic-structural interpretation of the quarry with high confidence.

Several examples are given to illustrate the process. The east wall of the quarry has always been an enigma to me, partly because of its complexity and partly because it is not now readily accessible. Rock units were initially misidentified and out of context. However, a high-resolution air photo of the quarry (Indiana Highway Department stereophotos furnished by James Plew) revealed a possible structural trend of one of the fault blocks, and Kodachrome slides taken from a helicopter at the proper angle in 1970 helped to resolve the identity of rocks and the structure of the block. The block has a sequence of the brown Pecatonica Dolomite overlain by the gray Mifflin Limestone with almost vertical strata. This sequence becomes the key to structural mapping in this part of the quarry since it forms the hanging wall for the Kentland Quarry Fault and the footwall for the newly designated McCray Fault.

Another case in point deals with the southwest quarry extension. Geologic mapping of the bedrock surface on the Means Quarry tract after it had been stripped of glacial drift (Gutschick, 1976) revealed the truncation and offset of the Kentland Quarry Fault by the newly designated Means Fault. Mapping also suggested the presence of the detached Galena and Platteville carbonates to the south in normal sequence south of the Salamonie, Brassfield, and Maquoketa map units. Core-drill exploration confirmed this observation, resulting in the opening of the new southwest quarry extension.

The location of the Kentland structural anomaly in the context of

the regional geology of the State of Indiana is shown on the geologic map of west-central Indiana (fig. 2). Most rock formations at the bedrock surface in Indiana dip only a fraction of one degree away from the arch into either the Michigan Basin or the Illinois Basin. With the exception of the Kentland anomaly, the oldest rocks exposed at the bedrock surface in Indiana are Upper Ordovician rocks found along the crest of the Cincinnati Arch. But in the Kentland Quarry Lower Ordovician rocks are exposed at the level of the bedrock surface, and the rocks throughout the quarry have very steep dips. The geometry of Kentland's four-dimensional jigsaw puzzle (3-D rock masses in space and time) is more than an academic exercise.

#### CHRONOLOGIC RESUMÉ OF SIGNIFICANT DEVELOPMENTS AT KENTLAND

The original land surface at Kentland probably had some natural outcrop(s) along a low semicircular topographic ridge which was underlain by thin glacial drift on its summit. Steeply dipping middle Platteville rocks form bedrock highs on which the two earliest quarries, Means and McKee, were located (fig. 3). The land was purchased by Samuel Means and John McKee in February 1865 and was subsequently divided into the Means and McKee farms. Apparently Means first opened a small quarry for foundation stone when he built his farmhouse, now gone from the Ford W40 tract, and shortly afterwards McKee opened another quarry on his farm in the same strata. This early history is taken from Shrock (1937) and from annual reports of the State Geologist of Indiana. A chronologic history follows:

1881--Professor John Collett, State Geologist, with G. K. Greene assisting him, visited the McKee quarry on two occasions for geologic observations and collecting of fos-

1952--Lucas made gravity and vertical magnetic intensity surveys of the area.

1953--Pullen presented a radio field-intensity survey map of the Kentland anomaly.

1953--Boyer did a geological study and made a geologic map of the McCray Quarry.

1961--Gutschick published a progress report on the geology of the McCray Quarry including a geologic map.

1961--Cohen, Bunch, and Reid reported the discovery of coesite in the St. Peter Sandstone at Kentland.

1963--Templeton and Willman reported and clarified Ordovician Champlainian stratigraphy used at Kentland as an update of Shrock (1937).

1971--Tudor produced a Ph. D. dissertation on a geophysical study of the Kentland disturbed area (Indiana University and Indiana Geological Survey cooperative study), which included an important core-drilling program that established the bedrock formations.

1976--Gutschick reported on the geology of the Kentland structural anomaly in an update on stratigraphy, structure, and geologic mapping.

1978--Laney and Van Schmus, in a structural and petrographic study based on a master's thesis, concluded that the structurally disturbed area is the result of a large natural impact event.

1980--Hoholick in a master's thesis made observations on the petrography of the St. Peter Sandstone along the main fault in the Kentland Quarry.

1980--Votaw observed the color alteration index of conodonts from the Kentland Quarry and speculated on their metamorphic significance.

1980--New quarry development was initiated to the southwest in an extension called the Ford W40 Pit (fig. 3).

1982--Gutschick produced a geo-

logic map and update of the stratigraphy and structure of the Kentland Quarry on the basis of a core-drill program and the quarry expansion Ford W40.

1983--Gutschick, the present progress report.

## STOP 1, KENTLAND QUARRY GEOLOGY

### STRATIGRAPHY AND STRATIGRAPHIC KEYS

We will have an orientation overview from the top of the northeast corner of the quarry before proceeding down the ramp into and through the quarry to the opposite southwest corner of the Ford W40 extension. The first sight of the quarry with its complex and chaotic appearance tends to overwhelm the observer on his or her first visit. Therefore, you should focus your attention on the following features of stratigraphy and structure.

Sources for stratigraphic resolution include Shrock (1937); Templeton and Willman (1963); Shaver and others (1970); Willman and others (1975); Willman and Kolata (1978); Gray (1972); Droste, Abdulkareem, and Patton (1982); and Rexroad and Droste (1982). Stratigraphic nomenclature is somewhat complicated since facies patterns fall between sedimentary basins or areas of paleoenvironmental changes in which the states of Indiana and Illinois each have adopted their own stratigraphic policies and nomenclatural standards. Thus a combination of names used in several states has been applied depending upon the relations of the rocks and their facies to those of the most typical areas, for example, Shakopee Dolomite and St. Peter Sandstone--Minnesota, Joachim Dolomite--Ozarks, Platteville and Galena Groups--Wisconsin and Illinois, Maquoketa Group--Iowa, and Salamonie Dolomite--Indiana.

