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A Seismic Study of an Impact Feature in Cass County, Michigan

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A SEISMIC STUDY OF AN IMPACT FEATURE
IN CASS COUNTY, MICHIGAN

by

Mancheol Suh

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Geology

Western Michigan University
Kalamazoo, Michigan
August 1985
A geophysical investigation, including a seismic study, of the subsurface structure of the Calvin-28 oil field, Cass County, Michigan, indicates that the structure's origin may be related to an impact event. The structural closures in the time structure maps and drilling results both show a central uplift. The fault system in the Trempealeau Formation shows a structure similar to other proven astroblemes. Undisturbed layers just beneath the central uplift also provide evidence of an impact structure. The result of mathematical modeling of the central uplift under the assumption that the structure is an impact structure corresponds well with the drilling results. Therefore it may reasonable to accept the impact origin for the Cass County structure.

The impact event occurred on the Utica shale of the Late Ordovician age. The diameter of the original crater was at least 2 kilometers. The mass of the meteorite was about $9 \times 10^4$ tons.
ACKNOWLEDGEMENTS

The author appreciates Dr. Gerry Clarkson of Western Michigan University for his suggestions and support during this research. He is also deeply grateful to Dr. W. Thomas Straw and Dr. William Harrison of Western Michigan University for their critiques of the manuscript during its preparation.

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Further thanks are extended to the Department of Geology of Western Michigan University for providing the GEOPRO 8012A seismograph, to the Academic Computer Center of Western Michigan University for providing computer time and to The Graduate College of Western Michigan University for funding the research.
Finally, he also would like to express his deepest appreciation and thanks to his wife Kyong-sook for her help in drawing the figures and taking good care of him and his daughter Jee-Eun.

Mancheol Suh
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CHAPTER I

INTRODUCTION

Objective

Since the 1930 discovery of a two-well Traverse Limestone field in Cass County, Calvin Township has emerged as a major oil field in southwestern Michigan. The Calvin - 28 oil field, located in sections 27, 28, 29, 32, 33, and 34, T14W, R7S of Cass County, Michigan (Fig. 1), has a circular production pattern with a diameter of 1.5 miles. This circular production pattern is very unusual when compared with typical oil fields. This unusual feature has led to research such as gravity and magnetic surveys and deep drilling in the center and on the edge of the circular producing area.

About 1200 feet of the Late Ordovician sedimentary rock are missing in the Hawkes-Adams 1-28 deep well located near the center of the producing area. However, in the Lawson 1-28 deep well, located 0.75 miles northeast of the Hawkes Adams 1-28, a complete Ordovician section is present. The sequence from the Utica shale to the St. Peter Sandstone was not penetrated in the Hawkes Adams
1-28 deep well and the Trempealeau Formation was at least 1000 feet structurally higher in comparison with that in the Lawson 1-28 well. Therefore, the Calvin township oil field has been considered to be similar to cryptoexplosive structures, which is a non-committal term about its origin. Similar features have been found in several identified astroblemes such as the Kentland structure in Indiana (Gutschick, 1976), Jeptha Knob (Seeger, 1960) and the Versailles structure (Seeger, 1972) in Kentucky, the Glasford structure in Illinois (Buschbach and Ryan, 1963), and the Serpent Mound structure in Ohio (Bucher, 1968).

The debate concerning whether cryptoexplosive structures are of terrestrial origin or extraterrestrial origin began about one half century ago. In general, features identified as being cryptoexplosive structures are roughly circular structures, with a ring depression surrounding a central uplift of disordered and brecciated rocks (Wilshire and Howard, 1968). Several origins, such as cryptovolcanic, meteorite impact, faulting, and diapirism, have been suggested to explain this type of structure. The gross structure, as well as the common occurrence of shatter cones and unusual mineral deformation, indicates an origin by explosive release of energy, either from impact or from volcanic gas (Wilshire...
and Howard, 1968).

In Cass County it is difficult to even identify the cryptoexplosive structure itself, as it is covered by thick Silurian and Devonian formations and about 300 feet of glacial drift. Therefore, geophysical methods combined with drilling data are the only way to study the structure.

The main purpose of this thesis is to outline the basic parameters which identify the subsurface geological structure of the Calvin - 28 oil field as a fossil crater using pertinent maps, cross sections, previous gravity and magnetic results, and seismic record sections.

**Location**

The area under investigation includes sections 14 through 35 of Calvin Township and sections 2 through 11 of Mason Township (Fig. 2). The study area is about 5.5 miles by 5 miles and it is covered by the Adamsville Quadrangle, 7.5 minute series, Michigan-Indiana (USGS Maps).
Approach

A geophysical study of the subsurface structure and its origin was made using results from drilling, gravity and magnetic, and seismic data. Most of the seismic data used in this study were obtained from Mannes Oil Company, Holland, MI and were processed by Hosking Geophysical Company, Mt. Pleasant, MI. The interpretation of these data is solely that of the author. For the area where seismic sections were lacking, a seismic exploration program was conducted using a GEOPRO 8012A 12 channel seismograph. These data were used to outline the Cass County structure and its origin.
Fig. 1. Location map of the study area.

