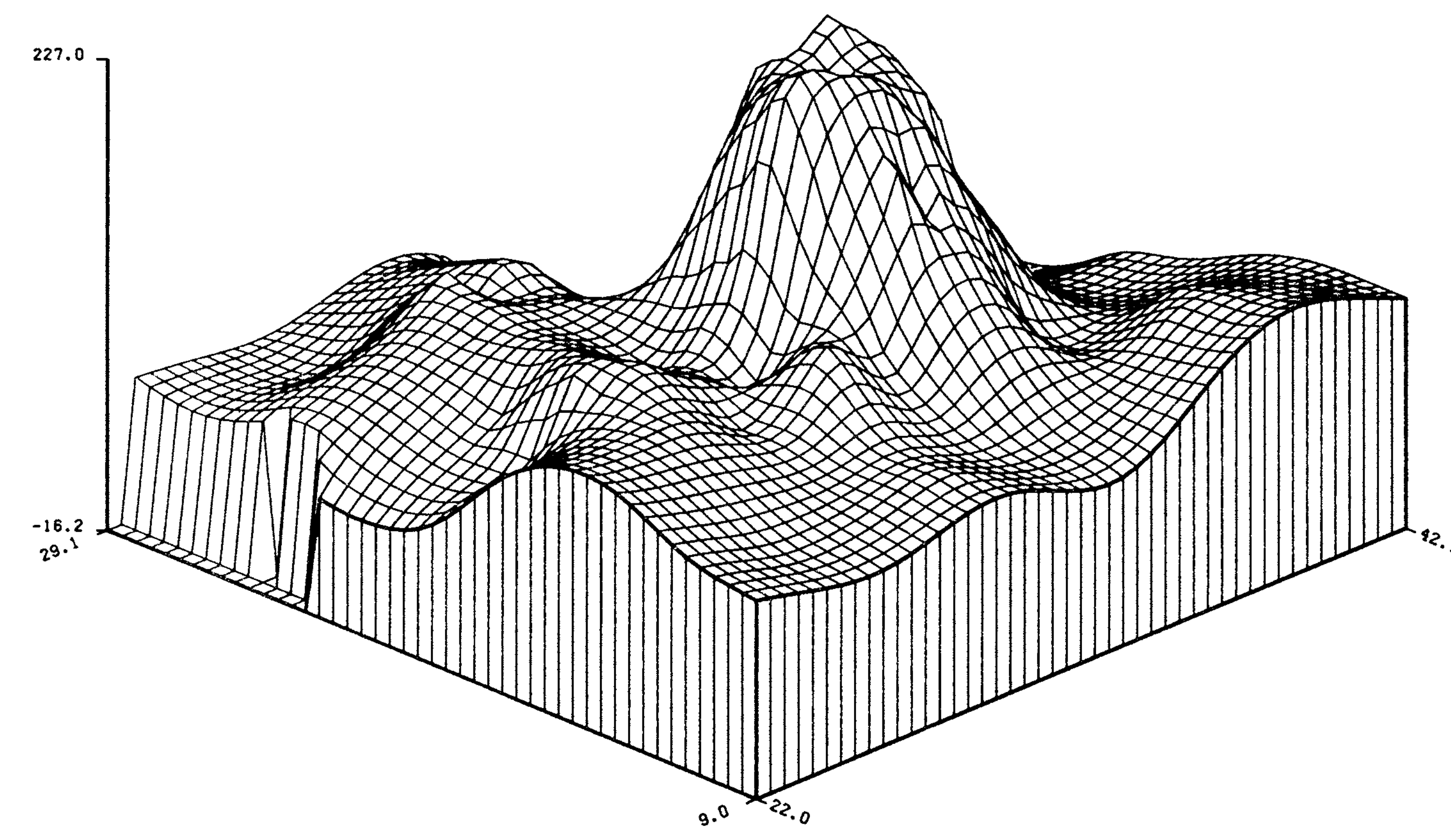
IMPACT ORIGIN OF THE CALVIN 28 CRYPTOEXPLOSIVE DISTURBANCE, CASS COUNTY, MICHIGAN

RANDALL L. MILSTEIN



Report of Investigation 28

Geological Survey Division
Michigan Department of Natural Resources DNR

Impact Origin of the Calvin 28 Cryptoexplosive Disturbance, Cass County, Michigan

by Randall L. Milstein

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Michigan Department of Natural Resources

Geological Survey Division

1988

STATE OF MICHIGAN

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MICHIGAN DEPARTMENT OF NATURAL RESOURCES

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ABSTRACT

The Calvin 28 cryptoexplosive disturbance is an isolated, nearly circular subsurface structure of Late Ordovician age in southwestern Michigan. The structure which is defined by 107 test wells, is about 7.24 km in diameter and consists of a central dome, an annular depression and an encircling anticlinal rim. Seismic and geophysical well log data confirm an intricate system of faults and structural derangement exists within the structure. Deformation decreases with depth and distance from the structure. U.S.G.S. topographic maps and aerial imagery show the structure is reflected as a surface topographic rise controlling local drainage.

Igneous or diapiric intrusion and solution collapse are rejected as possible origins for the Calvin 28 structure on the basis of stratigraphic, structural and geophysical evidence. A volcanic origin is rejected due to an absence of igneous material. Although shock-metamorphic features are unidentified, microbreccia occurs in deep wells that penetrate the structure. Morphology and structural parameters suggest an impact origin.

INTRODUCTION

Geophysical data, geologic mapping, and the extensive drilling of oil and gas test wells have delineated a subsurface structure in Calvin Township, Cass County, Michigan, centered 1.4 km southwest of the village of Calvin Center (Figure 1 and Figure 2). The structure consists of a central domal uplift bounded by an annular depression and an encircling anticline. The overall structure has a diameter of 7.24 km.

An exploratory well drilled through the central uplift penetrated roughly 485 m of regional, although thinned, Paleozoic strata down to the Late Ordovician Cincinnatian Series. Instead of encountering the Middle and Lower Ordovician stratigraphic sequence, the well bore entered into a shortened section of the Lower Ordovician Prairie du Chien Group. The contact between the Prairie du Chien and the Late Cambrian Trempealeau Formation were found to be roughly 379 m above normal regional levels. Continued drilling revealed the upper half of the Munising Formation is absent down to its Eau Claire Member. The Mt. Simon Sandstone Member, lying in its proper stratigraphic position below the Eau Claire, shows a vertical displacement of 415.5 m. Geophysical well logs from the test well reveal complex faulting in addition to steep and varied dips within the domal uplift.

McCall (1979) has identified similar intensely deformed circular structures, as "cryptoexplosive disturbances." This rather neutral and noncommittal terminology speaks for the uncertainty that surrounds the genesis of these structures. The term, "crypto-explosive disturbance", is a more accepted version of "cryptoexplosive structure" first advanced by Dietz (1959). Dietz uses this term to describe subcircular geologic structures formed by an apparently point-focused, explosive release of near-surface energy and exhibiting intense, often localized rock deformation. The energy release has no obvious relation to known volcanic or tectonic activity. The structures are characterized by some or all of the following: random distribution over a variety of geologic environments, a wide variation in diameters, and a central dome-shaped uplift with intense structural deformation. The central dome is often surrounded by a concentric annular depression and encircling ring-shaped uplift. The structures show complex high-angle faulting, minor folding, widespread brecciation and shearing. The presence of shock metamorphism in rocks and minerals is often noted. Shock metamorphism refers to distinct changes in rocks and minerals resulting from the passage of transient high pressure shock waves. These effects include the production of coesite, stishovite, suevite, baddeleyite, pseudotachlite, feldspar glass and diamond planar features in quartz. The occurrence of shatter cones (Dietz, 1959), a distinctive conical rock fragment with outward radiating, fanlike striated surfaces, is commonly noted. The presence of shock features in cryptoexplosive disturbances suggests the structures were the result of single, nearly instantaneous shock events (Dietz, 1959; French, 1968a). None of the individual features listed can be relied on as an unfailing diagnostic tool in the identification of a cryptoexplosive disturbance.

The author has chosen to identify the Calvin Township structure as Calvin 28. The choice is based on the location of the first deep test well which identified the disturbance, the central positioning of the structure beneath Section 28 of Calvin Township and the name of the most productive of three oil fields associated with the feature.

The main purpose of this study is to provide a possible explanation for the origin of the Calvin 28 cryptoexplosive disturbance. Structure contour maps, stratigraphic cross-sections, geophysical data, structural comparisons, petrographic analyses, neutron-activation analyses and recognized structural relationships have been employed to develop a hypothesis to account for the massive subsurface structural deformation.

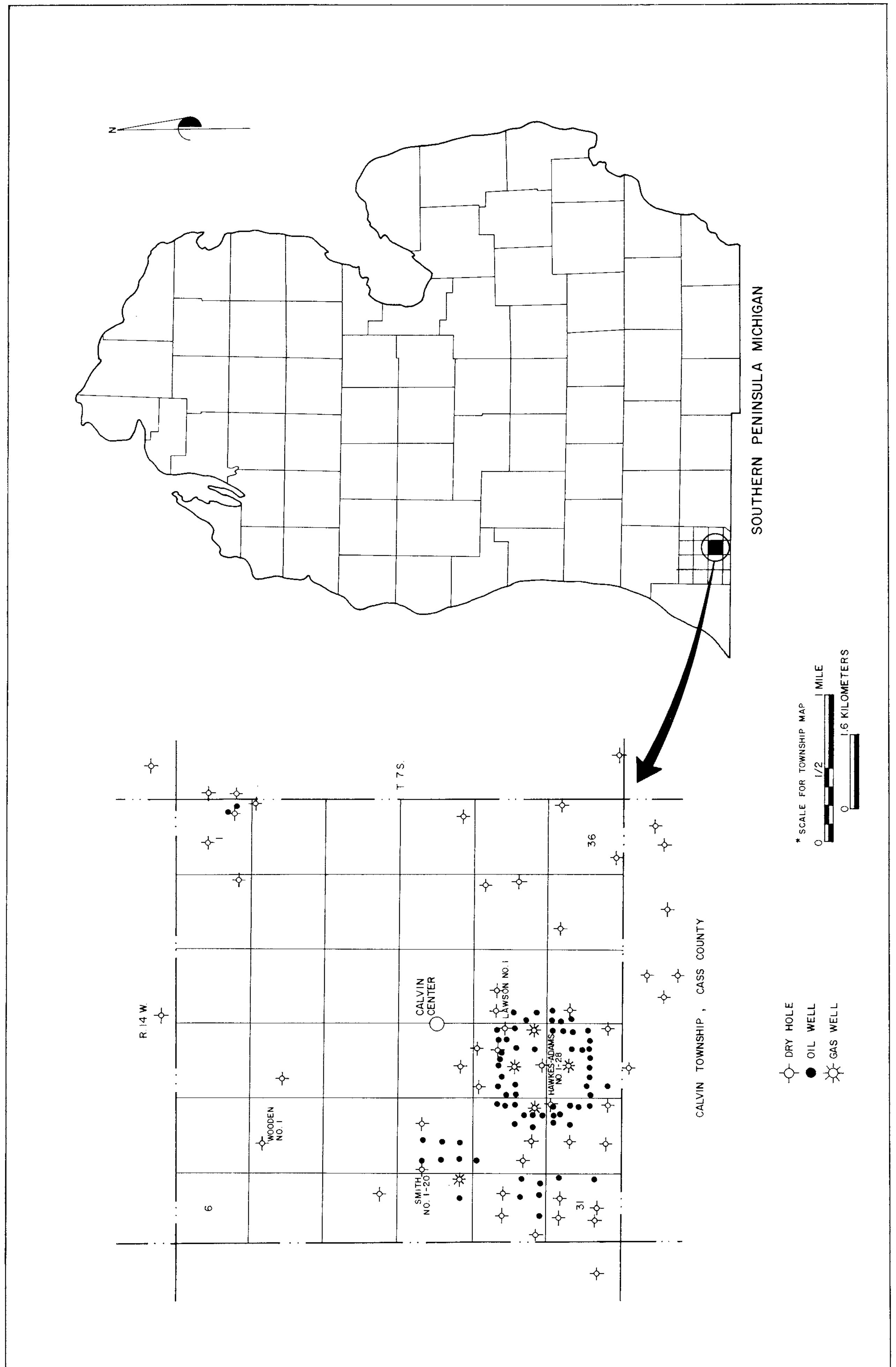


Figure 1. Location of study area, Calvin 28 cryptoexplosive disturbance, Cass County, Michigan.

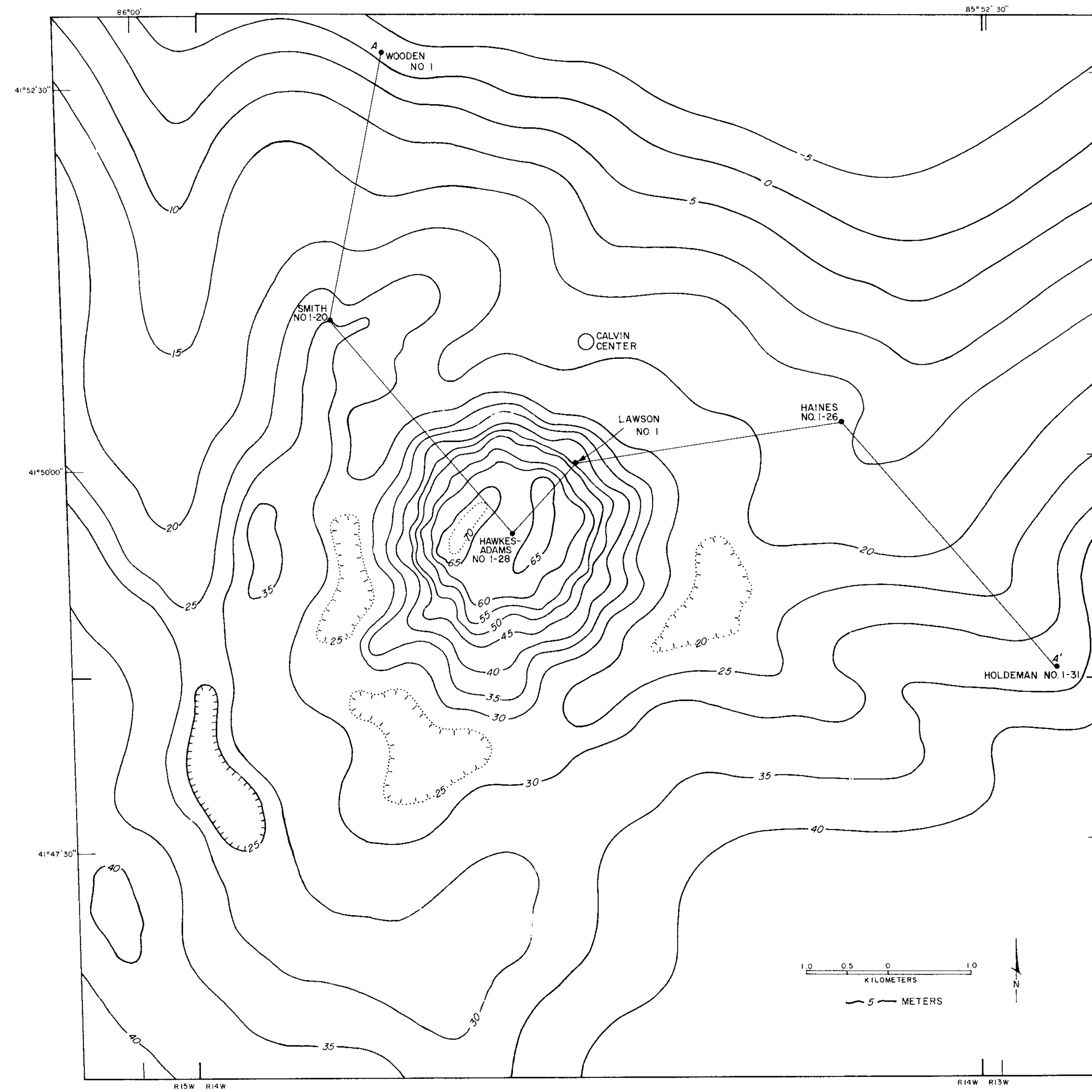


Figure 2. Traverse Limestone structure contour map and line of geologic cross-section, Calvin 28 cryptoexplosive disturbance.