More than 1000 feet (305 m) of stratigraphic section or succession

Table 1. Composite Measured Section in the Kentland Quarry

System and series	Unit and description
Quaternary	Glacial drift: rusty oxidized (about 8 ft; see fig. 14) over gray unoxidized till
Devonian Upper	New Albany Shale Group--black and green-gray shale; <i>Tasmanites</i> ; occurs only in fault breccia
Silurian Middle	Salamonie Dolomite--limestone and dolomitic limestone: light green-gray; brown shale partings; some fossils; Salamonie and Sexton Creek total about 250 ft in thickness with fault at top
Lower	Sexton Creek Limestone--limestone and dolomitic limestone in light green-gray and pink beds, white tripolitic chert, pyrite, glauconite, and agglutinated forams ( <i>Turritellina</i> )
Ordovician Upper	Maquoketa Shale Group (about 240 ft) Brainard Shale--shale and dolomitic limestone: gray-green; thin, even beds; trilobites, brachiopods (replaced by pyrite), and scolecodonts Fort Atkinson Limestone--dolomite: rusty; weathering color resembles that of Galena Group; thin unit; thick beds; associated with bright-green shale Scales Shale--shale: dark-gray, silty, unfossiliferous; has siltstone interbeds and thin planar bedding ribs Conspicuous disconformity represented by pyrite-marcasite layer, bone bed, fish and conodonts, black shiny bored ( <i>Trypanites</i> ) phosphate pebbles, heavy rusty weathering stain
Middle	Galena Group (about 150 ft)--dolomite, dolomitic limestone, and limestone; ubiquitous rusty weathering; gypsum efflorescence; some nodular chert; monolithic breccia; few fossils  Platteville Group (about 240 ft) Quimby's Mill Formation--dolomitic limestone and limestone: brown and gray, micritic; <i>Chondrites</i> Nachusa Formation--dolomitic limestone and limestone: brown and gray, fine-grained; <i>Chondrites</i> , some nodular chert, and colonial corals Grand Detour Formation--dolomitic limestone and limestone: variable; red-brown shale partings (Forreston Member); some nodular chert; <i>Chondrites</i> common Mifflin Formation (15 to 20 ft)--limestone and dolomitic limestone: gray and tan, very distinctive, thin- and wavy-bedded; shale partings, calcarenite beds, and fossils Pecatonica Formation (75 ft)--dolomite: brown, mottled, fine- to medium-grained, medium-bedded; some chert; <i>Chondrites</i> common; coarse quartz grains in Chana Member near base of formation; Hennepin Member (6 ft) is important key bed having green shale and white sandstone, weak shaly layers; is bioturbated having white sandstone burrow fillings in disturbed green-gray shale; pyrite nodules oxidize to produce conspicuous spots and rusty drip stain on bedding surfaces that are well exhibited on south wall of Kentland Quarry Fault  Joachim Dolomite (15 to 20 ft)--dolomite: very distinctive, very light gray, fine-grained, medium-bedded, tough, brittle; contains triplet beds of subtle alternating colors: tan to light-brown, very pale green-gray, and cream; "tile-mosaic" pattern along bedding surface near top of formation; bottom is unknown fault contact  Dense brittle fractured rock of hanging wall Kentland Quarry Fault zone Granulated, pulverized, fractured, cataclastic rock of footwall  St. Peter Sandstone (about 100 ft)--sandstone: white quartzose, fine- to coarse-grained, fractured, friable, rust-stained along fault in breccia zone; most recognizable unit; quartz grains rounded and frosted; top unknown fault contact; thickness depends upon abrasion, granulation, and pulverization between fault blocks and upon amount of stress: thinnest or absent in synclinal trough, thickest on flanks of syncline or crest of anticline; coesite reported Kress Member (5 to 10 ft)--shale: bright-green; white nodular chert with rust coating; reworked insoluble residuals of unconformity
Lower	Shakopee Dolomite (about 125 ft)--dolomite; green shale partings; white nodular chert, some oolitic; algal-mound stromatolites; limited exposure

quarry also contributes to our understanding of this domal structure. The oldest rocks at the bedrock surface are of the Shakopee Dolomite (Lower Ordovician) present near the center of the dome. These have been uplifted more than 2000 feet (610 m). A geologic profile of the Kentland Dome is shown in figure 6.

Undisturbed country rocks are essentially flat-lying Lower Mississippian shales and siltstones of the Borden Group. Borden strata were channeled by Pennsylvanian stream tributaries that deposited sandstones, shales, and coal. The basal Pennsylvanian shoestring channel-fill deposits remain as isolated outliers separated by erosion from the main Pennsylvanian basinal outcrops to the southwest. This bedrock pattern is pierced by the Kentland Dome, which is faulted on the south side by the Gutschick Fault (Tudor, 1971), a normal south-dipping structure that trends N65°W parallel to regional strike. A second normal fault on the west side trends N17°E. New Albany shale of Late Devonian age is dragged upward in the downthrown hanging wall against Silurian rocks on the opposite footwall along both faults. Otherwise, the dome is conventional, as mapped, with highly shattered Ordovician rocks in the center and presumably quaquaversal dip outward to flat-lying normal structure.

#### Kentland Quarry Geology and Structure

The quarry occupies the north, northwest, and west sides of the Kentland Dome so that exposed rocks generally dip steeply off the dome. The central Ordovician area is considered to be the core of the structure. Quarry stone objectives are the carbonates of the Platteville and Galena Groups and the Joachim Dolomite. As a result, the pit outlines the presence, or former presence, of these units which delineate the structural pattern. One

exception is the cross cut to the southwest extension on the west side that goes through Silurian and Ordovician (Maquoketa) rocks.

The pattern of distribution of formations and members found at the bedrock surface, along the quarry walls and floor, is shown on the geologic map (fig. 7) and geologic structure map (fig. 8). The west halves of the maps depict bedrock geology mapped shortly after the glacial drift was stripped off the bedrock. The east halves of the maps are combinations of upper bedrock surface, quarry wall, and floor exposures, so that some contacts are drawn continuously from the bedrock surface to the deep floor of the quarry. Therefore, care should be taken to visualize the geometry of the rocks and structures shown on this part of the map.

In general, the oldest rocks in the main quarry and Ford W40 quarry are to the south, and the youngest rocks are to the north. The beds are right side up, so their dips are to the north. The basic structural style is folding, with a steep NNW-plunging main quarry syncline flanked on both sides by anticlines which are cut transversely by faults on their distal limb (fig. 9). The major Kentland Quarry Fault parallels the fold structure and forms the south wall of the main quarry. Faulting is along the St. Peter Sandstone and the Joachim Dolomite.

There is a single sequence of Platteville-Galena carbonate rocks on the west limb of the Kentland Quarry Syncline and in the anticline of the Ford W40 southwest extension (fig. 9). The main quarry, shown on the east half of the geologic map (fig. 7), is much more complicated, as is evident from the duplicate patterns of Platteville and Galena rocks. This repetition of carbonate rocks accounts for the enlargement of the east half of the main quarry, except for the "narrows."