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CHAPTER II

GEOLOGY

The Calvin - 28 oil field is located in Calvin Township of Cass County, in southwestern Michigan just north of the Indiana border. Geologically, it is located in the southwestern flank of the Michigan Basin and has been assigned to the central basement province which consists of granite, felsic and mafic gneisses, extrusives, and metasediments (Fig. 3). Depth determination to the basement rock carried out by Kellogg (1971) on the basis of aeromagnetic data show that the average elevation of the Precambrian surface in Cass County ranges from 3495 feet to 3740 feet below sea level. The nearest basement drilling in section 10, Berrien County showed Precambrian metasediments at 3800 feet below sea level.

The surface geology of this area consists mostly of the Quaternary glacial drift which has an average thickness of about 300 feet. Bed rock is the Antrim shale or the Ellsworth shale of early Mississippian age (Table 1). The Calvin - 28 field produces gas and oil from Middle Devonian Traverse limestone.

The investigated area has a subsurface geology consisting of Precambrian basement, a complex sequence of
Fig. 3. Basement province map of the Southern peninsula of Michigan (Kellogg, 1971).
Table 1

Stratigraphic succession of the study area.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Age</th>
</tr>
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<tbody>
<tr>
<td>GLACIAL DRIFT</td>
<td>PLEISTOCENE</td>
</tr>
<tr>
<td>COLDWATER SHALE</td>
<td>MISSISSIPPIAN</td>
</tr>
<tr>
<td>ANTRIM SHALE</td>
<td></td>
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<tr>
<td>TRAVERSE FORMATION</td>
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<tr>
<td>TRAVERSE LIMESTONE</td>
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<tr>
<td>DETROIT</td>
<td></td>
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<td>SYLVANIA</td>
<td></td>
</tr>
<tr>
<td>C UNIT</td>
<td></td>
</tr>
<tr>
<td>NIAGARAN SERIES</td>
<td></td>
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<tr>
<td>CLINTON</td>
<td></td>
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<tr>
<td>CABOT HEAD SHALE</td>
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<td>MANITOULIN DOLOMITE</td>
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<tr>
<td>CINCINNATIAN SERIES</td>
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<tr>
<td>UTICA SHALE</td>
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<tr>
<td>TRENTON FORMATION</td>
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<td>BLACK RIVER GROUP</td>
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<td>GLENWOOD SHALE</td>
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<td>ST. PETER SANDSTONE</td>
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<td>PRAIRE DU CHIEN</td>
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<tr>
<td>TREMPEALEAU FORMATION</td>
<td></td>
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<tr>
<td>FRANCONIA SANDSTONE</td>
<td></td>
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<tr>
<td>DRESBACH SANDSTONE</td>
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<tr>
<td>EAU CLAIRE</td>
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<tr>
<td>MT. SIMON</td>
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Paleozoic sedimentary rocks, and Quaternary glacial drift (Table 1). The Paleozoic sequence overlying the Precambrian basement consists of the Mt. Simon Sandstone, Eau Claire, Dresbach, Franconian and Trempealeau Formations of Cambrian age; the Prairie du Chien Group, St. Peter Sandstone, Black River Group, Trenton Group and Cincinnatian series of Ordovician age; the Cataract Group and Clinton Formation, Niagrian Series, Salina Series and Bass Island Groups of Silurian age; and the Sylvania Sandstone, Detroit River Group, Dundee Limestone, Traverse Limestone and Traverse Formation of Devonian age. The Antrim Shale and Ellsworth Shales of Early Mississippian age directly underlie the Quaternary glacial drift (Table 1).

Structurally, the area is cut by several reverse faults with a NNW-SSE orientation below the glacial drift and a dramatic upward displacement in the Ordovician formations. Ordovician rocks from the St. Peter Sandstone to the Utica shale are missing in the Hawkes-Adams 1-28 deep well.
CHAPTER III

GEOPHYSICAL EXPLORATION

Gravity and Magnetic Survey

A gravity and magnetic survey was carried out over portions of the Penn, Porter, Jefferson, Mason, and Ontawa Townships in Cass County of southwestern Michigan (Fig. 1) by Ghatge (1984). The Bouguer gravity anomalies were analyzed using double Fourier series to obtain residual gravity values of the area.

The Bouguer gravity anomaly for south-central Cass County (Fig. 4) shows mainly a regional source. It does not show any local anomalous closures. The contours of anomalies show a roughly semi-circular feature for the entire survey area. The magnitude of the Bouguer anomaly ranges from -21 milligals at the north part of the area to -31 milligals at the south center. The second harmonic residual anomaly map with wavelength of 28 miles (Fig. 5) shows a positive anomaly of 0.75 milligal around the Calvin - 28 oil field.
Fig. 4. Bouguer gravity anomaly map of the South-central Cass County (Ghatge, 1984).
Fig. 5. Second harmonic residual gravity map of the South-central Cass County (Ghatge, 1984).
Seismic Survey

Field Procedure

A seismic exploration program including both refraction and reflection surveys was conducted using a GEOPRO 8012A 12 channel seismograph. At first, a 10-lb sledge hammer and 10-gauge blank shells were compared to determine which source was better in the research area. Seismic waves were recorded with each three shots of both the 10-lb sledge hammer and the ten gauge blank shells using a band pass filter of 75-440 Hz. The assignment of gain numbers for each seismic trace was exactly same for both energy sources. Figure 6 shows the sledge hammer to be a better energy source than the ten gauge blank shells for this area. This may result from the difference in the amount of energy transferred into the ground. In hammer blows, most of the energy is transferred into the ground through the steel plate, while in shot gun blows, much of the energy may be absorbed by the air and soft soil.