In many instances subsurface cryptoexplosive/astroblemes have proven to be highly successful hydrocarbon traps. Because of their random occurrence, an active exploration campaign for them is impractical. When detected, however, a proper understanding and knowledge of their structural nature and history will aid in the exploitation of their possible hydrocarbon reserves.

Previous work involving Calvin 28 is limited. DeHaas (1983), in a presentation to the Michigan Basin Geological Society, provided evidence of dramatic structural uplift associated with a dome beneath the Calvin 28 oil field. DeHaas suggested the "cryptoexplosive" nature of the domal feature based on superficial comparisons to other Midwestern and European cryptoexplosive disturbances.

Mata and Myles (1985) interpret the feature to be the result of basement faulting in a tectonically "tight" and compressed corner of the Michigan Basin. The southwestern portion of the Michigan Basin, which includes Cass County, being interpreted as a region of compression and stress due to its close proximity to the Illinois Basin. Mata and Myles suggest that comression along the regional zone of contact between the two basins resulted in fault blocks which "pop up and fold over."

A geophysical investigation of the structure by Ghatge (1984) shows no gravity anomalies or magnetic anomalies to 1 milligal or gamma associated with the structure. Ghatge concluded that any interpretation of the structure, based on his gravity and magnetic surveys would not be able to explain the intense uplift or missing Cambrian and Ordovician sediments. While Ghatge favored origin by impact, he felt his evidence insufficient to categorize the feature as anything but a "crypto-explosion structure."

METHOD OF STUDY

A seven-fold approach was used in this study to define and delineate the Calvin 28 cryptoexplosive disturbance:

1. Geophysical well logs, primarily gamma ray/neutron and compensated neutron/lithodensity logs were obtained from the Michigan Geological Survey in Lansing, Michigan. All available well logs in Cass County, Michigan have been used, thus establishing regional geologic trends for comparison to the study area. Because the State of Michigan has regulations barring the removal of well logs from State facilities and the reproduction of State-held logs, comparison and correlation were done at offices of the Michigan Geological Survey. Special permission was received to hand trace portions of specific logs for display in this study. In all, five mechanical log suites were traced and a total of 29 mechanical log suites were used to varying degrees in constructing the diagrams and illustrations of this report. Formation identification in Cass County wells in which mechanical logs were not run, was accomplished by use of well-site sample descriptions on file with the Michigan Geological Survey.

2. Samples of well cuttings, obtained from the Michigan Geological Survey, were used in conjunction with the well logs to aid in the identification of subsurface stratigraphic units from the deep test wells. All samples used were cuttings produced by rotary drilling. The cuttings from four wells within the study area were examined. The major emphasis of the sample examination was to aid in the establishment of formation contacts. A core from the Hawkes-Adams #1-28 deep test well's Middle Devonian Traverse Limestone interval, the producing formation associated with the study area, was inspected.

3. Samples also were examined for the possible presence of shock-related features. This search was greatly impaired by the small size, poor condition and small quantity of the available cuttings. Michigan law forbids the destructive analysis of State-held geologic samples. Special permission was sought, and granted, to use small portions of the samples for the preparation of petrographic thin sections to aid in the search for shock-related features. Thin sections were prepared from the deformed zone in the Hawkes-Adams #1-28, Lawson #1 and Mary Smith #1-20 deep test wells (Figure 2).

4. Special permission was sought, and granted, to irradiate small portions of the samples in two neutron activation analyses. The purpose of this experiment was to determine if abnormally high levels of iridium occur in rocks of Cincinnatian age which are associated with the structure. Palme (1982) has interpreted iridium as an element directly associated and correlatable with terrestrial meteorite impacts.

5. Stratigraphic information obtained from well logs and sample evaluation was used to construct contour maps, stratigraphic cross-sections and schematic diagrams. Additional structural information was obtained from the review of proprietary seismic assemblages.

6. Classification of the structure as a cryptoexplosive disturbance is based on examination of compiled data, review of literature about similar surface and subsurface structures, and personal communications.

7. Explanations for the origin of the structure were sought. Available data eliminated known endogenetic or tectonic processes. Hypervelocity impact emerged as the most probable cause of such a near-surface, centrally focused shock event. Data generally accepted as an indication of meteoritic impact were not available. Interpretive data were plentiful.

As a result of the lack of characteristic and generally accepted elements associated with impact craters, an alternative method of identification was employed. A series of recognized structural relationships used to define surface impact structures were applied to the subsurface Calvin Township feature.

Companies drilling within oil fields associated with the Calvin 28 cryptoexplosive structure have been concerned with production from Devonian-age targets. The main problem encountered in this study was the lack of specific subsurface data from those wells drilled into the structure to rocks older than Devonian age. Extensive testing and coring was not carried out on these deeper pool test wells. The lack of well cores virtually eliminates the possibility of finding many of the common identifiers associated with cryptoexplosive disturbances. Though comprehensive suites of geophysical well logs and drill cuttings are available from the deep test wells, such indicators as shock metamorphism or shock-induced breccias are not easily identifiable in subsurface structures without well cores.

Correlation of subsurface units from geophysical well logs is complicated by the scarcity of such logs and the disrupted nature of the strata associated with the feature. The correlations are based on the previous work of Lilienthal (1978) and Milstein (1983), in combination with the examination of well cuttings and well site sample descriptions.

Structure contour maps suggest the Calvin 28 structure underwent either structural uplift, rebound or compaction through the Middle Devonian. Identification of specific periods of continued or renewed uplift is not possible because of the lack of significant isopach maps. Significant isopach maps cannot be prepared because mechanical well logs from Devonian test wells are few, and many descriptive logs, prepared by non-geologists, conflict with the available mechanical logs.

During the course of this investigation, proprietary geological and geophysical data were reviewed. Findings from these sources are discussed in the text, but in agreement with those companies actively exploring for hydrocarbons in the region, and in agreement with Act 61, Public Acts of Michigan, 1939 and Act 315, Public Acts of Michigan, 1969, the data are not reproduced in this study.

A multitude of terms exists covering the stratigraphic sequence in the Michigan Basin. In order to standardize information for future research, the nomenclature used in this study is that employed by the Michigan Geological Survey. The terms used have proven themselves effective and reliable in past regional studies and in correlation problems (Ells, 1967; Syrjamaki, 1977; Lilienthal, 1978; Milstein, 1983; Reszka, 1983).

Comparisons between the Calvin Township structure and similar cryptoexplosive disturbances appear throughout this study. Conclusions reached in this study are confined exclusively to the Calvin Township structure. The findings of this study may be applicable to many similar features, but are not intended as a generic explanation of all such enigmatic structures.

GEOLOGIC SETTING

The Michigan Basin is a relatively shallow intercratonic basin encompassing all Michigan's Southern Peninsula and the eastern portion of the Northern Peninsula (Figure 3). The Basin also includes parts of Wisconsin, Illinois, Indiana, Ohio, and Ontario. The Michigan Basin is bounded on the north and northeast by the Canadian Shield, on the east and southeast by the Algonquin Arch in Ontario and the Findlay Arch in northern Ohio, and on the southwest by the Kankakee Arch in northern Indiana and northeastern Illinois, and on the west and northwest by the Wisconsin Arch and Wisconsin Dome. The Basin is roughly circular and has a slight northwest-southeast elongation.

Calvin Township is located on the southwestern flank of the Michigan Basin (Figure 3). The surface topography is gently rolling glacial terrain with 30 to 133 m of drift below. The underlying Paleozoic strata dip northeastward at 5 to 11 m/km (Ells, 1969). Structural trends plotted on the Traverse Limestone in this region show a north to northeast alignment (Ells, 1969; Prouty, 1983). This is in direct contrast to the northwest-southeast structural trend seen predominately throughout the Basin.

Geophysical well logs and well cuttings from the study control well, the C. A. Perry & Son, Inc., Wooden #1 deep test well (Figure 1), show all Paleozoic series through Kinderhookian time occur in the study region (Figure 4 and Figure 5). Roughly 533 m of Cambrian strata is present in this portion of the Michigan Basin. The Cambrian sequence is predominately quartz sandstone and sandy dolomite interspersed with shale in the upper and lower formations. Except for the Mt. Simon Sandstone, all formations contain some glauconite. The Ordovician strata are roughly 328 m thick and consist chiefly of shale, limestone, sandy dolomite and minor amounts of cherty dolomite. The Silurian strata consist of roughly 211 m of dolomite and evaporite. This is overlain by 224 m of Devonian strata consisting of shale, limestone and dolomite. Portions of Calvin Township are underlain by as much as 37 m of Mississippian strata, predominately shale.

Based on stratigraphic evidence discussed later, a Late Ordovician age is assigned to the event that produced the Calvin 28 structure. During Ordovician time, the Michigan Basin was a shallow, stable basin,

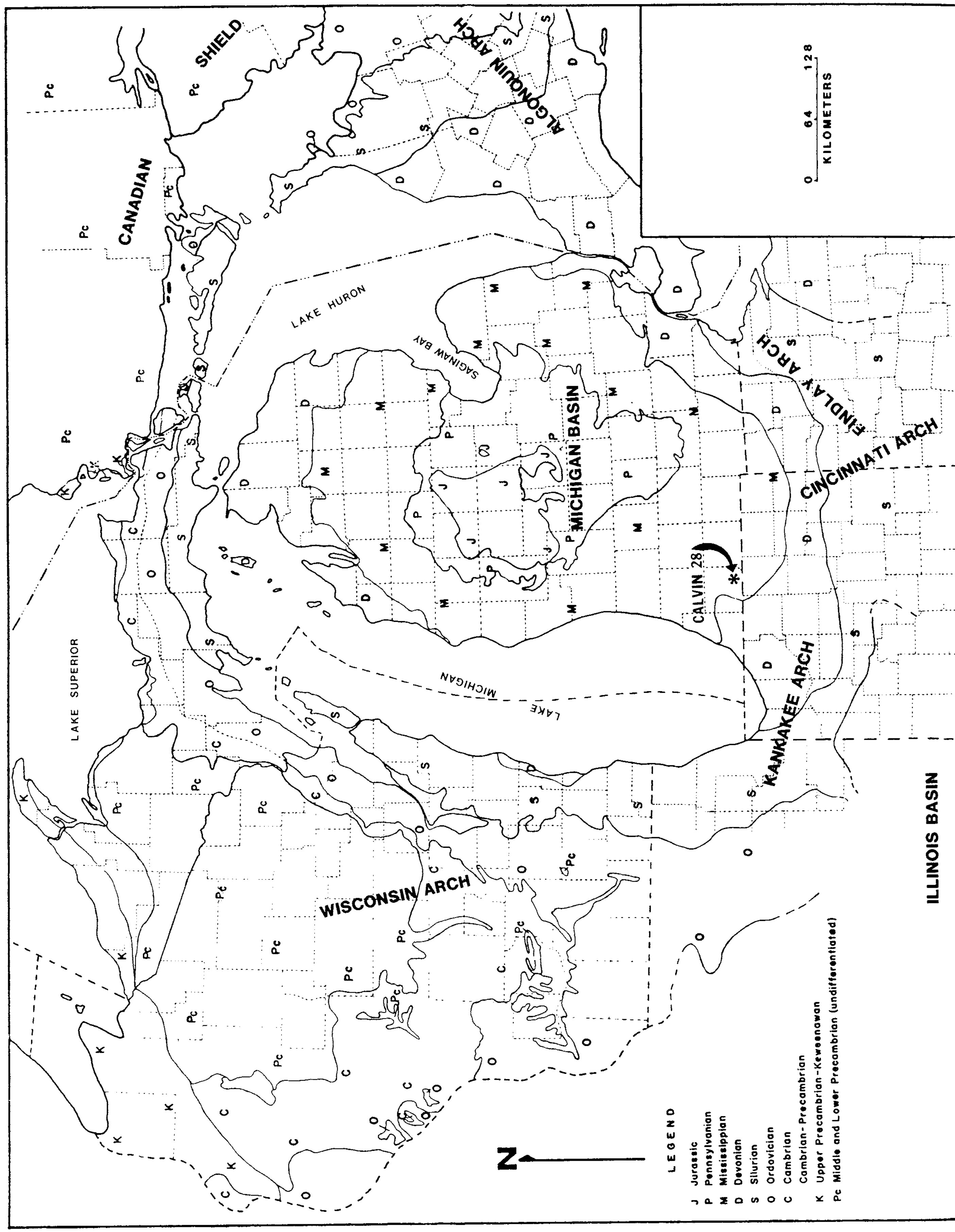


Figure 3. The Michigan Basin and surrounding geologic structures (modified from Stonehouse, 1969).