In summary, combination of doming,

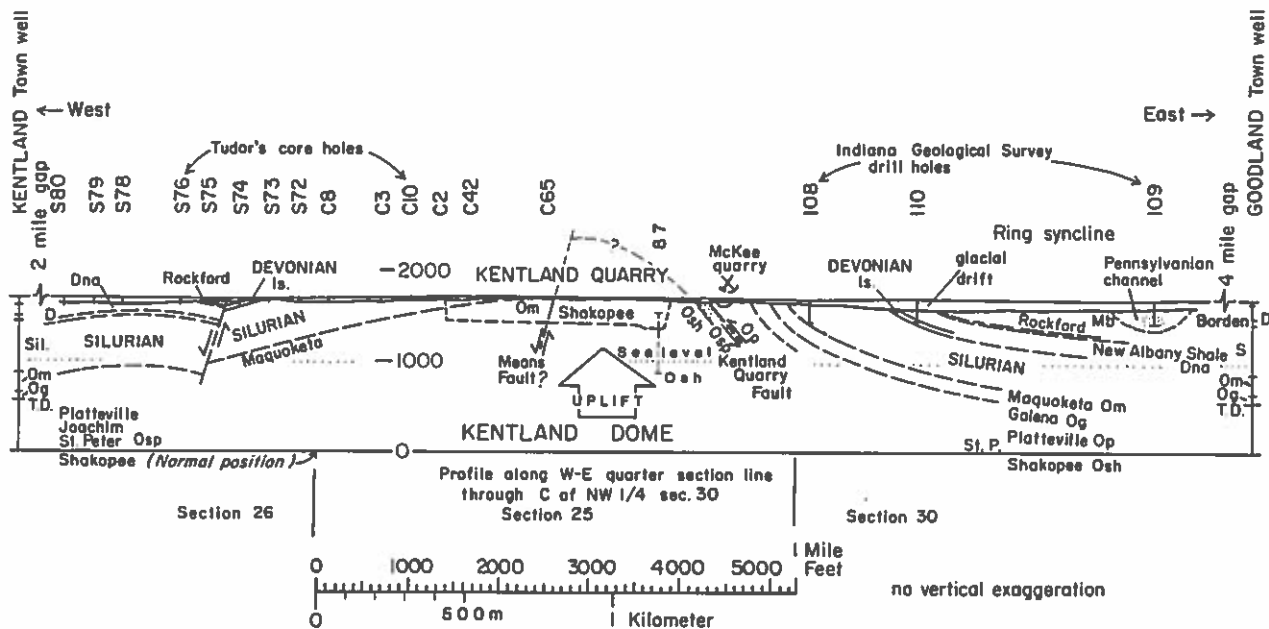


Fig. 6. West-east geologic section of the Kentland structural anomaly showing the faulted asymmetric domal nature of the structure. (See figure 5 for line of section.) Normal undisturbed stratigraphic sections are shown for deep townsite water wells in Kentland and Goodland. Note 2- and 4-mile gaps in the section adjacent to the town-well sections. Shakopee Dolomite is the oldest rock exposed in the quarry so that well-site sections are projected to the top of the Shakopee to provide a datum of reference for structural displacement.

where its orientation is consistent with the fold in the main quarry (figs. 7 and 10). Folding is indicated in the northeast part of the quarry by reconstruction of the duplicated strata and their bedding attitudes (figs. 9H and 11). The small fault block between the Means Fault and the Kentland Quarry Fault along the west wall (figs. 9D and 10) has Joachim and Pecatonica beds tightly folded into a NW-plunging anticline. This fold apparently was broken off the hanging wall of the Kentland Quarry Fault. The block also duplicates the strata, orientation, and folding of the folded block B (fig. 11A) in the north wall of the northeast part of the quarry.

#### Faulting:

The Kentland Quarry displays localized catastrophic disruption of strata in an area of otherwise

structural simplicity. Faulting is conspicuous on the structural map (fig. 8) and in photos (fig. 9) and is recognized by abrupt changes in lithology, changes in the structural trends, duplication of rock units, and the patchy mosaic of structural blocks. It is important to relate the fault pattern to the uplifted Kentland Dome, much like the experimental and analytical models of faults associated with domes presented by Withjack and Scheiner (1982). Unfortunately, a geologic map of the entire Kentland Dome is not available to evaluate the fold-fracture pattern for the entire dome. The following important faults have been identified in the Kentland Quarry: the Kentland Quarry, McCray, Means, McKee, Crusher, and Ramp Faults.