For the refraction survey, the geophone spread was offset from the shotpoint location by distances of 20 feet, 260 feet, and 500 feet while the shot point remained at the same location. This gave refraction data over distances of 20 - 720 feet. But the last geophone array
in which the offset was 500 feet, gave poor data because the arrival energy was too weak. For this problem, some energy source larger than the hammer is recommended. Four or five hammer blows were stacked for each shot to enhance the seismic data. A reverse shot was also done using the same method.

For the reflection survey, the geophone spread was 220 feet long with 12 geophones spaced at 20 foot intervals. This geophone array was shot with five or six stacked hammer blows at a distance of 100 feet from the first geophone. The spread was then moved to the next position in the seismic line. The geophones were buried in the ground to reduce severe noise. A 10-lb sledge hammer was used as the energy source. Several band pass filters such as 35 BE (BESSEL) - 200 BE, 75 BE - 440 BE, and 70 BU (BUTTERWORTH) - 1000 BU were tested to see which gave the best seismic data. With the 35 BE - 200 BE band pass filter there seemed to be much low frequency noise and ground roll. With some field experiments, it was found that a low pass filter of 440 Hz and a high pass filter of 75 Hz gave the best seismic data in the area.

Data Processing

In the refraction data interpretation, layer velocities and intercept times were determined from a T-X plot. The thickness of each layer was determined using
Fig. 6. Comparison of the energy sources; (a) Seismic wave with 10-gauge blank shell; (b) Seismic wave with hammer blow. All the other conditions are the same.
the calculated intercept time and velocity with the equation

$$T_{in-1} = 2 \left( \frac{Z_m}{V_m} \right) \left[ 1 - \left( \frac{V_m}{V_n} \right)^2 \right]^{1/2}$$ ---(1)

(Telford, Geldart, Sheriff, and Keys). With the refraction study for the geophone spread S-2-1 (Fig. 2) three horizontal near surface layers were detected with velocities and thicknesses of 1250 ft/sec, 2500 ft/sec, 5000 ft/sec and 20 feet, 60 feet respectively. The first layer appears to be a weathered zone above the water table, the second a saturated weathered zone and the third unweathered glacial fill. These results were used for weathering and elevation corrections of the reflection data.

The Traverse Limestone reflection was picked using the anticipated reflection time which was calculated using sonic logging data compiled by Mannes Oil Company, Holland, MI and drilling data stored at the Department of Natural Resources, Plainwell, MI. The picked times were static corrected using a datum level of 800 feet A.S.L. The weathering correction value ($T_w$) and the elevation correction value ($T_e$) were calculated using the following two equations:

$$T_w = \left( \frac{1}{V_1} \right) (Z_{s1} + Z_{g1}) + \left( \frac{1}{V_2} \right) (Z_{s2} + Z_{g2})$$ ---- (2)

$$T_e = \left[ E_s + E_g - (Z_{s1} + Z_{s2} + Z_{g1} + Z_{g2}) - 2D \right] / V_3$$ ---- (3)
where, \( V_1 \); the velocity of the unsaturated weathered zone

\( V_2 \); the velocity of saturated weathered layer

\( V_3 \); the velocity of glacial fill

\( E_s \); the elevation of the shot point

\( E_g \); the elevation of each geophone location

\( Z_{s1} \); the thickness of the unsaturated weathered layer at shot point

\( Z_{s2} \); the thickness of the saturated weathered layer at shot point

\( Z_{g1} \); the thickness of the unsaturated weathered layer at each geophone place

\( Z_{g2} \); the thickness of the saturated weathered layer at each geophone place

\( D \); datum level

Both correction values were subtracted from the picked reflection time and the corrected reflection time was used to make a \( T^2 - X^2 \) graph (Fig. 7).

From the \( T^2 - X^2 \) graph of seismic lines S-1 and S-2 (Fig. 7), two-way reflection times at the shot point from the top of Traverse Limestone were calculated using the equation

\[
T^2 = T_0^2 + \frac{1}{V_{rms}^2} \times X^2 \quad (4)
\]

where, \( T \); the reflection time at the distance \( X \)
$T_0$; the reflection time at the shot point

$X$; a distance between shot point and the 

first geophone

$V_{\text{rms}}$; the root mean square velocity

(Telford et al., 1976).

Then the reflection time at each shot point was 

plotted on the time structure map of the Traverse 

Limestone.

As the amplitude of the arrival wave was too small 

around the anticipated reflection time, no reflection 

event from the top of the Trempealeau Formation could be 

found. This may be due to the great depth to the top of 

the Trempealeau Formation and a strong absorption of the 

seismic energy.

For the seismic lines HAL-81-1, HAL-81-2, HAL-81-7, 

HAL-82-8, HAL-82-9, HAL-82-10, and MRH-82-1 (Fig. 2), the 

data were recorded for nine seconds using the DFS V type 

48 channel seismograph with a Vibroseis for energy source 

and a band pass filter of 18 - 128 Hz. The geophone group 

interval was 110 feet and the offset of the geophone 

spread was 220 feet. Data processing included a static 

correction using a datum of 800 feet A.S.L. and 

correction velocity of 5000 ft/sec, normal moveout 

correction, deconvolution, and automatic statics by 

Hosking Geophysical Company, Mt. Pleasant, MI. Then, the
corrected data were stacked from 12 fold to 24 fold and the stacked data for the time interval 0-2 seconds were printed. The printed seismic sections with their interpretations are shown in plates 1 - 7. Using these seismic sections the reflection times for the Traverse Limestone and the Trempealeau Formation were picked along each seismic line. Faults were also identified from these seismic sections.