ERA	PERIOD	EPOCH	SYSTEM	SERIES	GROUP	FORMATION	MEMBER	THICKNESS
CENOZOIC			QUATERNARY	PLEISTOCENE				133 m
PALEOZOIC	MISSISSIPPIAN	EARLY	MISSISSIPPIAN	KINDERHOOKIAN		COLDWATER		37m
	DEVONIAN	LATE	DEVONIAN			ELLSWORTH		224m
				CHAUTAUQUAN		ANTRIM		
		MIDDLE		SENECAN				
				ERIAN		BELL		
						DUNDEE		
				ULSTERIAN	DETROIT RIVER			
		EARLY						
	SILURIAN	LATE	SILURIAN	CAYUGAN	BASS ISLANDS			211m
					SALINA			
		MIDDLE		NIAGARAN	MANISTIQUE			
					BRUNT BLUFF			
		EARLY		ALEXANDRIAN	CATARACT	CABOT HEAD		
						MANITOULIN		
	ORDOVICIAN	LATE	ORDOVICIAN	CINCINNATIAN	RICHMOND			328m
							UTICA	
		MIDDLE		MOHAWKIAN	TRENTON			
					BLACK RIVER		GLENWOOD	
		EARLY		CHAZYAN		ST PETER		
				CANADIAN	PRAIRIE du CHIEN	SHAKOPEE		
						NEW RICHMOND		
						ONEOTA		
	CAMBRIAN	LATE	CAMBRIAN	ST CROIXAN	LAKE SUPERIOR	TREMPEALEAU	JORDAN	533m
							LODI	
							ST LAWRENCE	
						MUNISING	FRANCONIA	
							DRESBACH	
							EAU CLAIRE	
							MT SIMON	
PRECAMBRIAN								

Figure 4. Stratigraphic succession in Cass County, Michigan.

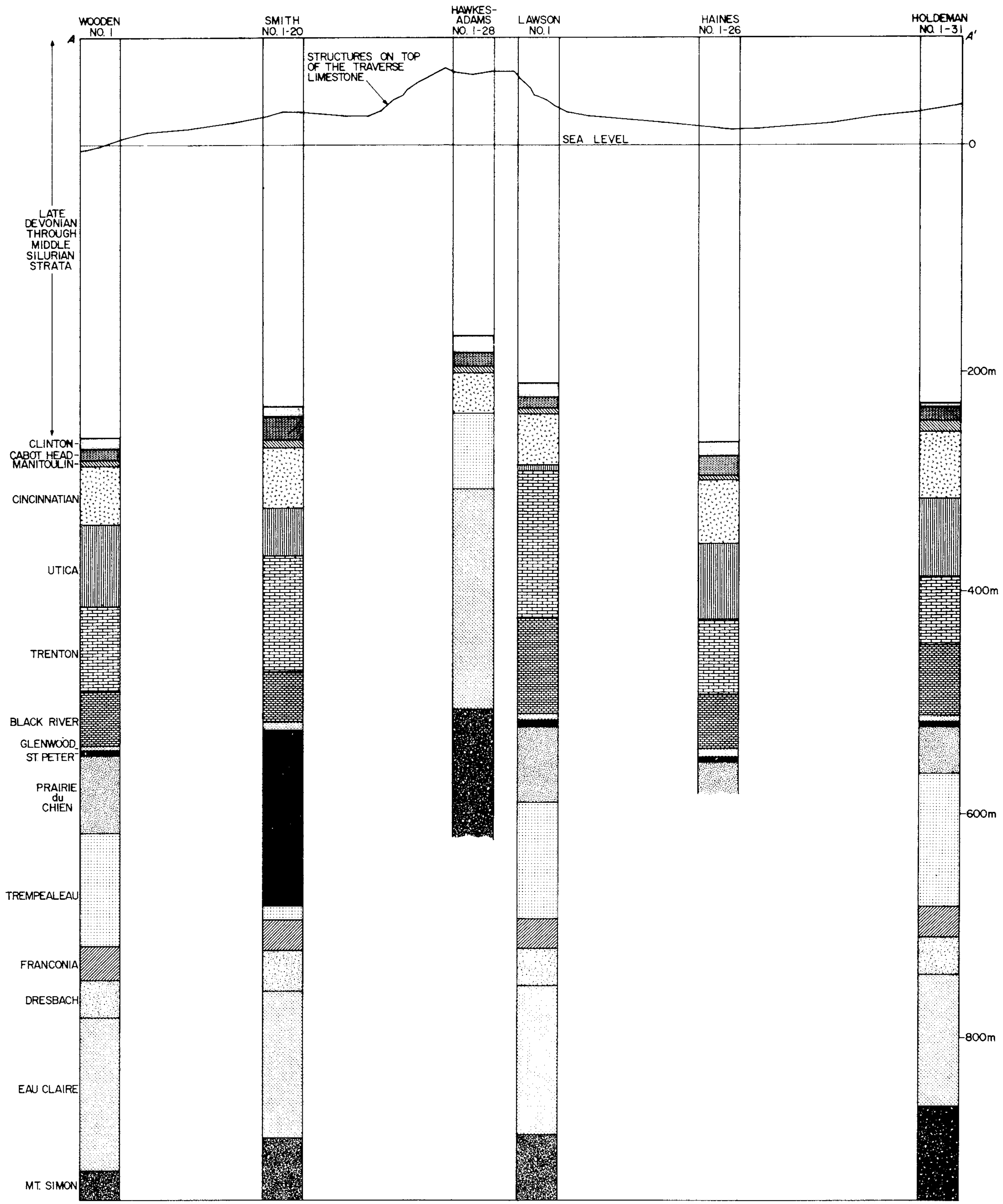


Figure 5. Generalized geologic cross-section and profile of Traverse Limestone tops, Calvin 28 cryptoexplosive disturbance.

centered 40 to 90 km northwest of the Saginaw Bay area (Milstein, 1983). During the Ordovician the Michigan Basin maintained a roughly circular shape with slight elongation to the north-northwest (Milstein, 1983) and was covered by a shallow sea. Isopach maps of Ordovician stratigraphy suggest major subsidence occurred in the Michigan Basin during Mohawkian and Cincinnatian times. The area under investigation in this subsurface study encompasses roughly 78 sq km, involving sections 8, 9, 17-23 and 26-36, Calvin Township (T7S, R14W); sections 1-6, Mason Township (T8S, R14W); sections 25 and 36, Jefferson Township (T7S, R15W); sections 1 and 12, Ontwa Township (T8S, R15W), Cass County, Michigan.

STRATIGRAPHY

The following lithologic descriptions are an overview of characteristics noted in southwestern Michigan for those rock units observed to be directly associated with the disruptive event responsible for the Calvin 28 structure. The descriptions are the result of combining major identifying characteristics from drill site sample descriptions, mud logs, electric and radioactive well logs, core inspection, microscopic analysis of well cuttings and petrographic thin sections.

Lake Superior Group

Munising Formation

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

In the southwestern portion of the Basin, including the study area, the arkosic nature of the lower Mt. Simon is very evident. The presence of feldspar in this lower section may have resulted from the reworking of a regolith which underlies an unconformity at the base of the Mt. Simon in many areas of the Basin. The Mt. Simon reaches a thickness of more than 365 m in the central Basin, while rapidly thinning to zero in southeastern Michigan. It also thins as it passes through the Allegan County area, 77 km north of the study area, thickening again in Berrien County, 32 km east of the study area, in the direction of the Illinois Basin. The Mt. Simon maintains a thickness of roughly 200 m in Cass County.

The Eau Claire Member is thinly bedded and contains dolomite, sandstone and shale. The dolomite often appears sandy or shaly, and has a variety of colors: gray to dark gray, pink, purple, red, green and brown. The sandstone is well sorted and held together with a light tan dolomitic cement. The shale exhibits the same range of colors as does the dolomite. Within the Eau Claire Member, fossil fragments, thin beds of muscovite, and locally abundant glauconite are common. The top of the Eau Claire Member is marked on the gamma ray log by an increase in radioactivity, in sharp contrast to the low gamma ray response of the relatively clean Dresbach Sandstone above it. The Eau Claire Member has an average thickness of 120 m in the southwestern portion of the Basin.

Above the Eau Claire is the Dresbach Member. The Dresbach Member has a regional thickness of 45 m in southwestern Michigan. The upper region of the Dresbach is a white to light gray dolomitic sandstone. This consists of subangular, medium-sized grains, and contains minor amounts of glauconite. The lower region is a well sorted, coarse-grained quartz sandstone with well rounded, frosted and pitted grains. This sandstone commonly contains thin beds of white dolomite and minor amounts of gray-green shale.

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

The Franconia Member usually can be identified on the gamma ray log as the radiation intensifies below the Trempealeau Formation, making it a very useful marker bed. The exception is where the bottom of the Trempealeau is laced with sandy stringers. Basin-wide, the Franconia maintains a thickness between 30 m and 150 m. In the region of the study area it has an average thickness of 31 m.

Trempealeau Formation

The Trempealeau Formation consists of a mostly buff to light-brown dolomite, often exhibiting a pink mottling. The dolomite appears fairly sandy, and in regions, slightly cherty. Indications of hematitic dolomite, dolomitic shale, shaly dolomite and glauconite are also common. The Trempealeau has a thickness of roughly 100 m in southwestern Michigan.

The Trempealeau Formation consists of three members: the Jordan Sandstone, the Lodi and the St. Lawrence.

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

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

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

Prairie du Chien Group

Based on outcrop lithologic descriptions, the Prairie du Chien Group has been divided into three formations by other workers. In descending stratigraphic order: the Shakopee Dolomite, New Richmond Sandstone and Oneota Dolomite. The extent to which any of these outcrop formations exist in Michigan's subsurface has yet to be ascertained. For correlation purposes in this report, the group has not been subdivided.

The Shakopee is a light-gray to light-brown finely crystalline dolomite. It contains minor amounts of oolitic chert, sand and shale stringers. The New Richmond is a fine- to medium-grained quartz sandstone. The grains are subrounded to rounded and often frosted. Color ranges from light gray to pink. The New Richmond is commonly interbedded with siltstone, argillaceous limestone, dolomite, shale and minor amounts of chert. The Oneota is a fine-grained, gray to buff to brown dolomite. Shows of oolitic chert are quite common along with dolomitic shale stringers, sand and glauconite.

The Prairie du Chien Group appears to be bounded by two unconformities: the Post-Knox Unconformity which separates it from the overlying Glenwood Shale and the St. Peter Sandstone in the study area, and another unconformity which establishes its lower limit at the top of the Trempealeau. In the Southern Peninsula of Michigan, the Prairie du Chien reaches a thickness of over 395 m. In the study area the average thickness is roughly 75 m.

St. Peter Sandstone

While assigned to the Ancell Group in regions surrounding the Michigan Basin, the St. Peter Sandstone is unassigned within the subsurface of the Basin proper (Shaver, 1985).

The St. Peter is a friable sandstone composed of well sorted, subrounded to well rounded quartz. The formation is considered supermature. The quartz grains are frosted and pitted, fine-grained in the upper portion and coarse-grained in the lower portion of the formation. Chert nodules and calcareous cementing are common.

The St. Peter Sandstone lies below the base of the Glenwood Shale and above an unconformity at the top of the Prairie du Chien Group. The St. Peter Sandstone is restricted to the southwestern margin of the Michigan Basin and exhibits large variations in thickness over comparably short distances (Milstein, 1984). Thicknesses range from 0 to a maximum of 10 m.

Black River Group

The Glenwood Shale is a basal member of the Black River Group. Because of the appearance of sandstones and carbonates within the Glenwood, it has been called a transitional bed between the St. Peter Sandstone and the Black River Group. In most portions of the Michigan Basin the Glenwood Shale exists as a stratigraphic unit regardless of the presence of the St. Peter Sandstone. The Glenwood is confined by the massive carbonates of the Black River Group above and, where it is present, the St. Peter Sandstone below. Where the St. Peter is absent, the base of the Glenwood is marked by an unconformity. The Glenwood is a waxy, green to greenish-gray, pyritic and sandy shale. It is interbedded with thin layers of red to dark-brown sandy and silty dolomite, dolomitic sandstone and limestone. Usually there are abundant quartz grains at the shale-dolomite contacts. The Glenwood has a regional thickness in the southwestern Basin of 6 m.

That part of the Black River Group above the Glenwood Shale has a lithology similar to the overlying Trenton Group in southwestern Michigan. It is a tan, semi-lithographic limestone, containing nodules of brown chert. Near the top of the Group a distinctive marker bed is identified as the "Black River Shale." It is a thin shale bed that induces a characteristic gamma ray log curve. This curve is a consistent and widely used marker bed throughout the Basin. The Black River Group has an average thickness of 75 m in the region of the study area.

Trenton Group

The Middle Ordovician Trenton Group overlies the Black River Group throughout the Southern Peninsula. The Trenton is a light-brown to gray bioclastic, finely crystalline to medium crystalline limestone. It also contains thin beds of black carbonaceous shale with associated chert nodules, usually black in color. The shales are most abundant at the base of the Group. The Trenton Group has an average thickness of 80 m in southwestern Michigan.

Richmond Group

Utica Shale

Gamma ray logs and samples show a distinctive, sharp contact between the basal Utica Shale Formation of the Richmond Group and the underlying Trenton Group. This contact is considered one of the most reliable lithologic markers in the Michigan Basin.

The Utica Shale Formation is a uniformly gray to black shale with minor amounts of green shale in its upper portion. The Utica ranges in thickness throughout the Basin from 60 m to 122 m. In southwestern Michigan it averages about 85 m. The variable thickness is attributable to subsurface structures.

While the term Cincinnatian denotes a time-stratigraphic unit rather than a rock-stratigraphic sequence, it is the generally used informal terminology identifying, yet unnamed, Late Ordovician sedimentary deposits in the subsurface of the Michigan Basin. These sediments lie directly above the Utica Shale Formation and compose the Upper Richmond Group (Shaver, 1985).

The Cincinnatian is the youngest sequence of Ordovician sediments in the subsurface of the Michigan Basin. The Cincinnatian rocks are composed of red, green and gray shales interbedded with gray to brown argillaceous and fossiliferous limestone, mottled dolomites, and relatively pure limestone. Individual beds and units within the Cincinnatian undergo facies changes in various parts of the Michigan Basin and can be tracked with relative ease by use of gamma ray logs. An unconformity exists at the contact between the Cincinnatian rocks and the overlying Silurian System in some areas of the Basin.