Kentland Quarry Fault--Apparently the weakest bond in the stratigra-



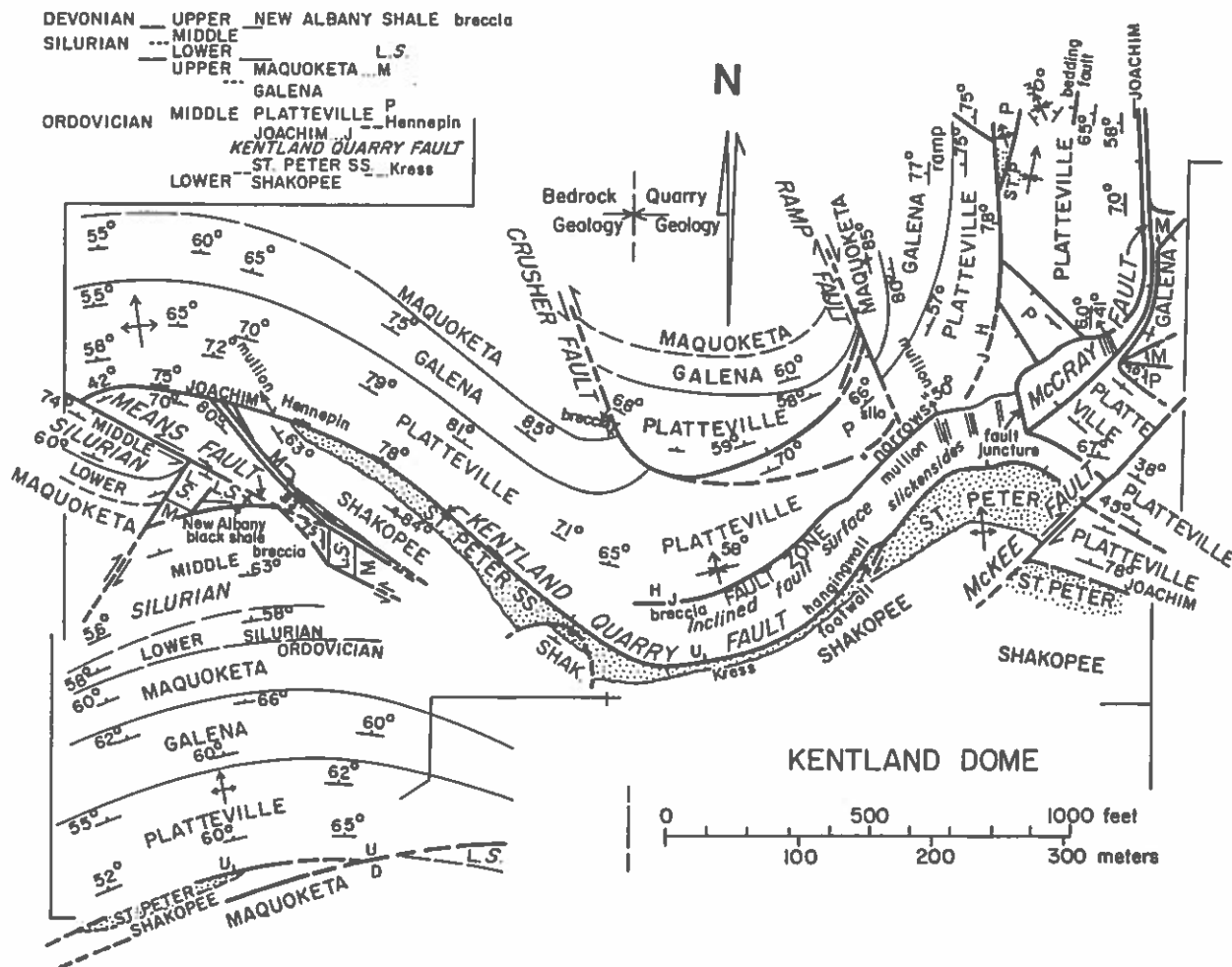


Fig. 8. Geologic structure map of Kentland quarry focusing on fault pattern, attitude of strata, and other structural details. Pattern in west half of map is from stripped bedrock surface; that in east half of map projected from quarry walls to quarry floor, especially the inclined Kentland Quarry and McCray Faults.

that a complete section of either unit is present. The St. Peter Sandstone has been almost completely removed along the trough axis of the main quarry syncline where the green shale of the Kress Member of the St. Peter is close to the fault contact along the footwall (fig. 8). Note how the St. Peter Sandstone thickens away from the axis of the syncline. The fault surface is steep at bedrock level and becomes less steep with depth, probably conforming to the geometry of the flank of the dome. The Kentland Quarry Fault

logically appears to be a reverse fault, but the net slip is unknown. Variable oblique slip is indicated along its length by change of the plunge of such lineations as slickensides and mullion (fig. 13G). Normal late-stage relaxation movement is also present.

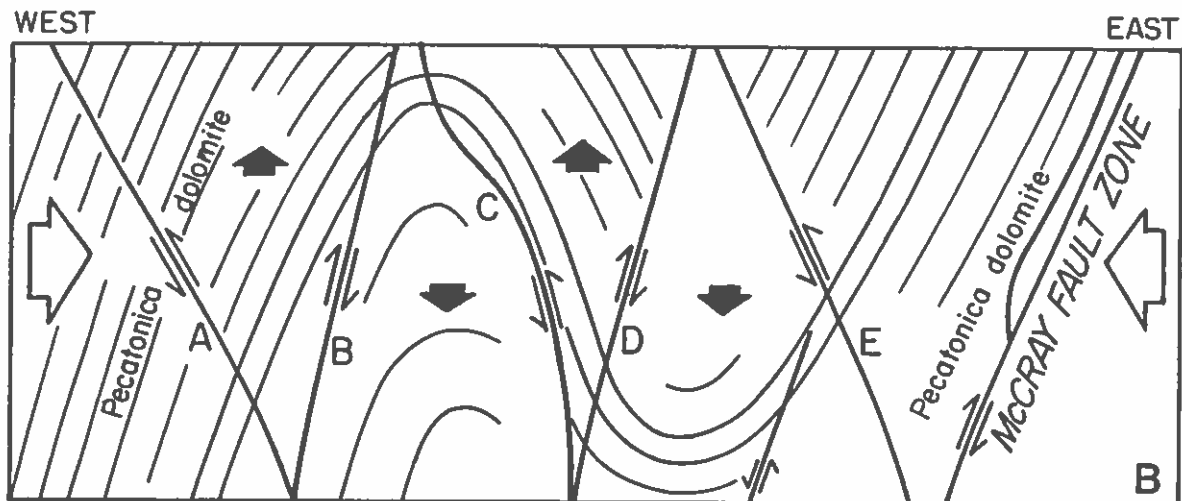
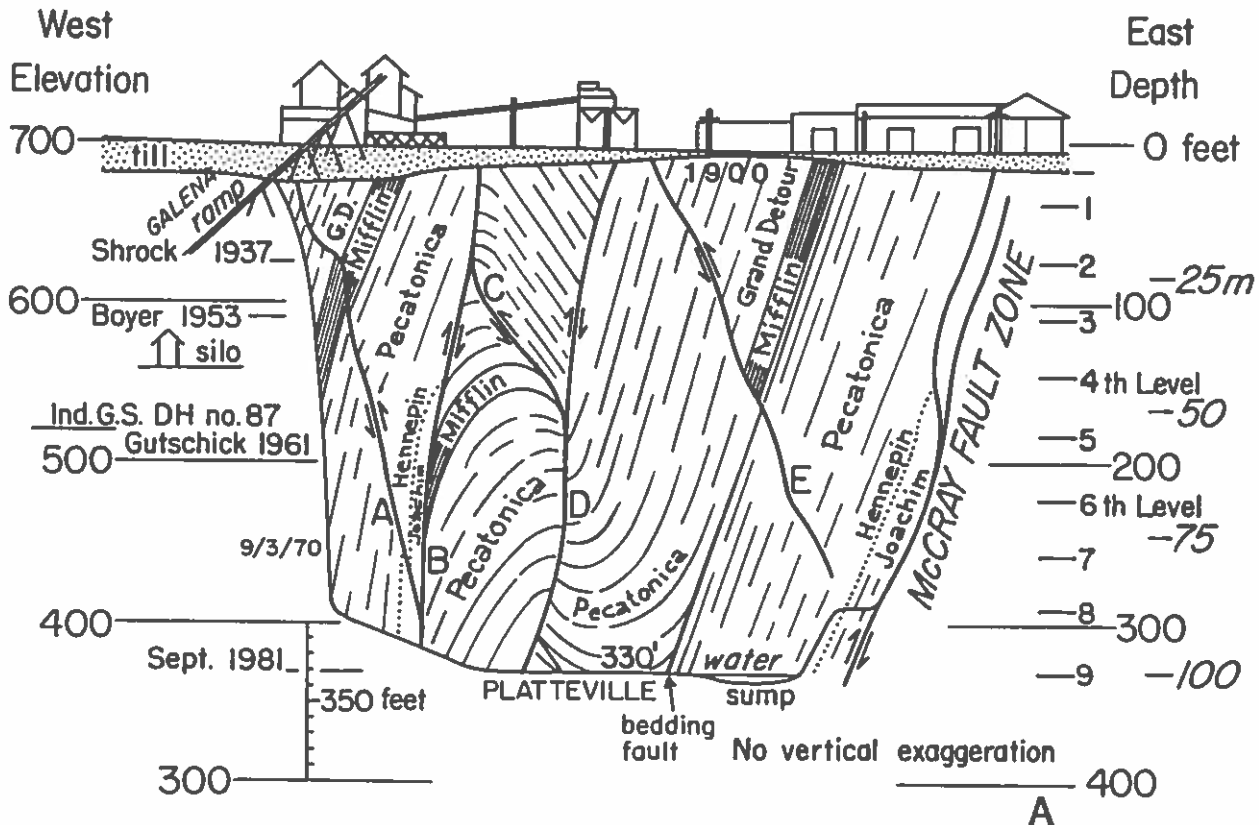
The fault zone is characterized by smooth, polished, slickensided surfaces; patches and cross-cutting dikes of mortarlike polymictic breccia involving lithologies present in quarry rock types; pulverization of iron sulphides; and iron-oxide stain

