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ORIGIN OF THE JEPTHA KNOB STRUCTURE KENTUCKY

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ABSTRACT. A magnetic survey of the Jeptha Knob structure showed that there is probably no basement counterpart to the surface feature. A gravity survey revealed about +1 mgal anomaly, which can be explained by the near surface lithologies. The existing drilling information indicates that the deformation decreases with depth and is shallow. The geophysical and geological (petrologic, structural geologic) facts can be used to eliminate an endogenetic origin. The most likely exogenetic origin is hypervelocity impact of a meteorite or comet. A model of the original Jeptha Knob crater was constructed with the following dimensions: apparent diameter 6600 ft; apparent depth 920 ft; rim height 290 ft; rim width 1300 ft; depth to the limit of major brecciation 1600 ft. This crater was subsequently filled and covered by sediments. The filling material was mainly fallback and slumped materials from the sides.

INTRODUCTION

The recent theoretical work in cratering (Shoemaker, 1962; Bjork, 1961; Baldwin, 1963, 1964) has shown the importance of hypervelocity impact of meteorites or comets as a geological process. Experimental work (Chao, Shoemaker, and Madsen, 1960; Innes, 1961; Chao, Fahey, Littler, and Milton, 1962; Beals, Innes, and Rootenberg, 1964) together with theoretical considerations has established beyond reasonable doubt that certain terrestrial features are due to this process; Monod (1965) lists 12 features as "Cratères météoritiques". Since some recent geologic structures have proved to be due to hypervelocity impact, it is clear that more ancient ones should exist, and some of the features called "cryptovolcanic" have been reexamined (Boon and Albritton, 1938; Cohen, Bunch, and Reid, 1961.) Monod (1965) lists 15 of these as "cryptoexplosions".

There are eleven "cryptoexplosion" structures in the central United States, and most have shown some criteria of hypervelocity impact formation. Jeptha Knob is more obscure; it has not shown criteria other than circularity and the presence of deformed rocks. Monod (1965) lists shattercones at Jeptha Knob, but written communication with him confirms that this is an error. A search by Dietz (1960) failed to locate any shattercones, and they have not been found by the author. The purpose of this investigation is to attempt to establish the mode of origin of the Jeptha Knob structure by reinterpreting the previous work in light of later theoretical and experimental evidence and by the use of additional methods of investigation.

THE JEPTHA KNOB STRUCTURE

The feature is a topographic high, extending up to small flat-topped knobs at about 1180 ft. The general elevations in the region immediately around the structure vary from about 750 ft in the valleys and 850 ft

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on the divides in the southwest to 850 ft in the valleys and 920 ft on the divides in the east.

The rougher, higher central portion of the structure is wooded. Farmlands surround it and extend into it from the west in the valley of Britton Run, and a few fields occupy the top, flat surfaces of the knobs. Plate 1 is a mosaic of aerial photographs that shows the details of the area and also the locations of the gravity sub-base net, drillings, magnetic survey stations, and deformed rocks on route I-64.

GEOLOGY OF JEPTHA KNOB

General setting.—Structurally the Jeptha Knob structure lies about 30 miles west of the axis of the Cincinnati Arch, an elongated anticlinal dome that strikes a few degrees east of north (Jillson, 1931). The rocks of the region dip very gently westward, at about 22 ft per mile on the west flank of the Cincinnati Arch. Topographically, Jeptha Knob can be considered a monadnock on the surface of the slightly rejuvenated Lexington peneplain of Tertiary times (Nosow and McFarlan, 1960). It lies in the Interior Plains portion of the Eastern Superprovince (Pakiser and Zietz, 1965). There is a large bipartite negative gravity anomaly in this general area, elongate in the northeast-southwest direction, the southwest lobe of which lies some 30 miles south (and slightly west) of Jeptha Knob. The Cincinnati Arch has stood relatively higher than its surroundings during and presumably since at least Ordovician times, for Ordovician and later rocks thin over it.

Previous investigations.—The first geologic report on Jeptha Knob was by Linney (1887). He held that sinking of the central core of the Knob below the general level of the surrounding countryside protected its Silurian capstone, while beds of the same and greater age were eroded away, thus leaving the downfaulted block finally as an upland mass above the general level of the plain around it. This theory had to be abandoned because of its "maladjustment to certain important structural details of the geology of the area, discovered late in the second decade of the present century—chiefly the absence of adequate subsidence criteria" (Jillson, 1962). Linney failed to indicate the remarkable ring of earth disturbances that circles Jeptha Knob.