Fig. 7. $T^2 - X^2$ graph of the seismic lines S-1 and S-2.
Data Plotting

The two way reflection times from the Traverse Limestone and the Trempealeau Formation at given locations were plotted on the California Computer Products (CALCOMP) 906 Drum Plotter using the FORTRAN program NEWMAP.FOR written by Mr. Kent E. Meisel, Department of Geology, Western Michigan University.
CHAPTER IV

GENERAL ASPECTS OF AN IMPACT SITE

Impact Sites

From modern studies of lunar craters, it seems that the major meteorite bombardment of the moon — and so of the earth — must have taken place three billion years or more ago, during the first half of the life span of the earth-moon system (Dietz, 1961). Since this time, the earth's tectonic and meteorological processes have obliterated the scars of this early bombardment, still so much in evidence on the moon.

The earth should retain a geological record of young impact events comparable to the youngest of the lunar craters, that is those lunar craters which have ray systems (Dietz, 1961). The near side of the moon displays about 130 impact sites of this kind in an area roughly equivalent to that of North America (Dietz, 1961). However there are only 36 impact sites that have been identified in North America according to Dietz (1961) and Sawatzky (1975) (Fig. 8). So, more impact sites can be expected to be found on the earth's surface or in the earth's crust.
Impact sites in the earth's crust have been classified as being of three types. The first, and the most obvious, type is impact sites with visible craters; the second is sites with well-preserved fossil craters; and the third type is sites in which only the deep radial fracture patterns from the crater remain. In the last type all other evidence has been removed by long exposure.
to the terrestrial environment. The origin of anomalous structures of the third type are likely to be very difficult to determine, particularly if subsequent structures such as a solution - collapse features are developed (Sawatzky, 1975). The highly altered impact structures found today belong to the third type of impact sites and are called astroblemes (Dietz, 1961).

As an astrobleme has few features characteristic of an impact site, it is not easy to determine its origin. In general, two features, shatter cones and coesite, have been recognized as indicators of the shock waves associated with an impact event. However it is not easy to find these features because the sites are so severely altered by various geological phenomena such as erosion, crustal movement, faulting, and folding.

A central uplift of the crater bottom is most characteristic of impact sites. The bottom of the crater is pushed up by isostatic processes. With a central uplift, some astroblemes that are scarcely discernible on the ground, can appear as a faint circular features in aerial photographs and in the geological maps of surface or subsurface formations. In many cases, older formations outcrop in the center of the circular feature and are encircled by younger formations. In the Versailles
astrobleme, the oldest formation (undifferentiated Cynthiana Formation and Lexington Limestone of middle Ordovician age) in the area exists in the center of the structure (Seeger, 1972). In the Hartney structure (Manitoba, Canada), granitic basement rock is located in the center of the structure (Sawatzky, 1975). In the Kentland structure, there is a large central uplift of about 2000 - 3000 feet and the uplifted part consists of Ordovician and Silurian formations while the surrounding area is consists of Devonian rocks (Gutschick, 1976). In the Sierra Madera structure, there is an outcrop of Permian rocks in the central uplift zone while Cretaceous rocks are present outside the central uplift area. This type of structure is explained easily by Sawatzky's (1975) model of the evolution of a fossil crater with the process of central uplift (Fig. 9).
Fig. 9. Evolution of a fossil crater (Sawatzky, 1975).
Geophysical Characteristics of Astroblemes

Frequently gravity studies of impact sites show a circular negative Bouguer anomaly approximately centered on the impact point. This centrosymmetrical negative gravity anomaly may be due to a density deficiency between the country rock and the rock debris which was produced by the impact event and by later sedimentation. If a central uplift is present, a central positive gravity anomaly with a surrounding negative anomaly generally exists.

A circular negative anomaly has been reported in most cases of identified astroblemes such as Lake Wanapitei of Canada (-15 mgal), Nicholson lake of Canada (-7.5 mgal), Deep Bay Crater of Canada (-20 mgal), Gosses Bluff of Australia (-50 mgal), and the Ries structure of Germany (-18 mgal) (Ghatge, 1984). In the Kentland structure of northwestern Indiana, there is a positive anomaly of 3.5 - 4.0 milligals which indicates that a central uplift is present (Gutschick, 1976). For the other astroblemes such as the Brent, Holleford, Clearwater Lake, and Carswell structures of Canada, Steinheim Basin of Germany, and Popigay Crater of U.S.S.R., circular negative anomalies of unknown magnitude were reported (Ghatge, 1984).

Some results of magnetic surveys show small variations in intensity over the central portion of the impact structure in a few astroblemes such as the Deep Bay
crater (+100 gammas), the Gosses Bluff structure of Australia (-75 gammas), the Ries structure of Germany (-100 gammas), and the Steinheim Basin of Germany (+2 gammas). However, the results of magnetic surveys are generally not as conspicuous as those of gravitational surveys.