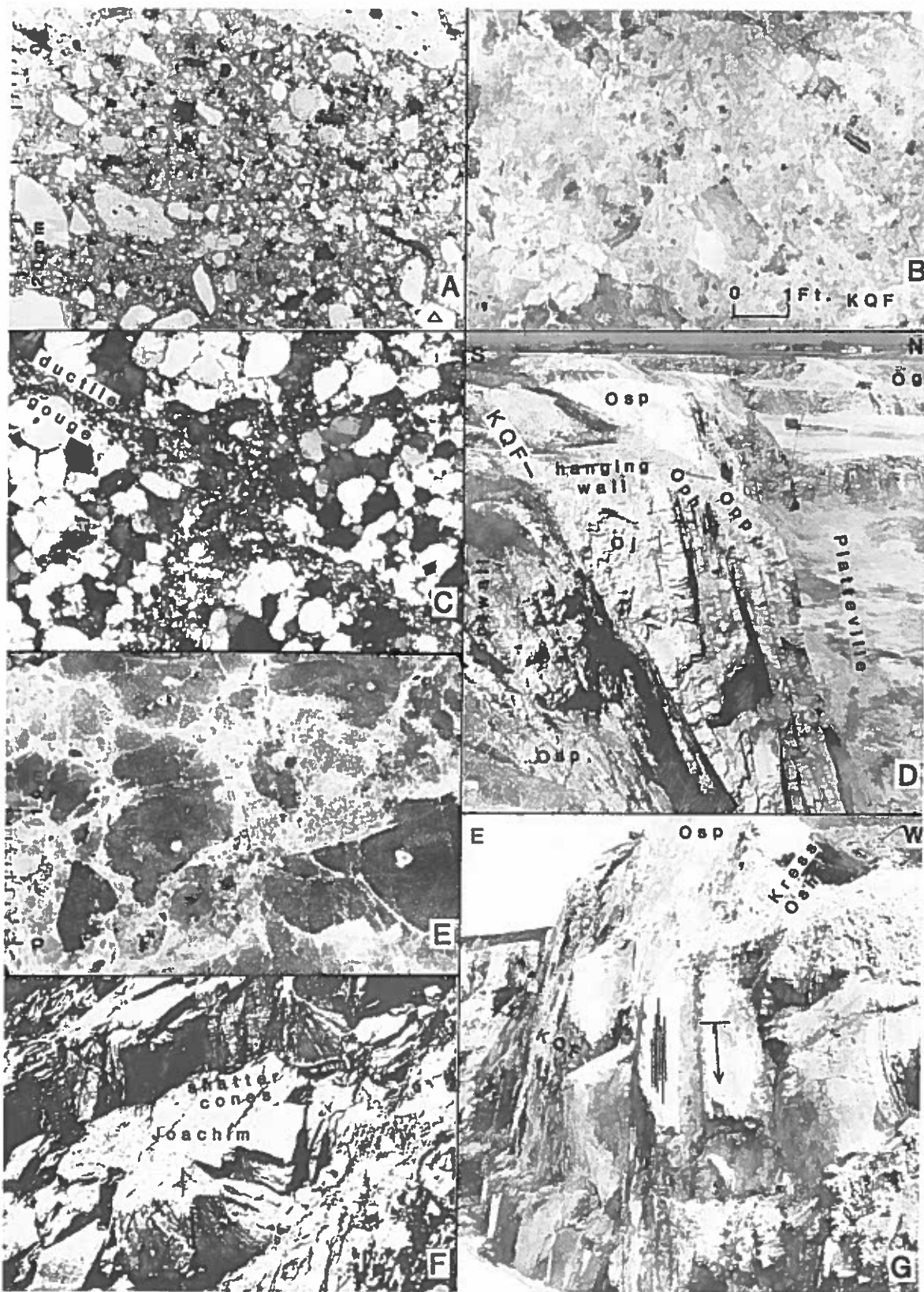
Fig. 9. Photographs of folded and faulted structures in the Kentland quarry. (See fig. 8.) A, Down-dip oblique overview of Kentland Quarry looking north northwest down plunge of central quarry syncline, which continues into anticline on its left (west) flank; photo taken from helicopter on April 4, 1975. B, Vertical air photo of Kentland Quarry where quarried stone of the Platteville-Galena carbonate rocks outline the main folded structure on north and northwest flanks of Kentland Dome; center of dome is approximately 500 feet south southwest of Mt. Newton, with Shakopee Dolomite at bedrock surface; photo taken by Indiana Highway Department. C, Oblique air photo of Ford W40 southwest quarry extension to show exhumed bedrock surface and plunging anticline; plunge is north northwest, about  $60^{\circ}$ ; west wall exposes excellent stratigraphic section from Pecatonica Dolomite (Ordovician) to Salamonie Dolomite (Middle Silurian) (fig. 10); glacially eroded bedrock surface shows differential scour and exhibits roche moutonnée scarps at top and middle of Platteville Group; weathered surface of Galena Dolomite (Og) scoured into low U-shaped trough parallel to strike of beds; other strata shown include rocks of the Platteville (Op) and Maquoketa Shale (Om) Groups; scarp dip-slope surfaces have horizontal glacial striae; barn is on Means-Ford farmyard location; photo taken from helicopter on Aug. 27, 1980. D, West wall of Kentland Quarry with spectacular structural detail; WSW-plunging anticlinal block of Joachim-Hennepin-Pecatonica (Opp, dark-colored brown dolomite) is bounded by Means Fault (F) to south and Kentland Quarry Fault (KQF) to north; light-colored Silurian (S) rocks are down-faulted along Means Fault, and Joachim (Oj)-Platteville rocks are upfaulted along reverse Kentland Quarry Fault; scale given by the shot-hole drill on quarry floor and by large Euclid truck along the right side of ramp; photo taken on July 10, 1980. E, View along west limb of quarry syncline where it turns left into anticlinal fold on far end; Kentland Quarry Fault (KQF) zone and footwall side is dramatically exposed, showing white St. Peter Sandstone; light-colored rocks on far west wall are Silurian (S) on south side of Means Fault (F), with darker Platteville (Op) and Galena (Og) rocks to right (fig. 9D); black rocks on right are Scales Shale of Maquoketa Shale Group (Om), truncated by the Crusher Fault (F); see figure 9F; photo taken on Nov. 3, 1982. F, View of Crusher Fault, a nested transverse structure that cuts across the quarry syncline to duplicate the Platteville-Galena sequence (Opp, Pecatonica Fm. of Platteville Gr.); jumbled light-colored Maquoketa rocks to left of fault are parts of Ft. Atkinson and Brainard; synclinal structure is well displayed in folded Galena (Og) strata on right side of photo; photo taken on April 4, 1981. G, View to show intersection of Kentland Quarry Fault (KQF) and McCray Fault, the latter terminating at the fault juncture; Pecatonica Formation of the Platteville Group (Opp) forms the hanging wall block of the Kentland Quarry Fault and the footwall block of the McCray Fault; small cul-de-sac quarry, now backfilled, contains both Joachim and Platteville rocks; see figure 13F for shatter cones in the Joachim; photo taken on April 28, 1965. H, North wall of northeast part of main quarry showing faulted duplicated section; see figure 11 for structural interpretation; the complicated wall section represents folded and faulted Joachim-Platteville strata; overlying continuous Galena sequence is exposed along west side of ramp; Opp and Opm, Pecatonica and Mifflin Formations of Platteville Group; F, fault; photo taken on May 28, 1982.