Then followed Bucher's exemplary mapping of the feature (Bucher, 1925). Bucher found that the only reliable stratigraphic section he could employ was a biostratigraphic one. Figure 1 compiles this on a chart, along with a general correlation chart, the stratigraphic section of Shelby County (McFarlan and Withers, 1950), and a chart derived from a recent paper by Brown and Lineback (1965).

Stratigraphy and structure.—In mapping, the deformed Ordovician rocks of the structure, especially in the central portion, are conveniently divided into parts: Bucher's "Lower division"—dominantly shale, and his "Upper division"—dominantly limestone. The difference shows in the aerial photographs as changes in vegetation, drainage and erosion pattern, topographic relief, degree of dissection, and gray tones; in the

PLATE 1

PLATE I

(legend on following page)

field it shows as changes in soil color and type, type and amount of float, changes in vegetation, and changes in weathering and erosion pattern.

The lower Niagaran age (Bucher, 1925, p. 216) of the capping Silurian dolomite combined with the finding of Brassfield (Lowermost Silurian) fossils in the breccias (Bucher, 1925, p. 225) means that the formation of the structure was rapid, at least in terms of geologic time. Most types of tectonism take considerably longer. The character of the rocks shows the environment at that time was neritic.

Structurally, Jeptha Knob is composed of a central area of greatly disturbed rocks, surrounded by rocks showing decreasing deformation (folding, faulting, and jointing) outward. The structural relations are such that all features could be explained by contemporaneous deformation, the source of the deformative force being at the center of the area. The central area, however, is capped by undisturbed Silurian dolomites and cherts that form essentially flat-lying ridges visible on aerial photos, the topographic sheets, and in the field. Thus they clearly postdate the event that deformed the underlying rocks.

Mapping of the deformed rocks of the central area by the writer using the changes listed above shows that they form a megabreccia. In the field, areas with one type of soil color, vegetation, weathering, and erosional dissection terminate abruptly against areas with different characteristics, with no apparent relation to elevation. These changes are also visible on the aerial photographs, mainly as changes in gray tones, vegetation, drainage, and degree of dissection. The degree of dissection is most significant for the recognition of shale soils, for they are highly dissected. Many areas of highly dissected topography of about 200 to 800 ft in extent are mappable in the central area with little or no correlation with elevation. There areas were mapped by Bucher (1925) as shales of the Eden group (probably the equivalent of the Clay's Ferry of the U. S. Geol. Survey), apparently because that was the oldest rock present in the float at the surface. Bucher lists nine fossils as distinctive of these rocks. Apparently eight of them are still considered index fossils of the Eden group equivalents or at least the Upper Ordovician. Thus, the correlation of the shales in the central area with the Eden group (and Lower Maysville, see fig. 1) is undoubtedly justified.

The only other dominantly shale formation in Shelby County is the Osgood of Early Niagaran age (McFarlan and Withers, 1950). If the shale in the central area is Osgood, this area could be essentially a collapse structure. However, the field relationships and the presence of these Eden group rocks indicate that substantial quantities of rocks are

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PLATE 1 (p. 632-633). Aerial photo mosaic of the Jeptha Knob area. Small circles with letters (A, B, C. . .) are gravity sub-base net station. Arrows (Neal, Hayden) show drilling locations. Crosses with numbers (1, 2, 3. . .) are magnetic survey stations. The corrected magnetic survey readings were projected onto the north-south and east-west lines. Large circle radius 0.7 mile, center at approximately 85° 07′ W, 38° 11′ N. Gravity sub-base station C is in Clay Village on U.S. Routes 60 and 460. Kentucky Route 714 is west of Jeptha Knob near gravity sub-base stations H and I. Interstate Route I-64 crosses the lower half of the photo mosaic.