Mathematical Consideration of Meteorites

From an analytical investigation of the quantitative aspects of a crater formation by Innes (1960), it is possible to estimate the volume of brecciated country rock in a meteorite crater. Assuming that both the crater floor and the lower boundary of the breccia zone have the shape of a paraboloid of revolution, it is possible to derive equations which permit predictions of the volumes associated with crater formation. The total volume of the country rock ruptured by the exploding meteorite can be expressed as a function of the crater diameter as follows;

\[ V = \frac{\pi}{24} \times D^3 \quad --- \quad (5) \]

(Innes, 1961). The total volume of the ruptured rock increases simply as the cube of the crater diameter. This relationship was confirmed by gravitational exploration conducted by Innes (1961).

Thus it is possible to estimate with some confidence the minimum energies required for crater formation by
direct calculation of the amount of work required to crush the rock. From the results of controlled underground nuclear experiments, the energy consumed in crushing was estimated to be about 47% of the total energy released, equivalent to about $6.4 \times 10^7 \text{erg/g}$ (Johnson et al., in Innes, 1961). This value, combined with the volume of fragmented rock as estimated from the equation (5), should provide an estimate of the minimum energies required to form a crater. This relation leads to the following general equation for the energy consumed in brecciation during the cratering process;

$$E_{\text{crushing}} = 2.39 \times 10^{11} \times D^3 \rho_C \text{ ergs} \quad (6)$$

for the diameter ($D$) given in feet, or

$$E_{\text{crushing}} = 8.40 \times 10^{12} \times D^3 \rho_C \text{ ergs} \quad (7)$$

for the crater diameter ($D$) given in meters (Innes, 1961), where $\rho_C$ is the mean density of the country rock.

The solid curve in Fig. 10 illustrates equation (6) for the general case, assuming a crustal density of 2.67 g/cm$^3$. The crushing energies estimated for six North American craters of probable meteoric origin are listed in column 5 of table 2 (Innes, 1961). In a large crater, there are some differences between the crushing energy from equation (6) (solid line, Fig. 10) and that from the gravity data (dashed line, Fig. 10). But for the craters
less than 8000 feet in diameter, the two results agree well. Continued geophysical and structural studies with drilling programs will provide important information about the effects of impact events for the higher energy ranges.

The estimates of total energy are based on the assumption that the proportions of the total available energy that go into heating, crushing, fracturing, and elastic effects in meteorite crater explosions are the same as in underground nuclear explosions and are given by

$$E_{\text{meteorite}} = 5.08 \times 10^{11} D^2 \text{ ergs}$$

for the diameter (D) given in feet (Innes, 1961). The corresponding meteorite mass can be estimated using the equation $E_k = \frac{1}{2} MV^2$ and the impact velocity of 20 km/sec (Innes, 1961) along with the equation (8). The total energy and corresponding mass of six meteorites are shown in Table 2. If the meteorite is spherical, then such meteorites would have diameters that are 1/40 or 1/56 of the diameter of their resulting craters, depending on whether the meteorites are of stone or of iron (Innes, 1961).
Fig. 10. Relationship between meteorite energy and crater diameter (after Innes, 1961).
Table 2

The energies and masses of six North America meteorite craters (Innes, 1961).

<table>
<thead>
<tr>
<th>Crater</th>
<th>Diameter ft</th>
<th>c g/cm</th>
<th>Total Mass ruptured, gr</th>
<th>Crushing Energy, ergs</th>
<th>Meteorite Energy Mt</th>
<th>Meteorite mass, Tons V=20 km/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odessa</td>
<td>550</td>
<td>2.6</td>
<td>1.60x10^12</td>
<td>1.03x10^20</td>
<td>2.19x10^20</td>
<td>5x10^-3</td>
</tr>
<tr>
<td>Barringer</td>
<td>4150</td>
<td>2.6</td>
<td>6.89x10^14</td>
<td>4.44x10^22</td>
<td>9.44x10^22</td>
<td>2.3</td>
</tr>
<tr>
<td>Holleford</td>
<td>7709</td>
<td>2.79</td>
<td>4.74x10^15</td>
<td>3.05x10^23</td>
<td>6.49x10^23</td>
<td>16</td>
</tr>
<tr>
<td>New Quebec</td>
<td>11290</td>
<td>2.67</td>
<td>1.42x10^16</td>
<td>9.14x10^23</td>
<td>1.95x10^24</td>
<td>47</td>
</tr>
<tr>
<td>Brent</td>
<td>11500</td>
<td>2.67</td>
<td>1.50x10^16</td>
<td>9.68x10^23</td>
<td>2.08x10^24</td>
<td>50</td>
</tr>
<tr>
<td>Deep Bay</td>
<td>40000</td>
<td>2.67</td>
<td>6.34x10^17</td>
<td>4.06x10^25</td>
<td>8.69x10^25</td>
<td>210</td>
</tr>
</tbody>
</table>

Note: Energy values in parentheses (col. 5) are based on gravity analyses.

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CHAPTER V

INTERPRETATION

Geological Results

Many wells have been drilled in the Calvin - 28 oil field, but most of them are shallow wells for oil production, and are not useful for studying the deeper subsurface geological structure of the area. Six holes drilled along the periphery of the production area and one deep hole at the center of the field were selected to determine the subsurface geological structure of this area (Fig. 2). An 8th well (William Gemberling 1), which is located 2.5 miles southeast of the Well 7, was selected as a reference point.