fault as shown by the disposition of the Hennepin key beds.

Means Fault--During westward expansion of the quarry onto the Means tract, it became apparent from bedrock mapping that the Kentland Quarry Fault was cut by a younger WNW-trending fault with left-lateral slip (Gutschick, 1976). Note that

the small folded Joachim-Pecatonia block that shows up in the west wall (figs. 9D and 10) did not appear at the bedrock surface between the faults near their intersection. Further exploration to the south on the Ford W40 tract encountered the detached Platteville-Galena block that is now fully exposed in the





named for John McKee, pioneer settler from Pennsylvania, who operated a quarry in 1881 on the McKee farm tract. Extension of the McKee Fault in either direction is unknown at this time. It is interesting that the Means and McKee Faults apparently are symmetrical about the axis of the main quarry syncline and flanking anticlines, both of which are cut off by these faults.

**Crusher and Ramp Faults**--A large arcuate block of Platteville-Galena-Maquoketa rocks, bounded on the west by the Crusher Fault (figs. 8 and 9F) and on the east by Fault B (fig. 11A) duplicates the sequence in the hanging wall along the Kentland Quarry Fault. This double sequence accounts for widening of the quarry on its eastern end, in contrast to the single sequence in the western portion of the quarry. The Crusher and Ramp Faults are part of this block, and fault B probably is a continuation of the Crusher Fault. Extrapolating from the interpretation of a fold (fig. 11B) that involves this block, it is possible that the duplication within the entire block is due to a fold which has broken along the Crusher Fault. The Crusher Fault is subparallel to the beds along most of its length, and it becomes a transverse tear fault along the west end of the block. It is a reverse fault similar to and parallel to the Kentland Quarry Fault. The "narrows" and the Ramp Fault are accommodations to the anticlinal bulge along the Kentland Quarry Fault. Movement of the arcuate block on its west end has been away from the Kentland Quarry Fault.

**Other faults**--High on the east wall of the quarry is a steeply inclined curved surface that is smooth and slickensided. This is the hanging wall of an east-dipping fault, and the block is regarded as the Galena Dolomite. Between this fault and the west-dipping McCray Fault are vertical north and south-striking siltstone ribs and dark

shale of the Scales Formation.

Two other interesting fault structures in the west half of the map are worth attention. One is a very narrow graben, 10 to 15 feet (3 to 5 m) wide, between the Kentland Quarry Fault and the Means Fault. This tensional feature runs diagonally NW-SE and drops the dark-gray Scales Shale of the Maquoketa Group against the Shakopee Dolomite at the bedrock surface, cutting out rocks from the St. Peter Sandstone to the Galena Dolomite inclusively. The south fault wall dips 82°N and is slickensided with vertical striae. The second fault feature is a small low-angle thrust block of the Shakopee Dolomite over the St. Peter Sandstone that involves the footwall of the Kentland Quarry Fault along the west side of the central syncline. This can be found on the south side of a long-abandoned quarry road south of the prominent white exposure of the St. Peter Sandstone.

The youngest strata recognized in the quarry, the New Albany Shale of Late Devonian age, occurs in a unique way. Small triangular fault blocks on the south side of the Means Fault involve the easily identified Maquoketa Shale and Lower Silurian rocks. In a triangular wedge of one of these fault blocks, chunks and brecciated wads of alternating dark brownish-gray and dark green-gray shale with *Tasmanites* (resinous green algae cysts) were found.

The fault interpretation at the south end of the Ford W40 quarry is based on information from cores; the fault is not presently exposed. There is a narrow slice of the Kentland Quarry Fault footwall where the St. Peter Sandstone and the Shakopee Dolomite have been identified. A short distance south beyond this slice, Maquoketa and Lower Silurian rocks have been recognized in cores. There is a substantial fault between the Shakopee and Maquoketa bedrock sites that eliminates the St. Peter

observed (Gutschick, 1976). Generally the finer and denser the rock, the better is the chance for shatter cones to be present. They occur throughout the Kentland Quarry and the McKee Quarry. Shatter cones have been found in almost all lithologies and formations in the Kentland Quarry. Striking examples have been seen in the Joachim Dolomite, the Platteville Group, the Maquoketa Shale Group, and even in the St. Peter Sandstone. Swarms of small cones have been observed in Silurian rocks in the southwest part of the quarry. Orientations related to the bedding range from near normal in the southeast corner of the quarry to highly oblique in the southwest corner of the quarry. Orientations should be related to the center of the dome if they are to support a meteorite-impact origin.

#### PLEISTOCENE GLACIAL EROSION AND DEPOSITION

##### Glacial Drift

Glacial deposits from the Wisconsin drift sheet cover the bedrock in the Kentland area. These deposits belong to the Cartersburg Till Member of the Trafalgar Formation (Wayne, 1966; Bleuer, 1974). Glacial drift over the Kentland Dome is generally thin, ranging from 1 to 30 feet (0.3 to 9 m) in thickness (fig. 14). The drift is thinnest over the resistant Mifflin Formation of the Platteville Group, which consists of thin-bedded micritic limestone, and is thickest over the Maquoketa Shale Group and the weathered Galena Group, especially over the lower part of the Dunleith Formation. The bouldery cobblestone-pebbly clay till is weathered (oxidized) down to about 8 feet in depth. There is a fairly sharp contact between the rust-colored oxidized till and the gray unoxidized till. Sand and gravellenses, probably melt-water stream deposits, are found in the till away from the quarry (Tudor,

1971). These lenses serve as groundwater aquifers in the area.