The uppermost zone of the Cincinnatian is marked by a red shale. The presence of this shale offers a reliable top to the Cincinnatian rocks. Where dolomite stringers occur in the upper portion or where the unconformity has stripped away some of the upper units the top is often difficult to pick. In the southwestern portion of the Basin the Cincinnatian has an average thickness of 58 m. Those rock units actively involved in the major structural deformation associated with the Calvin 28 cryptoexplosive disturbance, appear for the first time during the Early Cincinnatian.

Cataract Group

The base of the Cataract Group is represented in the Michigan Basin by the Manitoulin Dolomite Formation. The Manitoulin Dolomite is typically a thin to thick bedded, gray- to buff-weathering dolomite. In fresh samples it may often appear light blue-gray. The formation is locally cherty and includes interbedded shale. In southwestern Michigan, the Manitoulin is predominately dolomite, but shale beds become prominent to the north.

The Cabot Head Shale Formation occurs stratigraphically below the Niagara Group and above the Manitoulin Dolomite. The contact between the Cabot Head Shale and Manitoulin Dolomite is gradational and often difficult to discern in the subsurface. The Cabot Head consists of green, greenish-gray and some red shale.

Local reefs in the Cataract Group can cause considerable variation in lithology within a given region. The Cataract Group ranges in thickness from 14 m to 58 m throughout the Michigan Basin.

STRUCTURAL CHARACTERISTICS

The Calvin 28 structure consists of (1) a centrally located domal uplift 3.75 km in diameter, with a structural closure on the Traverse Limestone of 41 m, (2) a surrounding annular depression about 1 km wide and (3) an outer encircling anticlinal feature or rim, roughly 1.3 km wide with a structural relief of 34 m on the Traverse Limestone (Figure 2). The structure contour map deliniates the known limits of structural deformation associated with the Calvin 28 feature.

Figure 5 shows the extent of uplift evident on the Traverse Limestone along the line of cross-section A-A′ (Figure 2). Figure 2, with Figure 5, illustrates the apparent relationship between the Calvin 28 oil field, associated with the central uplift, and the Calvin 20 and Juno Lake oil fields located in the peripheral anticline.

Seismic assemblages and geophysical well log data confirm that an intricate system of faults and structural derangement exists beneath these fields, with the deformation waning with depth and distance from the structure. These data also imply these individual features are part of a single, interrelated, large-scale feature. Evidently a proper evaluation of the Calvin 28 disturbance must consider the peripheral anticlinal uplift, the annular depression and the central uplift as a single complex structure.

United States Geological Survey topographic maps and aerial imagery covering the study area show the structure is reflected as a subtle surface topographic rise, controlling regional drainage. Investigations of glacial drift thickness over the study area and mapping

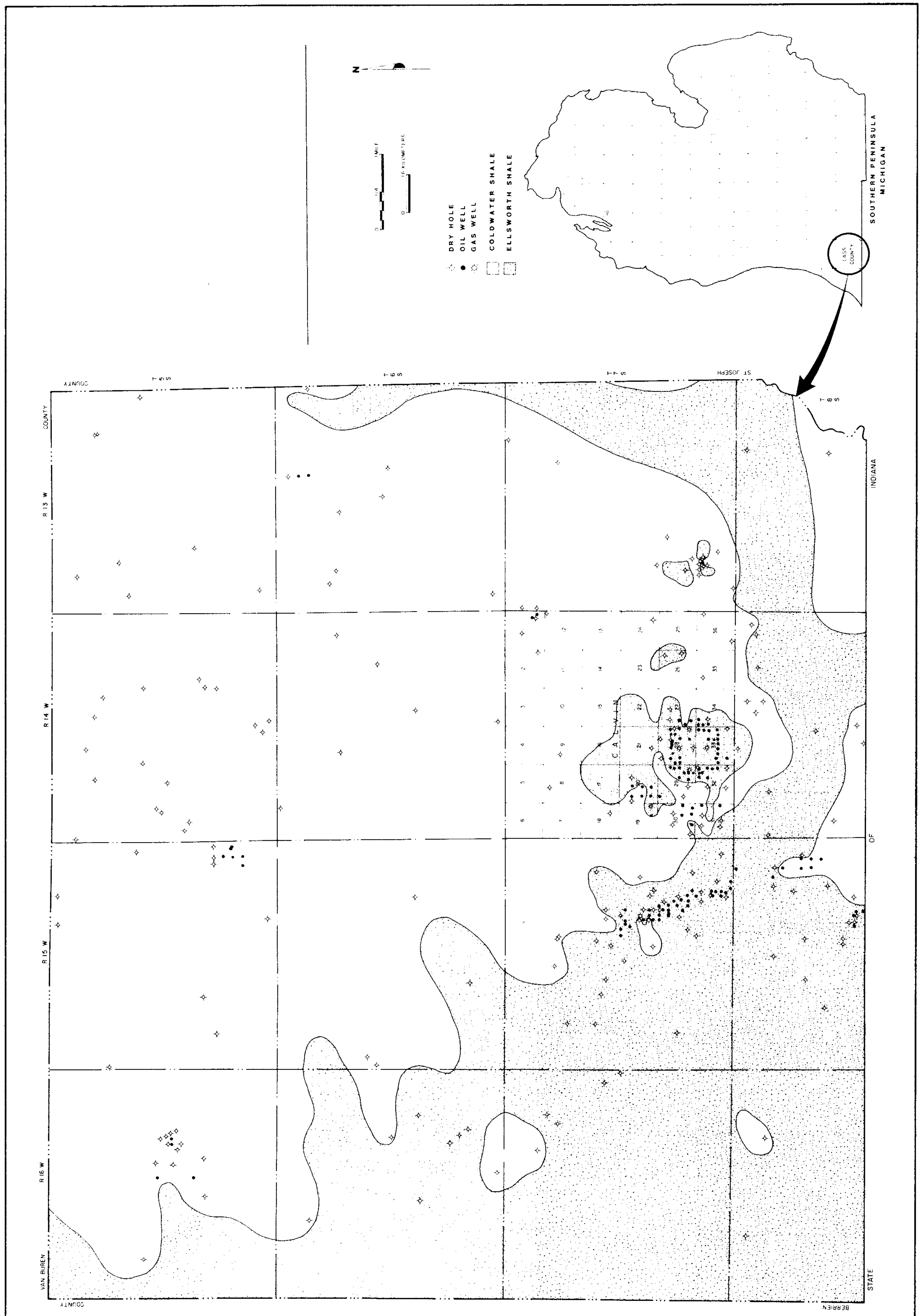


Figure 6. Bedrock Geology of Cass County, Michigan.

of the bedrock surface (Figure 6) confirm that surface rises reflect subsurface topographic highs and not glacial deposition features.

Rim Zone

The outer encircling rim of the Calvin 28 cryptoexplosive structure can be identified in Figure 2. Middle and Late Devonian formations in this region are 1.5 to 9 m higher than their equivalents in the annular depression. The rim has a maximum width of 1.5 km.

In an effort to examine the structure beneath the Calvin 20 oil field, located to the northwest of the Calvin 28 oil field, Halwell, Inc. drilled the Mary Smith #1-20 deep test well (Figure 2). After drilling to the Middle Silurian Clinton, rock units encountered showed thicknesses anomalous to regional trends. At roughly 777 m the well bore entered the St. Peter Sandstone. The local thickness of the St. Peter should not exceed 7 m (Milstein, 1984). Drill cuttings and geophysical well logs show the St. Peter in the Smith #1-20 to be over 172 m thick. Continued drilling showed no Prairie du Chien or Trempealeau identifiable in the well. Both the Prairie du Chien and the Trempealeau have distinctive, widely recognizable regional characteristics, and could easily be identified if present. The St. Peter appears to be in direct contact with the Franconia Sandstone.

A structure, classified as a cryptoexplosive disturbance, near Kentland, Indiana, exhibits similar characteristics (Buschbach and Ryan, 1963). Here the abnormal thickness of a regionally thin unit and the apparent absence of locally identifiable, distinct stratigraphic units were partially attributed to the high angle of dip in tilted blocks.

It is possible the Smith #1-20 well bore penetrated the regionally thin St. Peter in a block tilted at an angle nearing 90°. It is also possible that the St. Peter Sandstone has been thickened by repeated thrust faulting. In a cryptoexplosive/astrobleme structure located at Red Wing Creek, North Dakota, beds have been uplifted in the rim zone by thrust faulting over 300 m. The thrust faulting results in at least four repetitions of certain sections (Brenan and others, 1975).

Annular Depression

An inner annular depression about 1 km wide separates the outer rim zone from the central uplift (Figure 2). Devonian strata lie 28 m below their regional level and 41 m below equivalent strata in the central uplift. Oil and gas operators have been reluctant to drill in this depression as previous attempts to Devonian targets have resulted in dry holes (Figure 1). Within the annular depression, no test wells have been drilled to targets older than Devonian age.

Seismic data confirm the presence of the depression, at depth, implied by cross-sections and structure contour mapping of the Traverse Limestone. The identification by seismic means of specific marker beds within the annular depression, has proven difficult. This is due to an intense disruption of the stratigraphy, similar to that encountered in the deep test wells and incoherent noise. Although structural relief is evident, positive identification of stratigraphic units will have to await drilling of a deeper test well within the annular depression.

Central Uplift

Drill hole data from the Hawkes-Adams #1-28 and Lawson #1 deep test wells, both drilled on the central domal structure, suggest the dome resulted from the upward movement of strata (Figure 5).

The extent of structural uplift exhibited by the central dome was first estimated by DeHaas (1983) at 447 m. DeHaas's calculations were based on the difference in structural relief between Eau Claire tops in the Hawkes-Adams #1-28 and the Lawson #1 wells. This calculation overestimates the relief present. The Lawson #1 well is located on the uplifted flank of the central domal structure (Figure 2) and this leads to an inaccurate estimation of structural relief.

To arrive at a more accurate estimate of structural uplift, calculations were made between differences in Mt. Simon tops for the Hawkes-Adams #1-28, located near the approximate center of the domal uplift, and the Wooden #1 well, 6.3 km off structure to the northwest (Figure 2). The Wooden #1 was selected because of its depth of stratigraphic penetration and its location as the nearest deep well exhibiting regionally normal sections of those stratigraphic units missing or disrupted in the Hawkes-Adams #1-28. The Mt. Simon Sandstone was chosen as the marker bed because it is the lowest lithologic unit lying in its proper stratigraphic position and exhibiting the least structural deformation (Grieve and others, 1981) in the disrupted Hawkes-Adams #1-28.

Geophysical well logs show the top of the Mt. Simon Sandstone is at a sub-sea elevation of -919.3 m in the Wooden #1 and at -503.8 m in the Hawkes-Adams #1-28. The calculated difference is 415.5 m. This subtracts 31.5 m of structural uplift from DeHaas's original estimate.

Geophysical well logs, well site sample descriptions and sample analysis show the absence or anomalous thickness of many regionally distinct stratigraphic units in those deep test wells drilled into the central dome

(Figure 5). In the Hawkes-Adams #1-28, a thinned section of the Cincinnatian Series, rests directly on the Trempealeau Formation. The Utica Shale, Trenton, Black River, Glenwood Shale, St. Peter Sandstone and Prairie du Chien, totalling 276.5 m of strata, are missing. Sample inspection shows oolites present at a down-hole depth of roughly 511 m. Because oolites are a common indicator of the Prairie du Chien Group and Trempealeau Formation in this region of the Michigan Basin, it is possible that a very minor amount of Prairie du Chien may be present in the Hawkes-Adams #1-28. The Eau Claire Member of the Munising Formation is directly beneath the Trempealeau Formation and 167 m of strata are missing. The Lawson #1, while showing a full complement of regional strata, exhibits extreme variations in their thicknesses, especially the Middle and Late Ordovician sequences. Within the Lawson #1 the 67 m of regional Utica Shale is thinned to roughly 3 m and the regional 84 m of Trenton has thickened to 221 m.

Geophysical well logs show both well bores to be intersected by several faults. Dipmeter readings taken in the Lawson #1 show random dips throughout the disrupted section, with readings as high as 78°. In the lower 160 m of the well bore, the dip decreases, from top to bottom, from near 70° to roughly 5° with a persistant dip to the northeast, away from the central structure. This would suggest a waning of deformation at depth. Whether the apparent absence of many regionally distinct stratigraphic units in the Hawkes-Adams #1-28 is due to the high angle dip of beds in tilted blocks, as a result of which only a small portion of an entire section is encountered, or the result of ejection and fall-back during the initial formation of the structure, or a combination of both, is not known.

The high angle of dip apparent in the Lawson #1 adds support to the assumption the anomalous thickness of 172 m of St. Peter Sandstone present in the Smith #1-20 may be the result of the well bore penetrating this regionally thin unit tilted at an angle approaching 90°.

Microbreccia

A microscopic breccia was identified in thin sections from the Hawkes-Adams #1-28 at intervals between 506-509 m in Cincinnatian rock, 521-524 m, 543-546 m and 564-566 m in the Trempealeau Formation, in the Lawson #1 at intervals between 1017-1020 m in the Dresbach Member and 1157-1158 m in the Eau Clair Member, both of the Munising Formation, and in the Smith #1-20 at intervals between 792-794 m, 853-860 m and 914-917 m in the St. Peter Sandstone and 1183-1186 m in the Mt. Simon Sandstone Member of the Munising Formation. The breccia is composed of both fractured and unfractured, subrounded to rounded, floating quartz grains imbedded in a carbonate matrix (Figure 7).

The identification of the microbreccia at different narrowly defined stratigraphic intervals and its existence at multiple locations about the Calvin 28 structure, suggests the appearance of the breccia within a sampled interval is not the result of up-hole cavings. In addition, despite the small portion of well cuttings used to make each thin section (less than .5 grams), the microbreccia is apparent in each thin section. The lithology of the microbreccia remains constant regardless of the stratigraphic unit in which it has been identified. The microbreccia contrasts markedly with the normal lithology of the sampled stratigraphic units (see pp. 9—11). The variation of quartz grain morphology, in combination with the carbonate matrix, would suggest the need for distinctly different depositional environments if the breccia was to be attributed to normal sedimentary processes.