In the well descriptions of the Calvin - 28 oil field there is no evidence of an impact event such as shatter cones and coesite. Even if a crater is due to an impact event, however, it is difficult to find these features after central uplift and later erosion. Moreover, no circular feature is apparent in the surface geology because of later deposition and the thick glacial drift. Because post Ordovician sedimentary rocks and glacial drift mask the structure it is impossible to define the whole structure without geophysical methods. However
information from wells drilled for oil reveal some aspects of this structure.

Three wells (Wells 4, 5, and 8 in Fig. 2) reveal rough aspects of the geological structure in the Paleozoic rocks of the area and the five remaining wells define the circular area of oil production (Fig. 11). The data indicate a domal structure whose apex is centered on Well 4. The Traverse Limestone lies only 700 to 800 feet below the surface and the resulting feature is a roughly circular anticline about 2 miles in diameter (Fig. 12). Structural closure is at least 100 feet above regional and represents the greatest structural relief in the Cass County area. This kind of structure appears to have been caused by uplift during Late Ordovician time.

The entire Paleozoic section has been uplifted at Well 4 in comparison to Well 5 and Well 8. The Ordovician units from the St. Peter Sandstone to the Utica shale are absent in Well 4. This section (St. Peter Sandstone to Utica Shale) has apparently been faulted out, and the Trempealeau Formation is structurally higher by about 1000 feet. In contrast, rocks above the Utica Shale are only about 100 feet higher than regional. It seems likely that faulting occurred during deposition of the Utica Shale. The upthrown block was elevated into and above the surf zone of the Late Ordovician sea and was subsequently eroded. Erosion removed rocks from the top of the
Trempealeau Formation to the Utica Shale. This hypothesis is substantiated in part by the presence of a lens of white sandstone in the Utica Shale adjacent to the central uplift (Straw, Personal Communication, 1985). These facts seem to indicate some geological event such as an impact which caused an uplift in the Later Ordovician.
Fig. 11. Geologic cross section of the area
Fig. 12. Structure of the Traverse Limestone of the Calvin-28 oil field.
Gravity and Magnetic Results

According to the results of the gravity and magnetic surveys reported by Ghatge (1984), there is no gravity anomaly around the Calvin - 28 oil field in the Bouguer gravity map of the south-central Cass County, Michigan (Fig. 4). Nor did a magnetic survey show an anomaly in this area (Ghatge, 1984). A central positive anomaly representing the central uplift and linear trending features representing faults are present on the second harmonic residual gravity map with a fundamental wavelength of 28 miles (Fig. 5). However this positive anomaly closure is not associated with the anomalous Hawkes-Adams 1-28 deep test but is about 2 miles to the west of the well. Therefore, the interpretation of the genesis of the central uplift and the absence of the Ordovician sediments is inconclusive from the gravity and magnetic survey (Ghatge, 1984).

Most astroblemes that have a circular negative gravity anomaly are near-surface features or have not been deeply eroded. Structures like the Flynn Creek Crater in Tennessee do not have any gravity anomaly closures associated with them, even at the level of 1 milligal; this is similar to the Bouguer gravity map for the Cass County structure (Ghatge, 1984). Therefore, despite the
lack of evidence in the gravitational and magnetic studies, it is possible that the central uplift could be related to an impact event, especially if the site was deeply eroded after the impact event. A more detailed gravity survey might show a negative anomaly around the central uplift.

Seismic Results

Time Structure Map

Time structure maps of Traverse Limestone and Trempealeau Formation were made using an interval of ten milliseconds and were combined with some identified faults in each seismic section. As faults are present in this area, most contours were cut. Figure 13 shows that there is a main dome structure in the center of the investigated area as shown in the structure map of the Traverse Lime (Fig.12). The reflection time increases gradually from the center to the edge of the survey area in all directions. The reflection time ranges from 230 milliseconds at left middle part of the map to 190 milliseconds at the center.

The time-structure map of Trempealeau Formation also shows a dome structure in the center of the area. This structure appears to have a smaller area than that of
Traverse Limestone (Fig. 14). The contour lines appear to have a linearity in the east-west direction in the northern part of the area. The reflection time ranges from 460 milliseconds at the northern margin of the area to 350 milliseconds at the center of the circular structure (Fig. 14). The difference in reflection time for the Trempealeau Formation between the center of the circle and the background is larger than that for the Traverse Limestone. In fact, in the central uplift the Trempealeau Formation has been elevated about 1500 feet higher than regional whereas the Traverse Limestone is only about 100 feet higher (Fig. 11).

The difference in the size of the uplifted area between the time structure map of Traverse Limestone and that of Trempealeau Formation may come from the fact that Traverse Limestone was deposited after the large central uplift occurred and Trempealeau Formation was eroded. In this explanation, the Trempealeau Formation represents the section below the Late Ordovician unconformity and the Traverse Limestone represents the section above that unconformity.