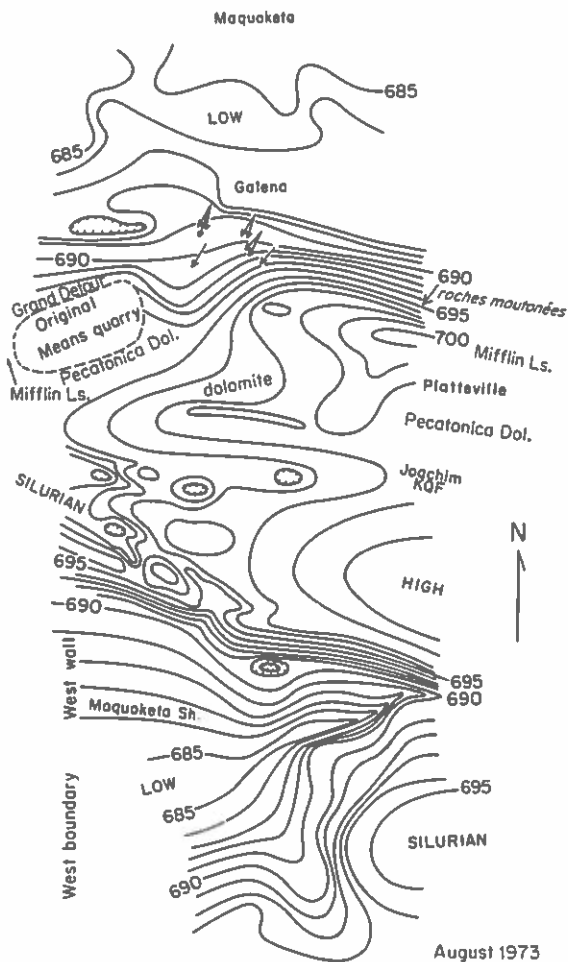
##### Glacial Erosion--Bedrock Surface

The topographic expression of the bedrock surface is related to its resistance to glacial scour and erosion (figs. 9C and 15). Glacial striae are present everywhere that bedrock is exposed. They generally trend S20°-30°W (fig. 7), which suggests identification with the distal margin of the Huron-Saginaw Lobe of the Wisconsin glacier. Differential ice abrasion produced as much as 15 to 20 feet (5 to 6 m) of relief on the bedrock surface of the truncated upturned strata (figs. 9C and 15). There is a direct correlation between rock types and glacial erosion, so that the amount of glacial abrasion furnishes an excellent index to the hardness and durability of particular rock units in the quarry.

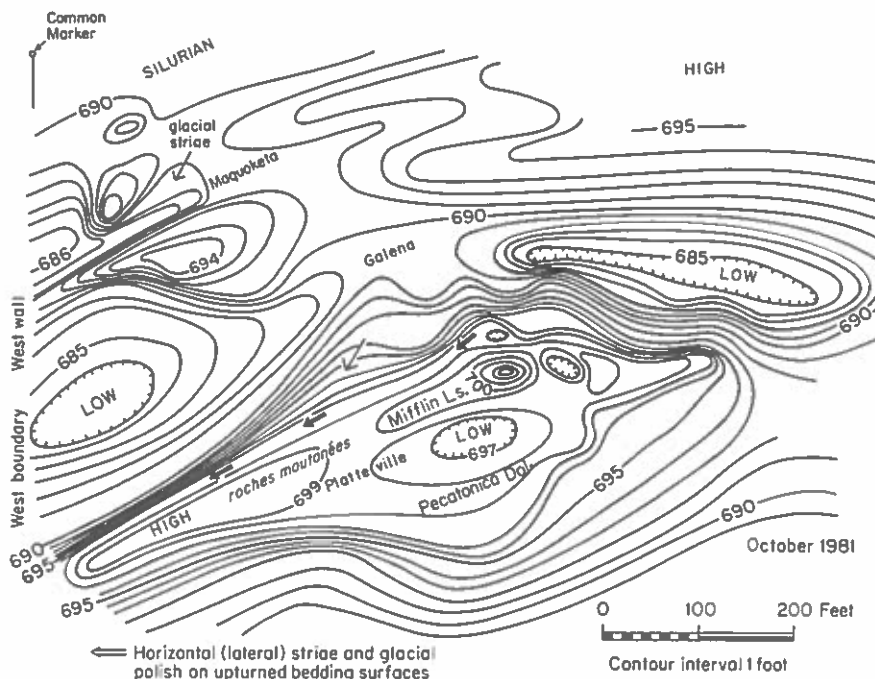
The Platteville Group was the most resistant to erosion by the ice, and it forms a prominent bedrock platform. It is surprising that the thin-bedded micritic limestone of the Mifflin Formation forms roches moutonnées in the main quarry and especially in the Ford W40 SW extension (fig. 15). This must have also been true for the Means and McKee sites. Upturned bedding surfaces of the Mifflin Formation are polished and striated horizontally where the ice moved sideways in a trough down-dip before it was able to go up and over the strike roche moutonnée on this rock unit. Glacial ice moved S30°W over the Ford W40 tract and encountered Mifflin limestone beds that strike E-W to WSW with steep dip about 60°N. The oblique angle between the directional movement vector of the ice and the strike of the rocks deflected the ice laterally and horizontally with a westward component to abrade, polish, and scratch the durable fine limestone on the bedding surface facing the ice. This currently (spring



Fig. 15. Bedrock-topography map in two parts: upper part of Means tract and lower part of Ford W40 quarry site. Mapped by plane table-alidade surveys after drift was stripped away and before quarry rock was removed. Rock-unit names are shown to illustrate a consistent relationship between ice abrasion and stratigraphic units. Striae on bedrock surface indicate that ice moved approximately  $S30^{\circ}W$ . Note position and geometry of highs and lows, location of the roches moutonnées, and horizontal striae along south wall buttress of U-shaped trough on the Galena Dolomite (SW1/4 of Ford W40 map). Thin-bedded micritic limestone of the Mifflin Formation is most resistant to ice abrasion, and the Pecatonica Dolomite forms a solid platform behind the Mifflin ridge.



face of the Galena is scoured out into a low U-shaped trough where the ice moved parallel to the strike of the rocks and where it was directed by the Mifflin buttress, which the



soft.