Similar microbreccias identified with other cryptoexplosive disturbances, impact craters and volcanic structures are attributed to the crushing, ejection and fallback of rock taking place during the initial formation of the structures (Short and Bunch, 1968; Grieve and others, 1981). Microbreccias are also commonly associated with structures resulting from solution subsidence. A discussion of these possible mechanisms appears later.

Shock-Metamorphic Effects

The term shock metamorphism is used to describe all changes undergone by rocks and minerals resulting from the passage of transient, high-pressure shock waves. The only known natural method of producing shock metamorphism is the hypervelocity impact of an extraterrestrial body (French, 1968a). Hypervelocity impact refers to the impact of a projectile onto a target surface at such a velocity that the stress waves produced on contact are orders of magnitude greater than the static bulk compressive strength of the target material. The minimum required velocities vary with target material, but in sedimentary targets they are generally 1-10km/sec. When shock-metamorphic features are identified in rocks they become important indicators for the recognition of meteorite impact sites. In-depth descriptions of shock metamorphic effects and their use as impact indicators are given by Bunch (1968), DeCarli (1968), French (1968b), Roddy (1968), Short (1968) and Short and Bunch (1968).

Natural shock metamorphism is produced by the nearly instantaneous transfer of the kinetic energy of an impacting body into the surrounding rock. The result-

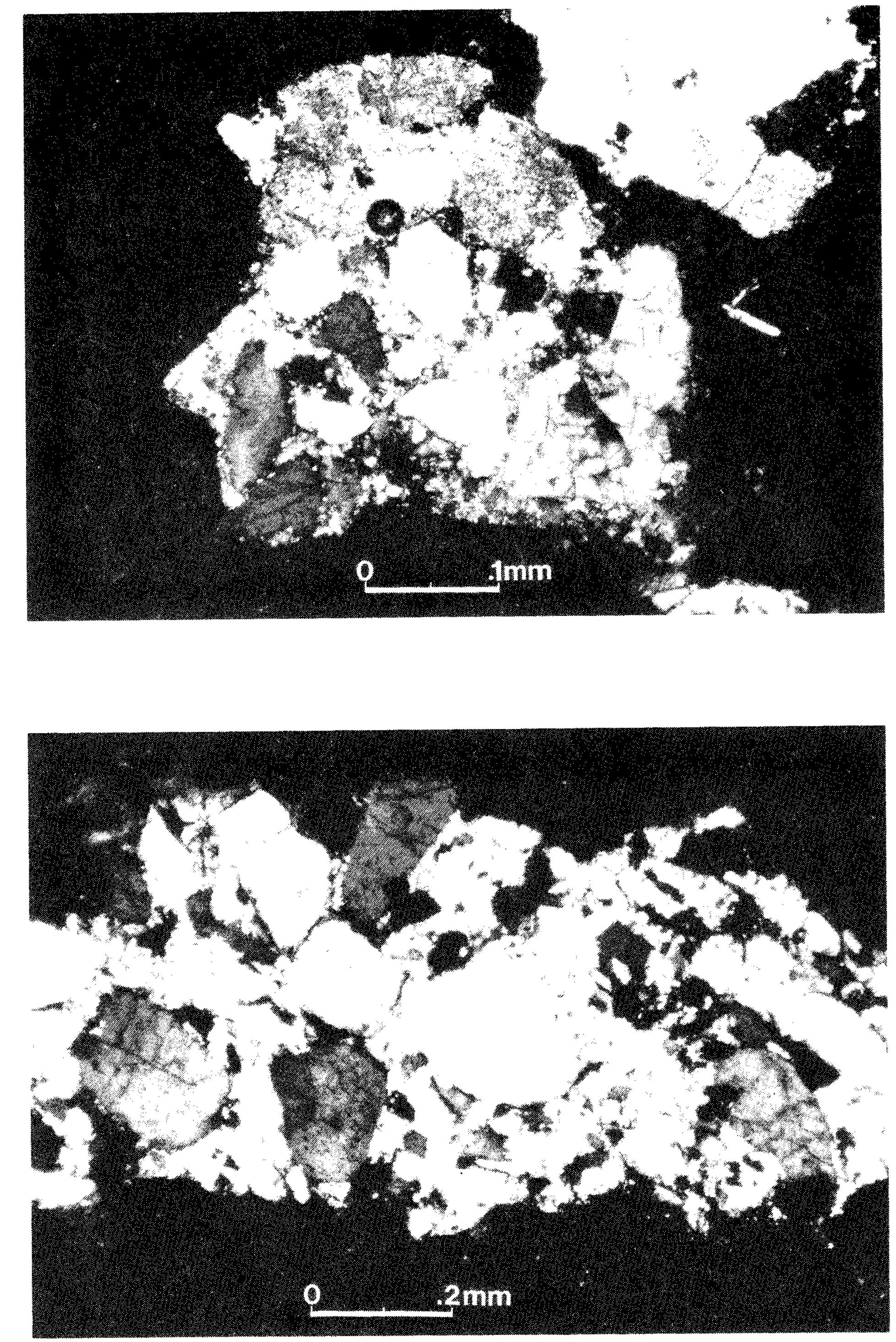


Figure 7. Photographs illustrating microscopic breccia from the Calvin 28 cryptoexplosive disturbance: Lawson #1, 1016.5-1018 m.

ing shock effects produced can be broadly classified into three major groups (French, 1968a):

1. High pressure effects characterized by the production of high-pressure polymorphs (coesite, stishovite and diamond).

2. High strain-rate effects involving the progressive dislocation and destruction of crystal lattices, the development of planar features (shock lamellae) in quartz, the transformation of original grains of quartz and feldspar in situ into isotropic phase minerals (plagioclase to maskelynite).

3. High-temperature effects produced by shock pressures so high that relaxation temperatures are hundreds of degrees above normal melting points for the component minerals, resulting in mineral decomposition and melting (quartz to lechatelierite).

Any one, or all, of these effects may be identified in a single sample. Therefore, one of shock metamorphism's most distinguishing characteristics is its complex nature, in combination with mineralogical selectivity (Chao, 1967, 1968).

A microscopic investigation for shock-metamorphic features was done on samples from the Hawkes-Adams #1-28, Lawson #1 and Smith #1-20 deep test wells.

Because rocks older than Devonian were not cored in these wells, the search for shock-related deformation features was limited to thin sections prepared from minute portions of well cuttings from selected stratigraphic intervals.

An additional sample from the Smith #1-20 was submitted for inspection to the U.S. Geological Survey, Denver, Colorado. Both investigations showed no evidence of high pressure, high strain-rate or high temperature shock effects. While the investigation revealed no evidence of shock metamorphism, the limited availability of samples for inspection was a major restriction. A thorough microscopic search for shock metamorphism would have to involve cores and the less restricted use of well cuttings.

Described previously (p. 14), an unusual microbreccia was found in three drill holes. The characteristics of the microbreccia are consistent with those noted in macro- and microbreccias associated with cryptoexplosive/astrobleme structures and impact craters (Short and Bunch, 1968).

Iridium Analysis

Compared with its normal abundance in the solar system, iridium is strongly depleted in the Earth's crust. Any significant terrestrial concentrations are probably restricted to the Earth's core (Goldschmidt, 1937).

Palme (1982) states that analysis of elements with high concentrations in meteorites but low concentrations in terrestrial surface rocks, such as iridium, can be used to identify large scale impact features (over 1 kilometer in size). Palme's study suggests terrestrial impact craters, with diameters up to 1 km, are usually found to contain remnants of the impactor. Projectiles responsible for larger craters, however, would strike the Earth with undiminished hypervelocities. During such an impact, shock pressures would be generated to such an extent as to completely melt or vaporize the projectile. In this case, rather than finding pieces of the bolide, chemical signatures of the projectile may be found in associated target lithology. Palme (1982) gives a detailed description using iridium as an indicator of meteoritic material.

A standard method for identification of rare earth elements, such as iridium, is neutron activation followed by radiochemical purification (Minor and others, 1981).

Owing to the lack of discernible shock-metamorphic indicators in the Calvin 28 cryptoexplosive disturbance which might suggest an impact origin, neutron activation analyses were done to determine if iridium is present in anomalous concentrations. If iridium enrichment were present at Calvin 28, it would most likely be identified along the structural perimeter and in a stratigraphic unit associated with the structure's time of origin (Dietz, R. D., University of Northern Colorado, oral communication, 1985).

Sample sets from the Cincinnatian interval of the Smith #1-20 well, 525-581 m, were submitted to both Michigan State University and the Los Alamos National Laboratory for neutron activation analysis. All test results were analyzed at the Los Alamos National Laboratory by Charles J. Orth. Results showed iridium concentrations of 0.010 ± 0.002 ppb from the irradiated samples. The findings were not considered anomalous. Anomalous iridium content normally is considered to be 1 ppb or greater (Palme, 1982; Orth, written communication, 1985).

Energy Requirement

The energy required to form the Calvin 28 structure can be calculated from the size and structural extent of Calvin 28 as suggested by subsurface mapping, and by using the empirical scaling law, $D = cfKnE^{1/3.4}$, derived from the effects of nuclear explosions on sedimentary targets (Shoemaker and Wolfe, 1982). D is the measured structural diameter, cf is the collapse factor of the structure, Kn the energy scaling factor, and E is the explosive energy. The collapse factor for craters created in sedimentary targets is 1.3 (Shoemaker and Wolfe, 1982) and results from slumping of the structure's walls after initial formation. The scaling factor Kn is 74 m for a one kiloton equivalent TNT explosion (Wetherill and Shoemaker, 1982). A one kiloton explosion equals an energy release of 4.185×10^{19} ergs. Correction factors for surface gravity and target density are neglected by the equation because they are considered equal or close to unity. Based on the above equation, the energy required to form the 7.24 km diameter Calvin 28 cryptoexplosive disturbance is 2.4×10^6 kilotons or 1×10^{26} ergs. The energy involved can be placed into perspective when compared with other high-energy processes. The energy released by the total airborne explosives used during World War II was 1×10^{23} ergs and the energy release of a single, 100 megaton hydrogen bomb would equal 1×10^{25} ergs (Dachille, 1962).

AGE OF THE STRUCTURE

Cincinnatian rocks of Late Ordovician age, (Upper Richmond Group) are involved in the deformation, so the Calvin 28 cryptoexplosive structure is clearly older than Early Silurian. Lithologic units within the Cincinnatian sequence are readily correlatable by gamma ray log characteristics. When combined with accurate descriptive logs, correlation between subsurface control points is quite reliable.

Correlations and comparisons of gamma ray logs, descriptive logs and well samples indicate rocks of Late Cincinnatian age are present in all control points both on and off the structure. Control points on structure display a lack of Early and Middle Cincinnatian stratigraphy. Correlating away from the structure, Early and Middle Cincinnatian lithology becomes evident. The overlying Cataract Group, while showing minor variations in thickness, is present both on and off structure, is undisrupted, and appears in its proper stratigraphic order.

The characteristics of the Cincinnatian stratigraphy identified in conjunction with the structure appear unrelated to the unconformity separating the Ordovician Cincinnatian rocks from overlying Silurian rocks. The inconsistencies appear more closely linked to the event responsible for the formation of Calvin 28. Rocks of the Middle Ordovician age, (Trenton and Black River Groups) are involved in the deformation, and appear faulted and abnormally thick on the flank of the central uplift and in the peripheral anticline. These rocks were deposited prior to the structure's formation.

The age of the event responsible for the formation of Calvin 28 has been placed prior to Early Silurian time, but after deposition of the Late Ordovician-Early Cincinnatian Utica Shale.

EVALUATION OF POSSIBLE ORIGINS

The Calvin 28 cryptoexplosive disturbance involves large-scale and intense structural deformation within a limited area of circular shape. Evidence suggests the structure was probably the result of a single explosive event resulting in a sudden, highly localized release of tremendous energy. Possible origins for such large-scale explosive structures involve both endogenetic processes, in which some unusual igneous or diapiric process is involved, and exogenetic processes, involving meteoritic or cometary impact. Excellent summaries of both arguments for the origin of cryptoexplosive structures have been given by French (1968a) and McCall (1979).

By comparing the Calvin 28 cryptoexplosive disturbance with both endogentic and exogenetic structures which exhibit similar characteristics, diagnostic elements emerge that aid in identifying the possible forces responsible for the disturbance. Endogenetic structures that exhibit characteristics consistent with structural patterns identified in the Calvin 28 feature include: maars, diatremes, calderas, kimberlite pipes, igneous intrusives, diapirs and solution subsidence structures. Exogenetic structures exhibiting similar characteristics are limited to cryptoexplosives/astroblemes and impact craters. Any explanation for the origin of the Calvin 28 structure must accommodate the following observations:

1. The structure is circular, containing a central uplift, surrounding annular depression and a peripheral anticline.

2. Structural deformation is intense, involving large-scale faulting and upward movements of strata.

3. Over 276 m of strata is missing in portions of the structure, while other locations show highly anomalous thicknesses of units.

4. Deformation wanes with depth beneath and distance away from the structure.

5. The structure exists as an isolated feature.

6. The event responsible for the structure's origin is estimated to have released at least 1×10^{26} ergs of energy, without the development of magma.

Volcanic Origins

<u>Energy Considerations</u>

The total energy released annually from the Earth's interior by heat flow, volcanism and earthquakes is roughly 10^{28} ergs (French, 1968a). The single most violent endogenetic event, recorded in historical times, is the 1883 volcanic eruption of Krakatau. Energy released by this explosive eruption has been estimated at 1×10^{24} ergs (Yokoyama, 1981). The calculated energy requirements for the formation of Calvin 28 has been shown to be at least 1 x 10^{26} ergs. This amount of energy, released during a single event in the near-surface environment of the Earth, is not approached in any normal geologic process. The largest man-made explosion, the Soviet 58 megaton test of October 31, 1961, produced an energy release of 2.5 x 10^{24} ergs (Glasstone, 1964).

Volcanic eruptions are the most violent known terrestrial endogenetic events. Extensive evaluations of their energy release have been done by Yokoyama (1981) and Steinberg and Lorenz (1983). Nakamura (1965) and Shimozuru (1968) attributed a total energy released during terrestrial volcanic eruptions to four major components:

1. Heat energy contained in the solid and fluid products.
2. Heat and mechanical energy required to heat subsurface rocks and vaporize meteoric water.
3. Mechanical energy expended by magma and gas.
4. Work done against gravity in elevating the volcanic rocks from their source.