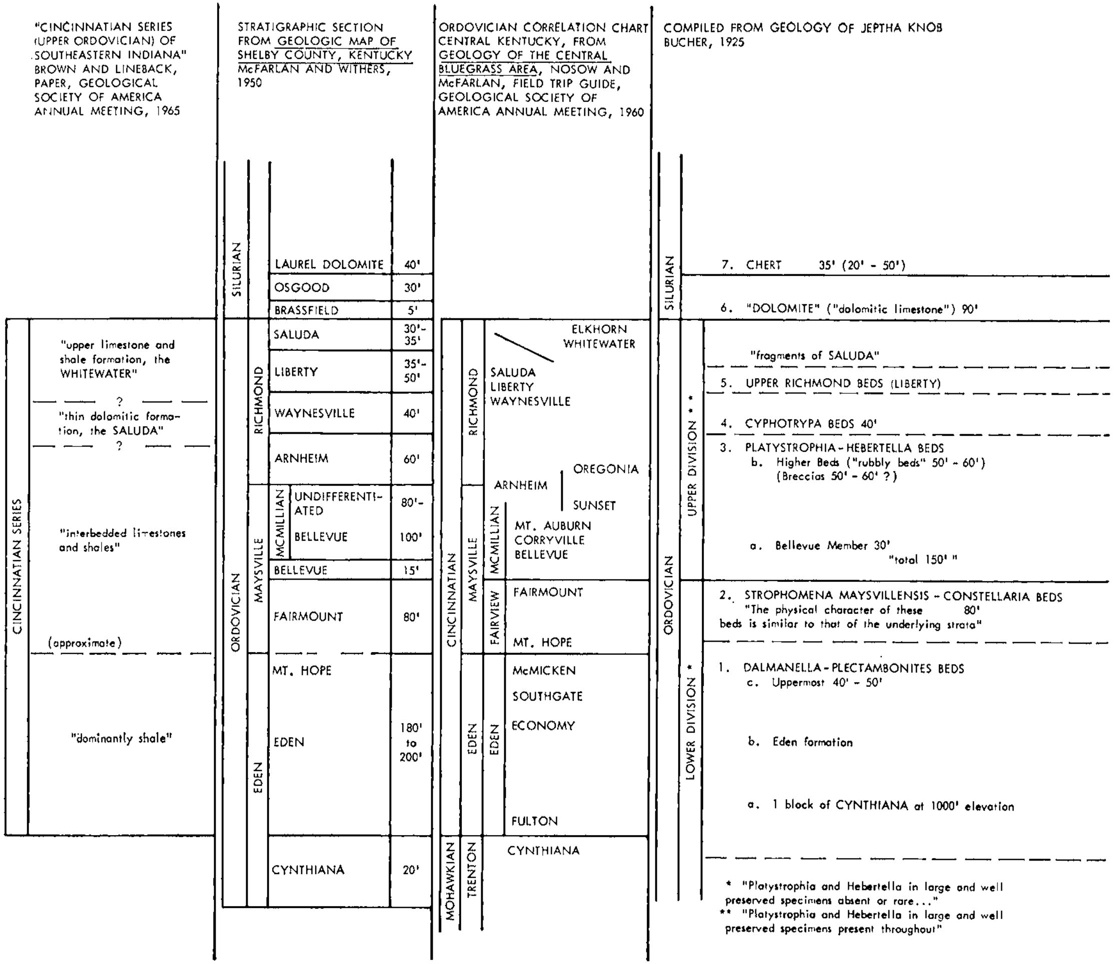


Fig. 1. Stratigraphic correlation charts.