Crushed carbonate stone can be used for aggregate in concrete and bituminous mixes for highways, drives, sidewalks, and building construction; for fill as base courses for roads and road metal; and for ballast on railroad beds. The other important use of carbonate stone is for agricultural lime, in which it must contain at least 80 percent calcium carbonate equivalent. Agricultural lime is useful for acid-rain neutralization; as a source of Ca, Mg, and trace elements for the soil; as an aid in nitrogen fixation; as a conditioner of a more efficient soil base for fertilizers; for improvement of the physical structure of the soil; and, in all these ways, to increase crop yields. Other uses of limestone are for cement, flux stone, chemical lime, and riprap.

Calculations of reserves for limestone and dolomite production are commonly made in terms of tons per acre-foot for proved or inferred thicknesses of deposits. The specific gravity of carbonate rocks varies with the amount of magnesium, and adjustments in weight per unit volume must also be made in accord with porosity and the amount of impurities, including water content. For example, pure dolomite has a specific gravity of about 2.86, and 1 cubic foot of nonporous dolomite weighs more than 178 pounds, meaning that 11.21 cubic feet are required to make up 1 ton and that 1 acre-foot contains about 3858 tons of such dolomite. These figures compare respectively with a specific gravity of 2.71, 169 pounds, 11.83 cubic feet, and 3681 tons per acre-foot for pure nonporous limestone.

Considering porosity and impurities of economic deposits of carbonate rocks in general, however, quarrymen commonly calculate limestone at 3500 tons per acre-foot and dolomite at 3700 tons per acre-foot. The structural complexity at Kent-

land greatly complicates the calculation of reserves, however, and this complication extends to the great range in kinds and attitudes of the juxtapositions among carbonate rocks, shales, and sandstones.

#### SUMMARY

The following theories have been proposed at various times for the origin of the Kentland anomaly: cryptoexplosion, cryptovolcanic, meteorite or comet impact (Silver and Schultz, 1982), fault, diapiric, and solution collapse of evaporite dome.

In attempting to evaluate the origin of this structure, one is impressed with such a major anomalous structural disruption in an otherwise undisturbed area, the geometrical pattern of the structure, and the rock mechanics of deformation. Structurally, the Kentland Dome is complexly faulted, with Shakopee Dolomite, the oldest bedrock formation, raised more than 2000 feet (610 m) vertically from its normal stratigraphic position (fig. 6). The quarry exposes the northwest portion of the Ordovician core of the dome (fig. 5). The dome appears to be faulted on its south and west flanks, and the Shakopee beds in the central part of the dome are all upended.

Folding and faulting are impressive in the central part of the disturbance exposed in the quarry. Fault surfaces are sharp and bold with extensive slickensides and mul-lion structure. Intense fracturing is present throughout the St. Peter Sandstone, and granulation gouge, shatter cones, polymictic breccias, and monomictic breccias are distributed throughout the quarry and in cores surrounding the quarry. Shatter cones have their apices pointing predominantly stratigraphically upward. Quartz grains have lamellae and cleavages produced by high strain rates of deformation. Asterism is present in the X-ray

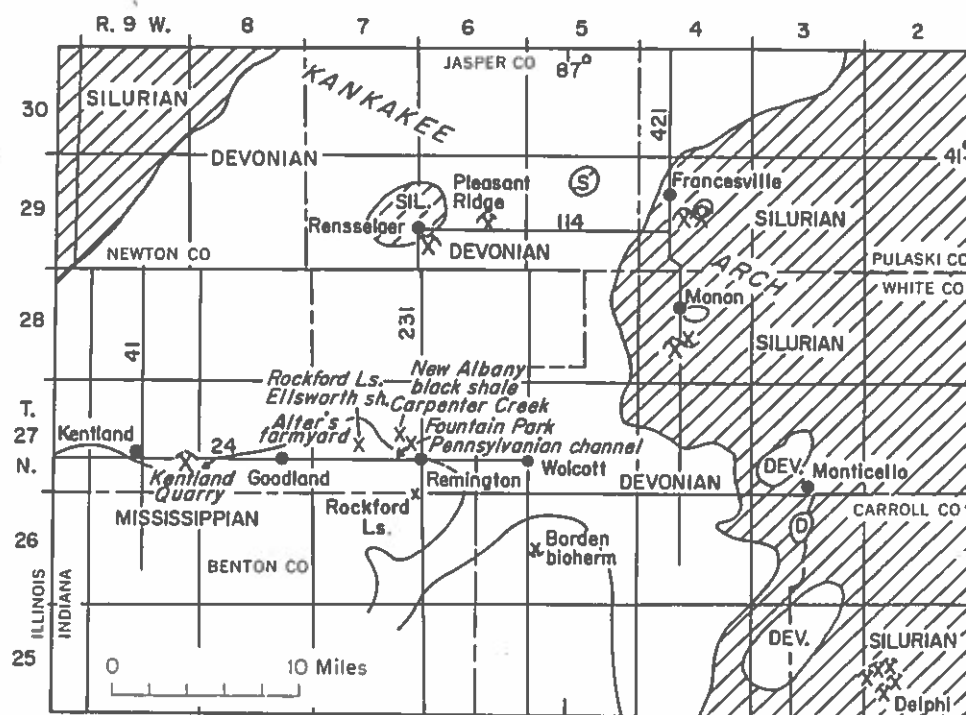


Fig. 16. Geologic map of part of northwestern Indiana showing relation of anomalous Kentland Quarry area (fig. 5) to the regional map pattern. Regional dip of strata is less than  $1^{\circ}$  southwest into the Illinois Basin. Map shows locations of stop 2 (Alter's farmyard, about 10 miles east of Kentland Quarry) and stop 3 (Carpenter Creek-Fountain Park).

*manites* can be found in the shale. Rocks at this locality probably lie directly beneath the section exposed on the Alter farm (fig. 17).

The small Fountain Park area consists of a wooded hillside of oak trees growing on sandstone that crops out in bold exposures along Carpenter's Creek. The sandstone is coarse grained with well-rounded quartz granules, and it has cross-stratification sets that dip towards the southwest into the Illinois Basin. The rock is part of the Raccoon Creek Group of Pennsylvanian age, and the sandstone outlier consists of remnants of a stream channel of the paleo-Michigan River system. This Pennsylvanian outcrop is well northeast of the main bed-rock pattern of the Pennsylvanian System that is related to the Illi-

nois Basin.

The Carpenter's Creek black shale outcrop is located to the northwest of the Pennsylvanian channel-sandstone exposure, in the adjoining quarter section. The contact between the two rock units is not exposed, but it is presumed that the Pennsylvanian rock rests unconformably on the Late Devonian black shale in the complete absence of Mississippian rocks. The Pennsylvanian stream flowed from the north across the Kankakee Arch into the Illinois Basin. It flowed on the Devonian black shale at this place, and it continued to flow to the southwest, as indicated by the fore-set bedding. A similar stream from this system is interpreted from the Pennsylvanian outlier patches in the vicinity of the Kentland Quarry.

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