The Trempealeau Formation is cut by more minor faults around the uplifted area than is the Traverse limestone (Fig. 13 and Fig. 14). Most of the minor faults near
the structural closures on the Trempealeau Formation are upthrown toward the center of the circle whereas they are dipping inward, thus they are reverse faults. This feature is predictable at the last stage of central uplift formation because the original formations move inward and upward on a shortened perimeter from their original flat-lying position (Wilshire and Howard, 1968). Several normal faults are present around the central closure and they also form a circular pattern that has a diameter of about 2 kilometers. It is common that several normal faults exist around the rim of an impact site which has a central uplift. So, the circular normal fault zone of this area appears to be a rim area of the original crater. Therefore, the central part is the horst and the surrounding part is the graben which is bounded by faults trending NNW-SSE, NW-SE, E-W, and NE-SW as indicated on the time structure map of Trempealeau Formation (Fig. 14). Such a horst-and-graben type structure has been observed in astroblemes such as the Wells Creek structure in Tennessee (Sterns et al., 1968).

Ghatge (1984) suggested two hypotheses to explain the cause of the central uplift and faulting, these are (1) the uplift may have been a result of isostatic adjustment with older faults being rejuvenated by the impact producing the horst-and-graben structure and the general
rectilinear fault-block pattern; and (2) the area could have been a focal point of regional stress with the presence of parallel left lateral strike-slip faults causing shearing within the central block. The second hypothesis can explain the general rectilinear fault blocks, but it can not explain the local circular structural closures as shown in time structure maps of Traverse Limestone and Trempealeau Formation. The different faulting system and the different amount of the central uplift in both formations also is not easily explained with the second hypothesis. The different faulting system between Trempealeau Formation and Traverse Limestone may mean that there was an abrupt event during the period between the deposition of these formations. The major faults running NW-SE could be a result of regional stress. However, the different fault systems, the structural closures and the different amounts of movement on the central uplift in the two formations can be explained well with the impact hypothesis.

Seismic Section along HAL-81-7

The seismic section along HAL-81-7 was selected to compare with Sawatzky's (1975) structural model because it goes through the center of the Calvin-28 structure. In this seismic section four layers, the Traverse Limestone and the Clinton, Glenwood, and Trempealeau
Fig. 13. Time structure map of the Traverse Limestone
Fig. 14. Time structure map of the Trempealeau Formation
formations are shown (Fig. 15). In general, the Traverse Limestone and Clinton Formation show very good continuity through the entire section and show a broad uplift centered around shot point 50. On the other hand, the Glenwood Formation and Trempealeau Formation show severe disturbance around shot point 50, and they are cut by several reverse faults. The Glenwood Formation does not exist around shot point 50 and the Trempealeau Formation shows much uplift. Therefore, the structure may be interpreted as a central uplift of the formations below the Cincinnatian Series with erosion prior to deposition of the Late Ordovician rocks.

Several horizontal layers are present beneath the uplifted section which indicates that there is no geological disturbance in these layers. This fact indicates that the origin that the local central uplift was generated from above, not from below and is further evidence for an impact event.

The seismic structure looks very similar to the last model of Figure 9. There is a severely disturbed central section, a surrounding synclinal depression, and a rim area in the seismic section. This structure is very similar to the generalized cross section of the Sierra Madera structure made by Wilshire and Howard (1968) using drilling data. From this seismic section and the general model of a fossil crater, the diameter of the original
crater can be determined. According to Sawatzky's model of a fossil crater, the point of discontinuity in the formation produced by an inward dipping normal fault at both sides of the central uplift could be regarded as a part of the rim of the fossil crater. This kind of discontinuity exists beneath shot points 27 and 68. Therefore, the diameter of the original crater may be at least 2 kilometers.

Mathematical Modeling of Isostatic Uplift

According to isostatic principles the pressure of the bottom of the ruptured zone should be the same as the pressure at the same depth outside the ruptured zone. Thus, since the ruptured rock has a lower density than the original country rock, isostatic uplift will tend to occur in the ruptured zone (Fig. 16). This relation can be expressed with the following equation

\[ X = \frac{D}{3} - \left( \frac{\rho_r}{\rho_c} \right) Z \quad \text{(9)} \]

where, \( X \); the amount of central uplift
\( D \); diameter of the original crater
\( \rho_c \); density of country rock
\( \rho_r \); density of ruptured rock
\( Z \); the thickness of ruptured zone at the center of the crater.

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Parameters such as the density contrast \((\rho_T/\rho_c)\) and the thickness of ruptured rock can be determined from the other craters which are similar to the Cass County structure but have no central uplift.

Fig. 16. A simple model for the calculation of the amount of central uplift.

Using equation (9), the anticipated amount of a central uplift at the Cass County structure can be calculated. The density contrast and the thickness of ruptured zone for the Cass County structure were estimated from the Holleford impact structure which has a diameter (7708 feet) similar to that of the Cass County structure. The density contrast and thickness of the ruptured zone are 0.77 and 0.24D respectively, Where D is the diameter of the original crater.
The calculated amount of central uplift for the Cass County structure is about 1000 feet. In fact, the Prairie Du Chien is about 1200 feet higher in Hawkes - Adams 1-28 than in well 8. Considering the isostatic uplift due to subsequent erosion after a uplift, the anticipated value of uplift calculated from the equation (9) is very reasonable. Thus the uplift in the Cass County structure can be explained by an impact event.