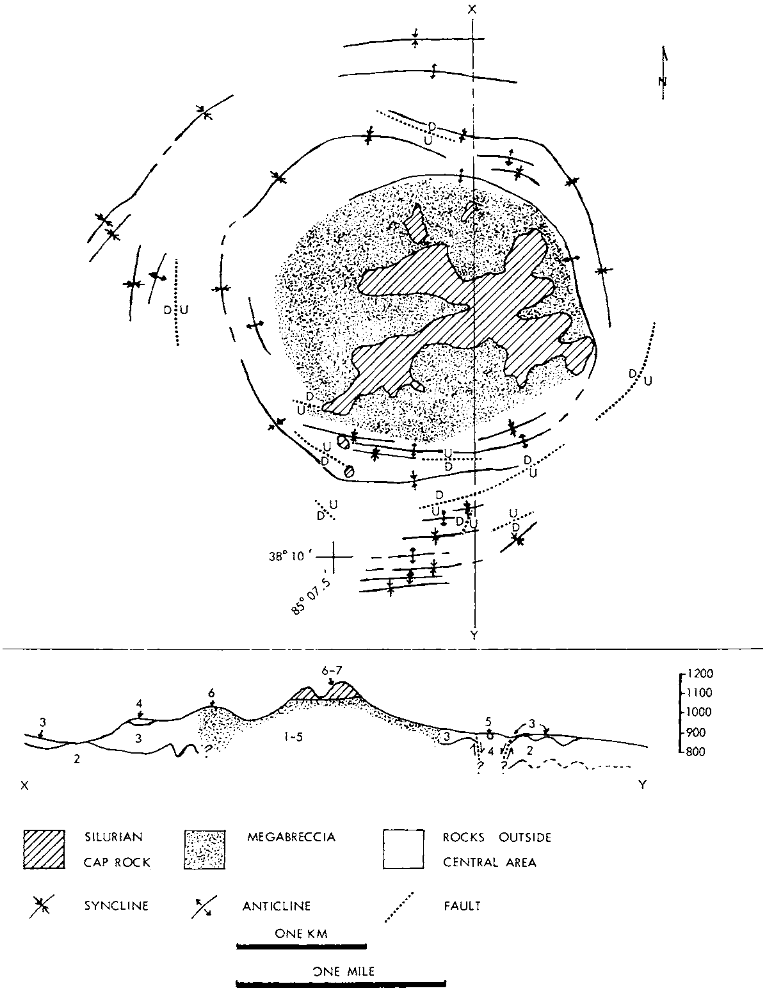


Fig. 2. Structural geology and cross section. The Silurian cap rock is the flat-lying undisturbed Silurian cherts and dolomites that cap Jeptha Knob. The megabreccia is composed of the highly disturbed rocks of the Eden group and higher (Bucher's beds 1 through 5, see fig. 1). The rocks outside the central area are composed of Maysville and Richmond Group rocks (beds 2 and 3 of Bucher, see fig. 1). The numbers in cross section X-Y refer to Bucher's units. The vertical exaggeration of the cross section is 5X, elevations are in ft above sea level.

in uplifted positions. Therefore, the rocks of the central area, under the cap of flat-lying, Silurian dolomites and cherts, must be considered a breccia whose fragments range from large blocks of extremely variable dips and lithologies down to microbreccia. Bucher (1925) discussed these blocks but reached a different conclusion.

Although continuous exposures are generally lacking, aerial photographic patterns and field observations are consistent with a gradation outward from breccia through faulted and folded rocks to folded rock. The intensity of the deformation decreases outward, until the sub-horizontal, undisturbed rocks of the region are reached.

The transition in the belt of folded and faulted rocks is best exposed in Wolf Run, where continuous exposures occur in the stream bed. Dips up to vertical were observed in the syncline nearest the structure center, and they decrease to about 30° in the limbs of the outlying folds. Five anticlinal axes are exposed between this syncline and the sub-horizontal rocks of the region (found about 300 ft southwest of pl. 2), simulating a sinusoidal waveform that damps out away from the source, amplitudes starting of about 200 ft and diminishing to a few feet. For example, in plate 2, the folding has diminished until the curvature is so great that the dip can be seen to change observably in an outcrop of only 2 ft or so.

Some faulting and brecciation are present in the folded zone. Jillson (1962) recorded such deformations in the new road cuts of Route I-64 about 1 mile south of the center of the Jeptha Knob area; similar deep road cuts would presumably expose similar structures all around Jeptha Knob. All these structural features are summarized on figure 2. They are consistent with the location of the deformative stress source at the center of this area mapped.

PLATE 2

Last fold observed in Wolf Run proceeding southward. Strike N 70° E, dip 30° to 40° N, changes visibly in the 2 ft of vertical exposure.

MAGNETIC AND GRAVITY CHARACTERISTICS OF JEPTHA KNOB

Summary of the geophysical results.—The geophysical results show that the basement takes no part in the structure of Jeptha Knob as presently exposed; sedimentary lithologies in place can explain entirely the geophysical characteristics found in this investigation.

Magnetic survey.—The magnetic survey was conducted in order to determine to what extent, if any, the basement rocks participate in the Jeptha Knob structure. The overlying sedimentary cover, as is well known, is essentially transparent to the magnetic observations for larger scale effects.

The survey was made with a Varian proton magnetometer, which measures the total field. Readings were taken to 5γ and are generally considered precise to $\pm 10\gamma$. Plate 1 shows the locations of the traverses of the structure. The survey was made on 27, 28, 29, 30 August 1965, and three of these days were listed as quiet days (Lincoln, 1966) for the month.

Since the basement is to be investigated by the magnetic survey, the first question to ask is whether the survey lines are long enough to detect an anomaly on the basement. Freeman (1953) shows that the depth to basement at Jeptha Knob should be approximately 5500 ft. Using Peter's methods (Dobrin, 1960), one can evaluate the length of a survey line necessary to detect an anomaly caused by a feature on the basement surface. The extreme case would be that of a fault with a "half slope" distance (slope ½ max) of about 2 miles. Since the north-south and east-west survey lines are about 3½ miles long, an anomalous magnetization on or in the basement, near or at the center of the structure, should be detected. The above considerations as well as those that follow assumed vertical magnetization. In fact, this was not what was measured; the magnetometer measured the total field. However, the inclination at this latitude is about 71° and the sine of 71° is about 0.95, so that the readings are probably high by about 5 percent. This means the calculations are slightly in error but not by a significant amount.