All the listed energy forms are derived from the original heat content of magma (Williams and McBirney, 1979). No volcanic material has been identified in association with the Calvin 28 cryptoexplosive disturbance. Mineralization attributable to hydrothermal or known volcanic processes has not been recognized in deep well samples recovered from the structure. Microbreccia associated with the structure contains no volcanic material, making its origin by volcanic processes unlikely. Uplifting of strata by an explosive volcanic-gas expansion produces dilation that is generally represented by simple upward or downward movements on steeply dipping faults (Offield and Pohn, 1979). This is not a pattern observed at Calvin 28. The repeating of beds in the central uplift and peripheral anticline would be more indicative of some form of horizontal stress.

If a volcanic mechanism is still to be considered a possibility for the origin of Calvin 28, such a mechanism would have to conform to characteristics observed for cryptoexplosives by French (1968a). French states the required mechanism must: (1) be capable of generating hundreds of kilobars of pressure near the surface of the Earth, (2) be able to contain such pressures over areas of tens of square kilometers until they can be released as a shock wave, (3) operate in a confined space at shallow depths, since the structures do not appear to continue deep into the subsurface, (4) release total energies estimated at 10^{24} ergs and greater to account for brecciation and evacuation, (5) develop temperatures greater than 1500°C to account for unusual melting and decomposition reactions noted in many cryptoexplosives, (6) involve rapid cooling and quenching periods to account for unstable phase changes often noted in quartz associated with the structures, and (7) produce all these effects, in most cases, without producing any true volcanic or igneous material.

While such characteristics would define a highly unusual and yet unidentified volcanic event, they should not preclude the possibility that geologic processes capable of such characteristics existed earlier in geologic time. McCall (1979) suggests that an endogenetic explosion resulting from adiabatic expansion could account for some cryptoexlosive disturbances. Adiabatic expansion from the sudden release of a gas phase as a deep-seated magma approaches the surface and the possibility that the new gas phase might be a highly reactive one such as hydrogen. This would result in a tremendous release of near-surface energy and still not involve the extrusion of volcanic material.

Maars and Diatremes

Pike (1980) states the closest volcanic analog to cryptoexplosive disturbances is the maar. Based on a set of general structural characteristics for maars and diatremes compiled by Roddy (1968), marked differences exist in size, shape and location between these features and Calvin 28.

Roddy's study identifying characteristics of globally scattered maars and diatremes suggests that maars are broad, low-lying volcanic craters often surrounded by a ring structure and commonly occurring in groups, or in association with other volcanic or tectonic features. The Calvin 28 cryptoexplosive structure occurs as an apparently unique, circular feature within the region. The individual maars range in diameter from a few tens of meters to nearly five kilometers. The craters are circular to elliptical and bowl-like, with a maximum depth of 250 m. Diatremes are pipelike intrusions or vents that commonly accompany maars and extend many kilometers in depth. They are usually circular to elliptical in plan and decrease in diameter with depth.

Roddy states that maars and their vents appear to form mainly by local brecciation of a column of strata, with only minimal lateral compression of their walls. In contrast, the encircling rim zone of the Calvin 28 disturbance, as exhibited by the Smith #1-20 well, is severely uplifted and faulted. The walls of maars and diatremes appear to have sharp contacts with surrounding country rock. Where structural deformation is present in their rims, it is commonly restricted to a narrow zone several meters in maximum width. Increasing the size of the maar or diatreme does not appear to proportionally increase the width of the narrow deformation zone. This deformed and fractured zone is commonly the site of intense compression and often mineralization. Maars show slumping within their craters and concentric normal faulting in their rim structures. Slumping is unidentifiable in the Calvin 28 structure, but seismic data, subsurface mapping and

geophysical well logs imply the presence of concentric normal faults.

The Calvin 28 cryptoexplosive disturbance has a centrally located domal rise, with structural uplift of 415.5 m. Some maars are known to have central or noncentral small volcanic cones within their craters. Roddy (1968) states that large, centrally uplifted blocks have not been identified in either maars or diatremes.

The pyroclastic material present in maars and diatremes, especially those approaching the size of Calvin 28, consists of a mixed assemblage of volcanic tuff and breccia derived from both upper and lower stratigraphic horizons. Maars commonly have an ash and pyroclastic ejecta blanket overlying the rim and immediately adjacent area. No igneous materials have been found associated with the Calvin 28 cryptoexplosive disturbance.

Pike (1980) found that maar and diatreme craters differ markedly from cryptoexplosion structures in such geometric parameters as depth, diameter and structural uplift. Pike (1980) suggests the largest terrestrial maar is 5 km in size and considers this a conservative cutoff for maximum diameters achieved by the energy discharged during their origin. The 7.24 km diameter of Calvin 28 places it well above the known terrestrial maar maximum diameter of 5 km.

Kimberlite pipes (diamond bearing diatremes) have been identified in the Michigan Basin (Reed, R. C., oral communication, Michigan Geological Survey, 1986). Cannon and Mudrey (1981), describe five suspected "cryptovolcanic" structures located within their study region (Figure 8). The described structures have several common features. All the structures are relatively small, ranging from 500 m to 1.5 km in diameter. The features are synclinal or basinal structures characterized by inward dips of between 5 and 70° and display localized complications caused by faulting and small-scale folding. All the structures exhibit strata dropped at least 50 m below their normal regional levels. All the disturbances appear to have occurred during Ordovician time or later.

Cannon and Mudrey suggest these features could be "cryptovolcanic" structures formed as a result of collapse over deeper-seated kimberlite pipes. They feel that different levels of erosion could account for the disturbed strata noted and that the erosion level is simply not deep enough to reveal underlying intrusions. However, magnetic and gravity studies do not support this conclusion (Hoehl, 1981). Cannon and Mudrey considered two alternative explanations; that the structures might either be solution collapse features or grabens related to Proterozoic basement faulting. Cannon and Mudrey rejected both alternatives because soluble rock does not exist below the disturbed strata, and no known faults in the region have well documented post-Ordovician throws of 100 m or more. The circular, rather than linear, nature of the structure's downthrown areas discount further the likelihood of these alternatives.

Kimberlite-bearing structures appear to be produced by endogenetic explosive events, and specific mineralogical and structural features label them unique. To assume a relationship between unidentified kimberlite pipes and cryptic surface features, based on interpretive gross geologic trends is not prudent. Without positive evidence suggesting these features are the result of an endogenetic event, the author suggests they be identified by the more neutral term, cryptoexplosive disturbance.

Similarities are noted when comparing the Calvin 28 disturbance to Cannon and Mudrey's structures. Though Calvin 28 is considerably larger and exhibits a centrally uplifted dome, all the structures show high-angle dips, extensive faulting, displaced strata, Ordovician age, random distribution and are of enigmatic origin.

Calderas

Calderas are large volcanic collapse depressions, roughly circular in form, with diameters many times greater than that of the original volcanic structure.

Williams and McBirney (1979) state that calderas can usually be classified in one of seven known groupings. In each case the caldera is the result of collapse or subsidence of a volcanic edifice inward on an evacuated magma chamber. Large amounts of volcanic material is involved in each instance.

While the ringed structural pattern associated with the Calvin 28 cryptoexplosive disturbance is not unlike the final structural pattern of calderas, the lack of any volcanic material identified with the feature effectively eliminates the caldera model.

Intrusive Origins

Ghatge (1984) examined the possible existence of a shallow, buried, igneous intrusive body beneath Calvin 28. Ghatge's geophysical investigation showed no gravity anomalies to the level of 1 milligal are associated with the structure, and no magnetic anomalies are present. Seismic profiles confirm the lack of any intrusive body beneath the structure. Based on such evidence, it appears unlikely that an intrusive body was responsible for the formation of the Calvin 28 structure.

Diapiric Origins

The structural characteristics and geometry of Calvin 28, with beds forced upward to form a central uplift

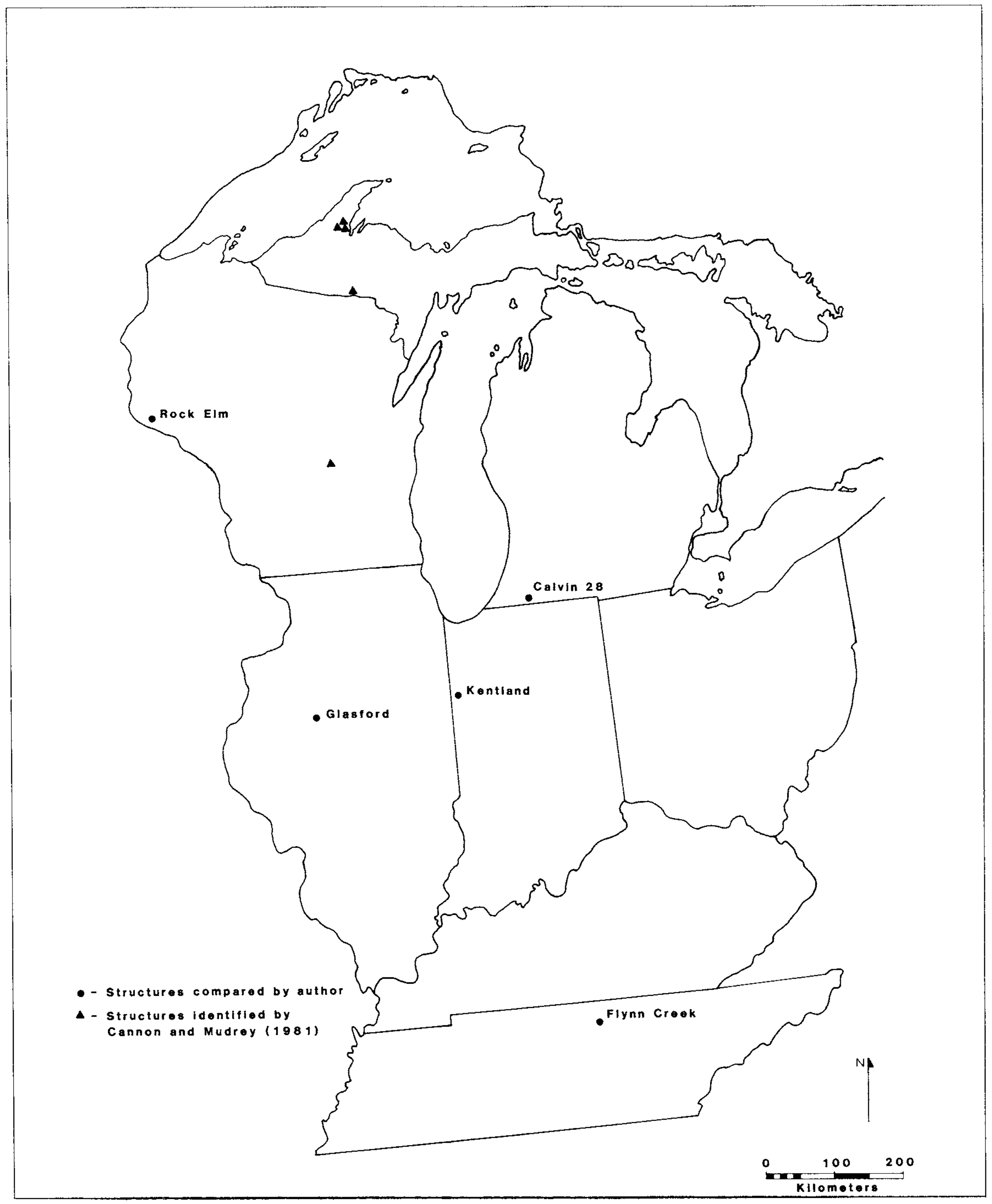


Figure 8. Location of selected Midwestern cryptoexplosive disturbances.

and the accompanying development of a surrounding annular depression and encircling anticline, are unlike any terrestrial structures except diapirs and impact craters.

Nicolaysen (1973) interprets cryptoexplosive disturbances as diapirs obtaining release from strong lateral confinement. Nicolaysen implies that density inversions and fluids under high pressure, combined with the development of a mechanically weak character in limestone or anhydrite layers in a region, will result in the development of a fluid-pressure-driven rock diapir. It seems unlikely that this type of diapiric action, manifesting itself as a single, nearly instantaneous event, would be capable of generating 1 x 10^{26} ergs of energy required to evacuate the missing host material at the Calvin 28 structure.

The Mt. Simon Sandstone (density=2.65), at the shallow depths at which it occurs in the Calvin 28 structure, is not capable of forming the significant density inversion with overlying strata (density=2.79) which could result in the buoyancy and flowage necessary for diapiric uplift. The lack of a significant density inversion rules out the origin of the structure by diapirism. Seismic profiles confirm the lack of any bulbous or flat-topped cylindrical intrusive bodies beneath the structure. The singular nature of Calvin 28 is also in contrast to the normal clustering of diapiric structures.

Solution Subsidence

Collapse structures (sinkholes) are formed in sedimentary rocks by the downward movement of strata into voids created by the solution of underlying strata. Most collapse structures result from the solution of the evaporites gypsum, anhydrite, and halite; the remainder, from the solution of limestone.

Collapse structures induced by solution subsidence have been identified having diameters and geometry similar to Calvin 28 (Taviani, 1984). The absence of significant carbonate and evaporite deposits within the Cambrian and Ordovician stratigraphy underlying the Calvin 28 structure (see pp. 9–11), effectively eliminates the solution subsidence/collapse scenario.

Moreover, the upward movement of beds to form the central uplift and encircling anticline of Calvin 28 is direct contrast to the gravity-induced downward movement of strata associated with collapse structures.

Solution breccias, associated with collapse structures are typically composed of very angular clasts and are poorly sorted (Middleton, 1961). The angular clasts are due to the lack of weathering and limited, predominately downward transportation. The microbreccia identified within Calvin 28, however, exhibits highly weathered quartz grains of similar size, and both fractured and unfractured grains appear in the same sample.

Impact Origins

Impact Structures

Throughout the region surrounding the Michigan Basin a number of cryptoexplosion disturbances have been identified in the surface and subsurface. Many of these agree more readily in size and structural characteristics with Calvin 28 than those cryptoexplosive structures, interpreted as possible kimberlite pipes, by Cannon and Mudrey in Northern Michigan. Cryptoexplosive structures located in Kentland, Indiana, Glasford, Illinois, Flynn Creek, Tennessee and Rock Elm, Wisconsin (Figure 8) were compared with Calvin 28 based on specific characteristics (Table 1). The results of the comparison suggests that a structural similarity exists between the features. Especially strong are the associations with morphologic characteristics.