Consideration of the Meteorite

From the interpretation of the seismic data, the original crater diameter was at least 2000 meters. Using Baldwin's hypothesis that the depth of broken rock for a meteorite impact is very nearly equal to one third of the crater diameter (Baldwin in Innes, 1961) and the results of controlled underground nuclear experiments (Johnson et al in Innes, 1961), the minimum energy of a meteorite which makes a crater of diameter D in feet is expressed by equation (4). The corresponding meteorite mass can be estimated using the equation for kinetic energy, an impact velocity of 20 km/sec (Innes, 1961), and equation (4). As the impact is considered to have occurred on the upper part of the Utica shale, which has a density of 2.7 g/cm$^3$ (from density logs, Manes Oil Company, Unpublished), the total energy of the meteorite can be calculated to be about $1.8 \times 10^{23}$ ergs and with a mass of
9 \times 10^4 \text{ tons}. The diameter of the meteorite would have been about 36-50 meters depending on whether the meteorite was composed of iron or stone. By comparison with the data from six North American meteorite craters (Table 2), the original size of the meteorite and the Cass County crater seems to be slightly larger than the Barringer Crater of Arizona (Fig. 10).
CHAPTER VI

MODEL FOR FORMATION OF THE CASS COUNTY STRUCTURE

A history of the subsurface geological structure of Calvin - 28 oil field can be developed using Sawatzky's model (Sawatzky, 1975), the drill hole data and the results of the seismic study. The initial impact occurred on the Utica Shale of upper Ordovician age and several underlying formations were also affected by the compressional shockwave. As there was some mass deficiency owing to dispersion of rock debris and rupturing of country rock, the bottom of the crater started to uplift as an isostatic process (Stage 3 of Fig. 9). With the uplift, some inward-dipping normal faults were produced around the rim area. Faults were also produced by inward and upward movement of rock formations due to the central uplift. Layers such as the Utica Shale, Trenton Limestone, Black River Limestone, Glenwood Shale, and St. Peter Sandstone of the uplifted section were eroded and this eroded material was deposited in the ring synclinal depression area which surrounds the central uplift zone (Stage 4 of Fig. 9). Later formations such as the Cincinnatian Series and several Silurian and Devonian formations were deposited across the uplifted
topography (Fig. 17). Therefore, the Prairie Du Chien Group of early Ordovician age contacts with the Cincinnatian Series of Late Ordovician age at the Hawkes-Adams 1-28 deep hole section (Fig. 11). A subsequent dome structure was developed in the Silurian and Devonian formations. The Traverse Limestone, which is the pay zone of the Calvin - 28 oil field, is also included in the subsequent structural closure. The structural closure of the Silurian and Devonian may also be the result of a delayed isostatic adjustment.

Fig. 17. Subsurface geological model of the Cass County structure

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CHAPTER VII

CONCLUSIONS

In general, it is not easy to determine the genesis of an astrobleme because of severe disturbances. As no conclusive geological evidence such as shatter cones and coesite that would support the impact theory have been found, the structure in Cass County has been called a crypto-explosive structure.

Several lines of evidence support the concept of a central uplift in the Cass County structure: (1) the results of drilling data, (2) structural closures in the time structure maps of Trempealeau Formation and Traverse Limestone, and (3) and discontinuities in the Glenwood Shale and Trempealeau Formation in the seismic section of HAL-81-7. The structure of the central uplift appears to be a horst-and-graben feature surrounded by several reverse faults. Such structures are very similar to those in proven astroblemes.

The coincidence between the amount of the central uplift observed at the Hawkes - Adams 1-28 well and the calculated isostatic uplift associated with an impact also support the idea that the structure is the result of a meteorite impact.

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The section from the Utica shale to the St. Peter sandstone is missing in the Hawkes-Adams 1-28 deep well and there are some differences between the upper section and the lower section of the omitted part. The first is the difference of the amount of uplift and the second is the difference in the faulting systems. These differences can mean, with a certainty, that the central uplifts in both sections are not the result of the same process or at least that they did not occur at the same time. These differences can be readily explained by the impact hypothesis. No disturbance in the rock beneath the Trempealeau Formation in the seismic section of HAL-81-7 also supports an impact origin of the Cass County structure.

Although there is no direct geological evidence of a meteorite impact, it is reasonable to accept the impact origin of the Cass County structure on the basis of several lines of indirect evidence such as a central uplift, a horst-graben structure surrounded by several reverse faults, and the results of this seismic study. Then, a geological history of the structure can be developed with Sawatzky's model (Sawatzky, 1975) using drilling and seismic data. A meteorite fell on the Utica Shale and the bottom of the resulting crater was uplifted by isostatic forces. Then the top of central uplifted
section was eroded and the later formations were deposited on the top of the eroded section. So the Early Ordovician Prairie Du Chien Group is in direct contact with the Late Ordovician Cincinnatian Series in the Hawkes-Adams 1-28 well. The Devonian and Silurian formations also have structural closures which may be a result of a delayed isostatic adjustment or of a draping over the uplifted section. Therefore, the Traverse Limestone makes a circular oil field.

By a comparison of the seismic section of the HAL-81-7 with the Sawatzky’s model of the evolution of a fossil crater, the original diameter of the impact crater was at least 2000 meters. The mass of the meteorite can be calculated as being $9 \times 10^4$ tons and the diameter was about 36-50 meters depending on whether the meteorite was composed of stone or iron.
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