Three of the four cryptoexplosive structures compared to Calvin 28 in Table 1 are classified as Class IV impact structures (McCall, 1979). McCall's classification criteria are shown in Table 2. The structure at Rock Elm, Wisconsin, is too recently identified to be included in McCall's listing. McCall further subdivides his Class IV structures morphologically (Table 2). Based on this classification system, Calvin 28 and Rock Elm should both be listed as Class IVa/3 impact structures. Class and subclass for all structures compared appear in Table 1.

When placing cryptoexplosive disturbances into his impact classification system (Table 2), McCall (1979) states that there is no direct evidence of meteoritic involvement in any cryptoexplosive structure of Class III, IV or V, and very meager evidence, if any, in almost all structures of Class II. There may exist a body of strong indirect evidence of impact involvement, but there is no certainty that any specific piece of evidence cannot be accounted for by endogenetic means. It should be noted that McCall's classification system is not widely excepted, and is used in this study simply to illustrate certain comparisons.

Grieve and others (1981) state that structures now identified as terrestrial impact scars (astroblemes) appear in two forms, each of which have distinct structural characteristics.

Form one, the simple crater is usually less than 2 km in diameter in sedimentary targets, is bowl shaped, has rim rocks that are uplifted and overturned, and is surrounded by an ejecta deposit up to one diameter beyond its rim that exhibits inverted target stratigraphy. The crater is usually breccia filled to some extent. The crater exhibits intense deformation, complex internal fracturing and faulting, with deformation waning at

	STRUCTURES				
GENERAL CHARACTERISTICS	GLASFORD, ILLINOIS	KENTLAND, INDIANA	CALVIN 28, MICHIGAN	FLYNN CREEK, TENNESSEE	ROCK ELM, WISCONSIN
CLASSIFICATION	IVa/2	IVa/2-3	IVa/3	IVa/2-3	IVa/3
CRATER DIAMETER (kilometers)	4	5	7.24	3	6.5
STRUCTURAL UPLIFT (meters)	305	610	415.5	100	274
BEDDING DIPS (degrees)	40-90	17-82	5-78	35^+	20-70
ESTIMATED AGE: A. LATE OROVICIAN; B. MID-ORDOVICIAN; C. POST-ORDOVICIAN	A	B	A	C	B
GRAVITY ANOMALY	●				●
MAGNETIC ANOMALY					●
STRUCTURAL MORPHOLOGY:					
CIRCULAR SHAPE	●	●	●	●	●
CENTRAL DOMAL UPLIFT	●	●	●		●
ENCIRCLING ANNULAR DEPRESSION		●	●	●	●
INTENSE FAULTING	●	●	●	●	●
FOLDING				●	●
ANOMALOUS BEDDING THICKNESSES	●	●	●		
DEFORMATION DECREASING WITH DEPTH	●	●	●	●	●
VOLCANIC MATERIAL					
SHOCK METAMORPHISM					
SHATTER CONES		●		●	
BRECCIAS	●	●	●	●	●
MICROSTRUCTURES		●		●	
MINERALIZATION		●		●	
SURFACE FEATURE		●		●	●
SUBSURFACE FEATURE	●		●		

Table 1. Comparative features of selected Midwestern cryptoexplosive disturbances.

depth. Large sections of strata are randomly missing or unidentifiable. Structural deformation diminishes with distance from the structural perimeter. The crater exists as an isolated feature.

Form two, the complex crater, usually appears as a relatively shallow, circular crater over 2 km in diameter in sedimentary targets. Complex craters exhibit the same general characteristics as the simple crater form. The principle geological difference from simple craters is the occurrence of a central core of uplifted, shocked rocks, surrounded by one or more concentric, peripheral depressions. The central uplifted core is expressed topographically as a dome, peak, or ring. The broad characteristics for complex crater forms compare favorably with features identified in the Calvin 28 structure.

Pike (1980) and Grieve and others (1981) state that craters attributed to impact exhibit specific characteristics and that these characteristics can be calculated based on relationships between the crater's observable depth, diameter and structural uplift. Grieve and others (1981) suggest a final complex crater form will exhibit an apparent diameter (Da), which can be considered approximately equivalent to the observed distance from rim to rim, a true depth (dt), which can be determined only by extensive drilling, and an amount of structural uplift (SU), calculated by measurable uplift of the deepest in place marker horizon.

Only three deep test wells have been drilled into the disrupted sections of Calvin 28 and no reliable estimate of dt is available.

Based on measurements made from structure contour maps of the heavily drilled Devonian Traverse Limestone (Figure 2), the Da of Calvin 28 is estimated at 7.24 km. This estimate may be considered the maximum, observable value for Da. Structural relief and size noted in the Devonian is attributed to rebound, slumping and settling at greater depths.

CLASSIFICATION

Class I	Proved meteorite impact-fragmentation craters and meteorite impact-explosion craters
Class II	Craters showing shock effects, but no material association of meteorites (all meteorite impact-explosion craters).
Class III	Craters showing the characteristic physiographic form and structure of meteorite craters, but no shock metamorphism, meteoritic material, or bolide association.
Class IV	Structures either deeply eroded or buried, or else of considerable complexity, which do not display an immediately apparent physiographic form of meteorite craters. These include some relatively young but highly complex features, but the majority are of considerable geologic age. The eroded and infilled examples include a number of simple craters, but the majority are of considerable complexity. All are possible meteorite impact-explosion structures.
Class V	Structures concerning which there is too little evidence available at this stage of knowledge to determine origin, and concerning which more information is needed.
Class VI	Structures erroneously attributed to extraterrestrial agencies.
	CLASSIFICATION SUBGROUPS
a	Displays some form of shock metamorphism or brecciation.
b	No shock metamorphism or brecciation identified.
	CLASS IV MORPHOLOGICAL SUBCLASSES
IVa/1	Simple structures.
IVa/2	Complex structures with central uplift.
IVa/3	Complex structures with both central uplift and enclosing ring depression.
IVa/4	Complex structures with only a central depression.
IVa/5	Complex, irregular structures.

Table 2. Classification of meteorite and astrobleme craters (McCall, 1979, modified from Shoemaker and Eggleton, 1961).

Geophysical well logs give a minimum estimate to SU for Calvin 28 of 415.5 m. This is based on comparitive measurments of the lowest, observable in place marker bed, the Cambrian Mt. Simon Sandstone, between the on structure Hawkes-Adams #1-28 and the off structure Wooden #1 (Figure 2 and Figure 5).

By studying the relationships between stratigraphic uplift and the apparent diameter of accepted terrestrial complex craters, Grieve and others (1981) find, $SU = 0.06Da^{1.1}$. By solving for SU and Da with the observed values, a calculated SU of 529m and a calculated Da of 6.93 km are found.

The author believes minor disagreements between calculated results and observed values are acceptable given the maximum and minimum limitations placed on the observed values. Calvin 28 is considered to exhibit a recognized relationship between stratigraphic displacement in the central uplift and its present form and dimension.

Figure 9 shows Calvin 28 compared to known terrestrial impact structures, based on $SU = 0.06Da^{1.1}$. A positive correlation with known impact structures in sedimentary targets is suggested.

Structural similarities between impact craters identified on the lunar and Martian surfaces and the mapped structural characteristics of Calvin 28 are shown in Figures 2 and 10.

The general structural nature of the central domal uplift is shown in Figure 2. The uplift appears similar to central peak structures in lunar and Martian impact craters. Hale and Head (1979) state that central peak structures in impact craters can be classified morphologically by complexity (simple and complex) and geometry (linear, arcuate, or symmetric). A simple peak consists of a single uplifted "peak" while a complex form consists of many "peaks" often appearing in clusters. Geometry refers to peak orientation, symmetric ones being those oriented concentric to the crater center, while linear or arcuate peaks, ridges or

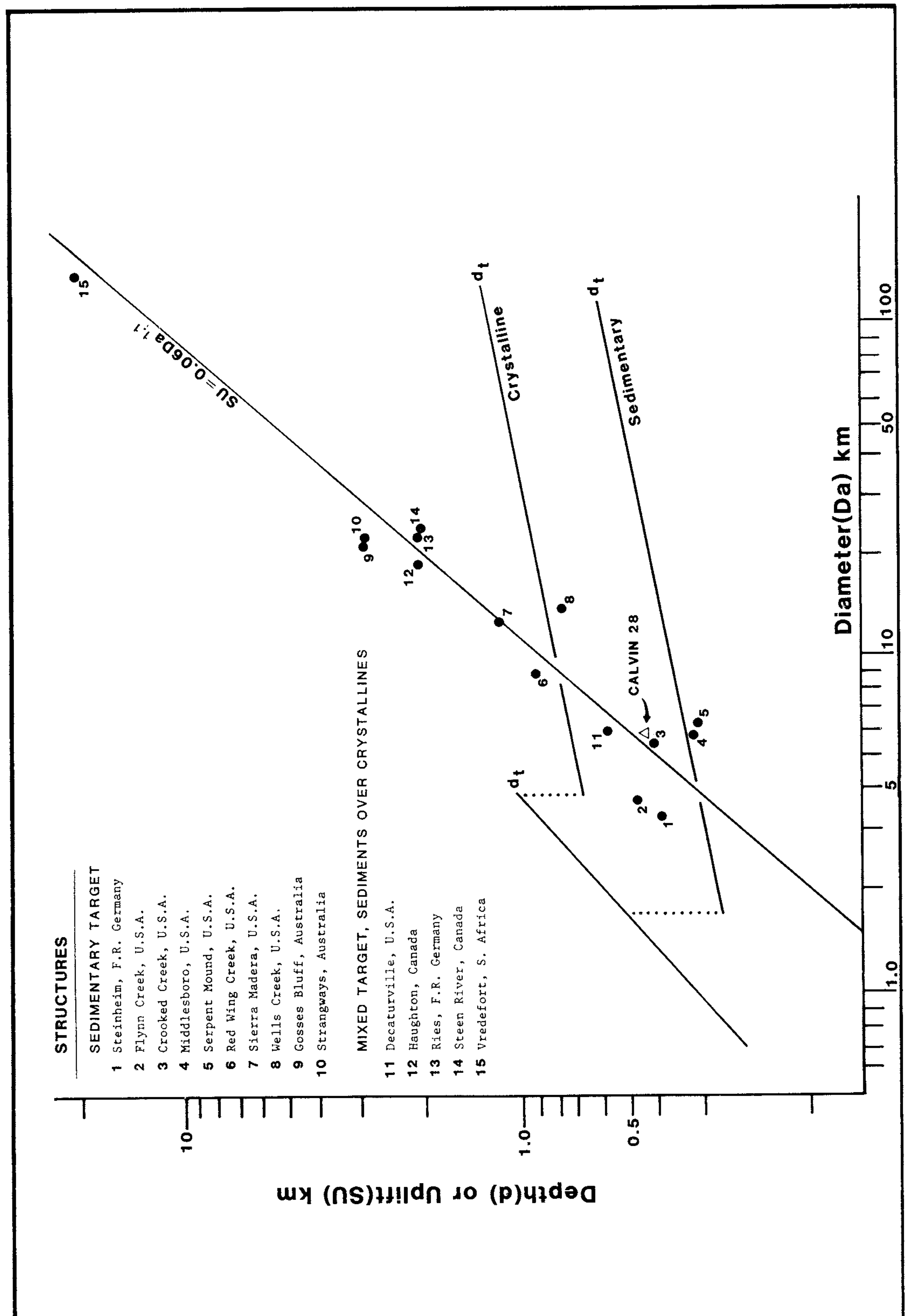
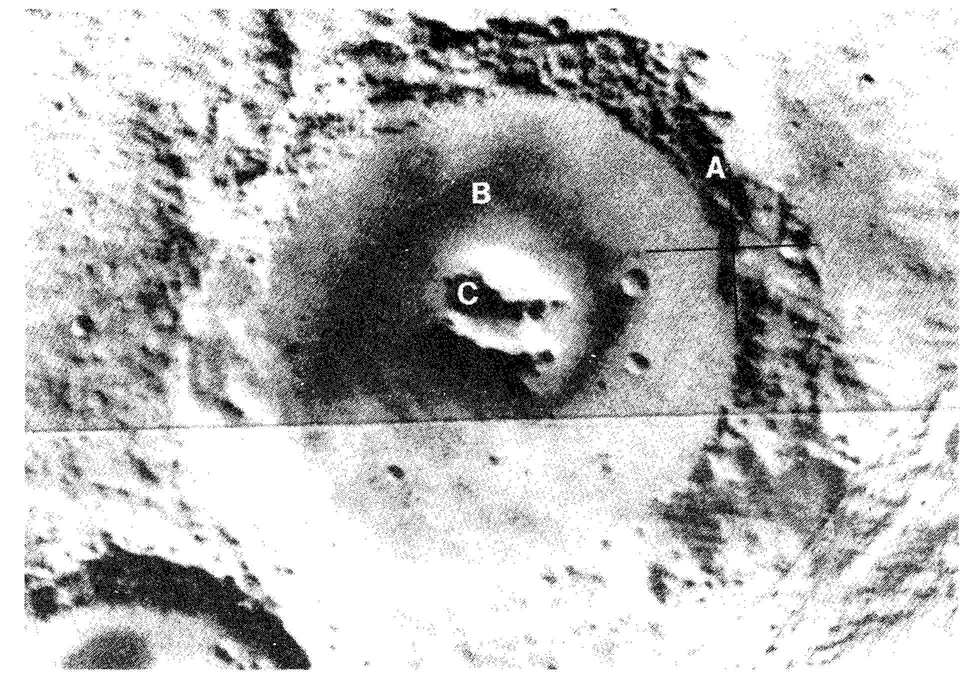
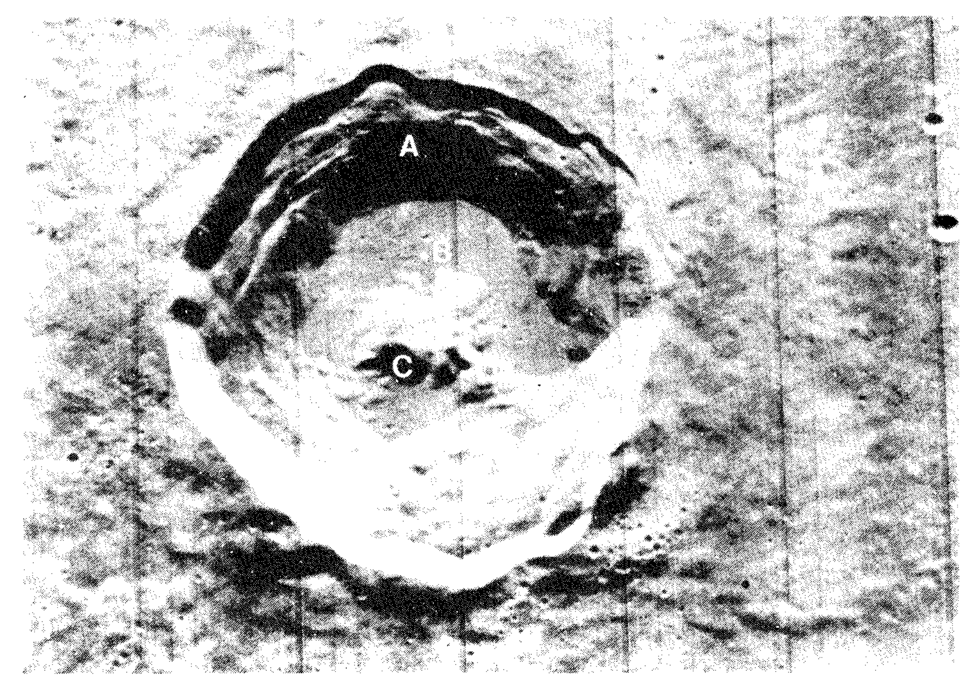


Figure 9. The Calvin 28 cryptoexplosive disturbance compared with stratigraphic uplift/diameter relationships for terrestrial impact structures (modified from Grieve and others, 1981).



Viking Orbiter image of the crater Martz; 34°S, 217°W; Eridania north-central quadrangle of Mars (U.S.G.S., 1987).



Lunar Orbiter image of the crater Bërg; 45°N, 28°E; northeast region of the Moon (Schultz, 1976).

A. Rim B. Annular Depression C. Central Uplift

Figure 10. Photographs illustrating structural similarities between impact craters on other planets and the Calvin 28 cryptoexplosive disturbance.

clusters display some preferential orientation. Milton and Roddy (1972) and Head (1978) suggest the formation of central peaks is in response to high stresses associated with shock and rarefaction waves concentrated below the impact point during the cratering event.

Though two possible mechanisms have been proposed, the origin of linear peak morphology is unclear. Schultz (1976) and Gault and Wedekind (1978) attribute linear peak morphology to impact angle, while Hale (1980) interprets linear peaks as a result of some type of discrete structural control by the target. Hale's study of 200 lunar central peak structures suggests preexisting regional structural trends act as stress concentrators or barriers to shock wave propagation, controlling the final geometry of the central peak and directing them in a preferred elongation. If regional structural features trend in a specific direction, the central peaks prefer the same direction.

By applying Hale's technique to the central uplift of the Calvin 28 structure, it appears the feature aligns roughly N17°E. This would be consistent with the north-northeast structural trends noted in the southwest portion of the Michigan Basin, and also with the nearest major deep seated regional feature, the Royal Center Fault System, which appears to trend roughly N20°E (DeHaas, oral communication, 1985).

Described earlier (pp. 11 – 17), the central uplift and peripheral anticline of the Calvin 28 structure exhibit a repetition of beds indicative of some form of horizontal stress. While this type of movement is not consistent with structural patterns associated with volcanic activity, horizontal movement associated with upthrusting and telescoping of beds, is characteristic of impact craters (Offield and Pohn, 1979).

Structural comparisons between Calvin 28 and accepted cryptoexplosives/astroblemes and impact craters suggest Calvin 28 is a complex crater form resulting from a hypervelocity impact. While this conclusion could be reached based on the substantial amount of interpretive data available, the identification of definite impact-signature characteristics, such as shock-metamorphic features or chemical anomalies, would be necessary to substantiate an exogenetic model of the structure.

Summary

In comparing endogenetic structures to the Calvin 28 feature, no significant evidence exists to suggest that volcanic eruption, igneous intrusion, solution subsidence or a diapiric mass of sedimentary material is responsible for the structure's origin. No igneous material occurs in association with the structure. If igneous material had been present at the structure, even in small amounts, it would be difficult to explain its absence by weathering processes. Diapirism is ruled out by a stratigraphic configuration that would not allow the significant density inversion necessary for flowage. The structural pattern of Calvin 28 and lack of soluble strata below the structure rule out the possibility of solution subsidence.

While French (1968a) and McCall (1979) dispute an endogenetic origin for most cryptoexplosive structures, the possibility exists that a yet unidentified endogenetic process may have formed Calvin 28. It is unlikely though that such an event could generate the tremendous energy required to form Calvin 28, without the presence of magma.

Seven characteristics of the feature in particular strongly favor origin by impact:

1. The Calvin 28 structure is circular, with a central uplift, surrounding annular depression and a peripheral anticline.
2. Terrestrial surface impact structures with central uplifts (complex craters) exhibit a recognized relationship between stratigraphic displacement in the uplift and the final crater form (Grieve and others, 1981). The subsurface Calvin 28 structure exhibits this relationship.
3. The waning of structural deformation beneath Calvin 28 is shown by seismic profiles and dipmeter readings from deep test wells. The lessening of derangement with depth would not be expected from a tectonic or volcanic origin, but would be consistent for structural deformation incurred from a downward projected shock envelope (Shoemaker, 1960; Lindsay, 1976).
4. No igneous material has been recovered from core samples or identified in petrographic studies involving the structure.
5. Calvin 28 is an isolated structure involving intense, large-scale deformation in otherwise flat-lying strata.
6. The presence of a microbreccia consisting of fractured and unfractured floating quartz grains in a carbonate matrix is similar to microbreccia associated with impact craters in sedimentary targets (Short and Bunch, 1968).
7. The energy required to produce the 7.24 km diameter structure, the apparent structural relief, the missing strata and the intense structural deformation is at least 1 X 10^{26} ergs. While this value exceeds energy estimates for known singular explosive endogenetic events, it would be considered a conservative value for energy released by a hypervelocity impact (Shoemaker and Wolfe, 1982).

These seven characteristics would account for all major features listed earlier in this chapter and considered essential in the evaluation of Calvin 28's origin. The structural parallels evident between Calvin 28 and identified Midwestern cryptoexplosives/astroblemes, terrestrial and extraterrestrial impact craters, in combination with energy considerations necessary for the structure's formation, would be consistent with what would be expected from a hypervelocity impact in a sedimentary target.

CONCLUSION

Comparison of the Calvin 28 cryptoexplosive disturbance with known endogenetic structures has shown a notable lack of analogs. A yet unidentified endogenetic mechanism may be responsible for the origin of Calvin 28, but the available evidence makes this unlikely. Comparison of Calvin 28 to known or suspected structures of exogenetic origin suggest consistent structural and physical analogs. While a considerable body of interpretive data favors an exogenetic origin for the structure, specific physical data indicative of impact cratering events is not available.

Based on the arguments presented in this study it is concluded that the Calvin 28 cryptoexplosive disturbance is the result of a near surface, high-energy event, and that the event can best be attributed to hypervelocity impact.

APPENDIX

EXPLORATION HISTORY

Hydrocarbon production associated with the Calvin 28 cryptoexplosive structure was initiated by the successful completion of the Veron E. East, Charlston #1 in September of 1978. The Charlston #1, SE-NE-SE, sec. 31, T7S, R14W, the discovery well of the Juno Lake oil field, carried an initial production rate of 15 barrels of oil per day at 36 A.P.I. gravity from the Middle Devonian Traverse Limestone.

While attempting to expand the limits of Juno Lake and to test what seismic coverage revealed as a pronounced subsurface anomaly east of section 31, drilling commenced in section 28 of Calvin Township. In September of 1980, Vernon E. East successfully completed the Burns #1, NE-NE-SE, sec. 28, T7S, R14W. The Burns #1 initially produced 70 barrels of oil per day with an A.P.I. gravity of 21.3 from the Traverse Limestone. This well was designated by the Michigan Geological Survey as a new oil field discovery and established the Calvin 28 oil field.

The success of the Juno Lake and Calvin 28 oil fields stimulated interest in the nature of the structure associated with their production. Prompted by the drilling to stratigraphically deep Ordovician targets in the northern portion of Michigan's Southern Peninsula, several deeper pool tests were drilled into the structure. Though the deep tests supplied a large quantity of data about the nature of the structural anomaly, they failed to establish additional producing horizons.

While continuing to extend the boundary of the two Middle Devonian fields, the Fayette Drilling Co. successfully completed the George Smith #1-20, NE-SE-NW, sec. 20, T7S, R14W, in October of 1982. Initial production from the Traverse Limestone was estimated at 165 barrels of oil per day with a 26 A.P.I. gravity. The Smith #1-20 was classified as the discovery well of the Calvin 20 oil field.

By November of 1983 Calvin 28 field had become the most extensively drilled and largest hydrocarbon producer of the three fields. During that month Michigan Petroleum Geologists, Inc., acting for the Mannes Oil Co., requested a hearing before the Supervisor of Wells and the Michigan Oil and Gas Advisory Board to change the spacing pattern previously established for drilling in the Calvin 28 oil field.

The field had originally been developed on 40 acre drilling units with each well situated in the NE 1/4 of the unit. The extent of the Calvin 28 Traverse Limestone Pool had been well defined by drilling. The gas/oil and oil/water limits of the field had been determined and experience suggested the best development of the field would take place by drilling between the 45 and 54 m Traverse Limestone contours of the structure. In addition, the field produces low gravity oil, an average of 19.2 A.P.I., and has very poor permeability. The gas produced from the field is not marketable and all gas production from oil wells is used by production facilities. To maximize oil production and minimize water and gas production, the petitioners felt a spacing pattern of 20 acre units was necessary and desirable.

In February of 1984 the Supervisor of Wells issued Order 1-1-84 granting the drilling of two producing wells per 40 acre drilling unit, provided the wells were located no closer than 100.58m (330 ft) from a unit boundary and no closer than 182.88m (600 ft) from another well.

By December of 1986 a total of 107 wells had been drilled into the three oil fields associated with the Calvin 28 cryptoexplosive structure. Of these, 72 were producing oil wells, 5 were nonproducing gas wells and 30 completed as dry holes. Since the initial discovery date of the Juno Lake oil field in September of 1978, through December of 1986, 417,566 barrels of crude oil and 537,990 barrels of brine have been extracted from the three associated fields. At this date, all production is limited to the Traverse Limestone, with the exception of the Fayette Drilling Co., Boulanger #1-19, NE-SE-SE, sec. 19, T.7S., R.14W., producing from the Middle Devonian Sylvania Sandstone. As of December 1986, total Sylvania production totaled 920 barrels of crude oil and no brine production.

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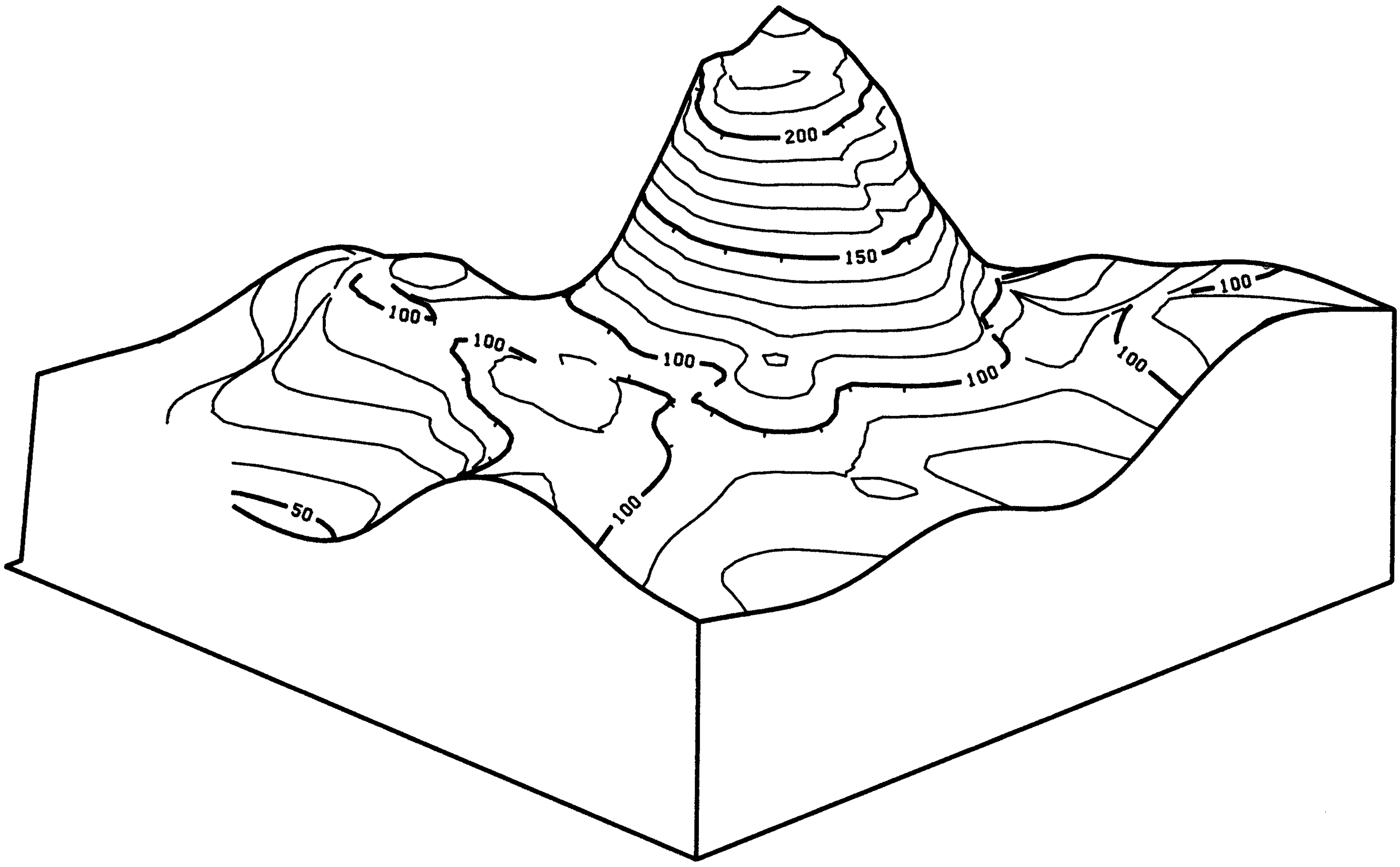

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