The writer considered these traverses to provide a kind of wavelength data, in which he looked for a fluctuation of proper width to be in, or on, the basement surface. The readings taken in the field were projected onto the north-south and east-west lines shown in plate 1, and the profiles are shown in figure 3. The north-south traverse shows an increase toward the north in excess of the regional gradient, which is 5.80γ/mile increasing northwardly (Vestine and others, 1959). When analyzed for depth this indicates an anomaly of much larger extent than could concern just the Jeptha Knob structure. The minimum depth would be more than 2.5 miles, and it would have to be centered at least that far north or south, horizontally. A similar analysis can be made of the east-west traverse. For this the regional gradient is only 0.11γ/mile increasing westwardly.

Figure 3 also shows many small fluctuations. When these are analyzed for depth, they are all found to be centered in the range between 300

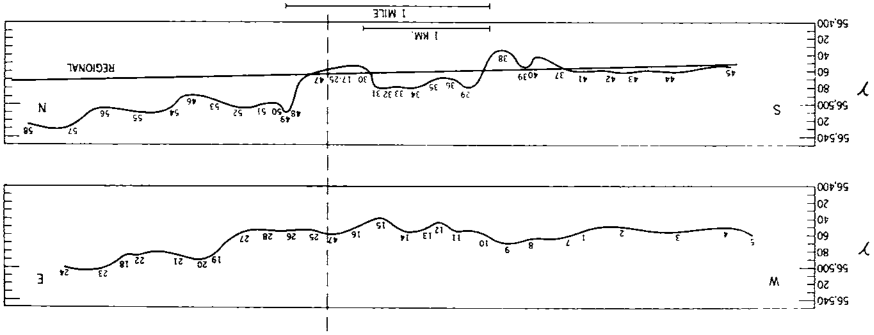


Fig. 3. Magnetic profiles of the Jeptha Knob structure. The dotted line is the regional change, values in γ.

to 550 ft. These fluctuations are associated with the deformed rocks of the Jeptha Knob structure (compare fig. 7).

Therefore, the answer to the question posed is that there is nothing of proper size to be caused by an anomalous magnetization in or on the basement surface at the position of the Jeptha Knob feature. Therefore, the basement can be excluded from further consideration in this study, and we must look in the sedimentary rocks to determine the origin of Jeptha Knob.

Gravity survey.—To find the density of the regional rocks, a density profile (Nettleton, 1940) was run outside the disturbed area at an elevation of 700 to 800 ft, across the rocks that recur in the central portion of the Jeptha Knob structure. It indicates a density of 2.4 or 2.5 g/cm^3. As a further check on the regional density, all the gravity points outside the disturbed portion of the Jeptha Knob area were reduced, based on densities of 2.0, 2.4, 2.5, and 2.7 g/cm^3, and these values were plotted against station elevation. There was considerable scatter in the points, but a rather clear direct dependence between elevation and Bouguer anomaly value was evident in the 2.0 g/cm^3 curve, and an inverse relationship was found for the 2.7 g/cm^3 values. Both 2.4 and 2.5 g/cm^3 curves appeared to be flat, but the scatter was too great to permit a choice between them.

The gravity survey results are shown on figure 4, a residual gravity map of the Jeptha Knob area. A density of 2.4 g/cm^3 was used for the Bouguer and terrain corrections in order to emphasize the gravity feature associated with the Knob, insuring that the interpretation will be adequate to account for the entire anomaly. Had a density of 2.5 g/cm^3 been used, the feature would show a positive anomaly of half a mgal instead of about 1 mgal, as seen on figure 4, thus requiring less density contrast to explain the anomaly.

The most important feature on figure 4 is the local positive residual gravity anomaly of about 1.0 or 1.2 mgals (depending upon whether the −0.2 mgal contour closes or not). It is a little more than 3 miles in

PLATE 3

A. Sedimentary breccia block in slide block of Silurian dolomite, Wolf Run, elevation approx. 1000 ft.

B. Photomicrograph of matrix from sedimentary breccia block shown in A. Plane polarized light (× 45).

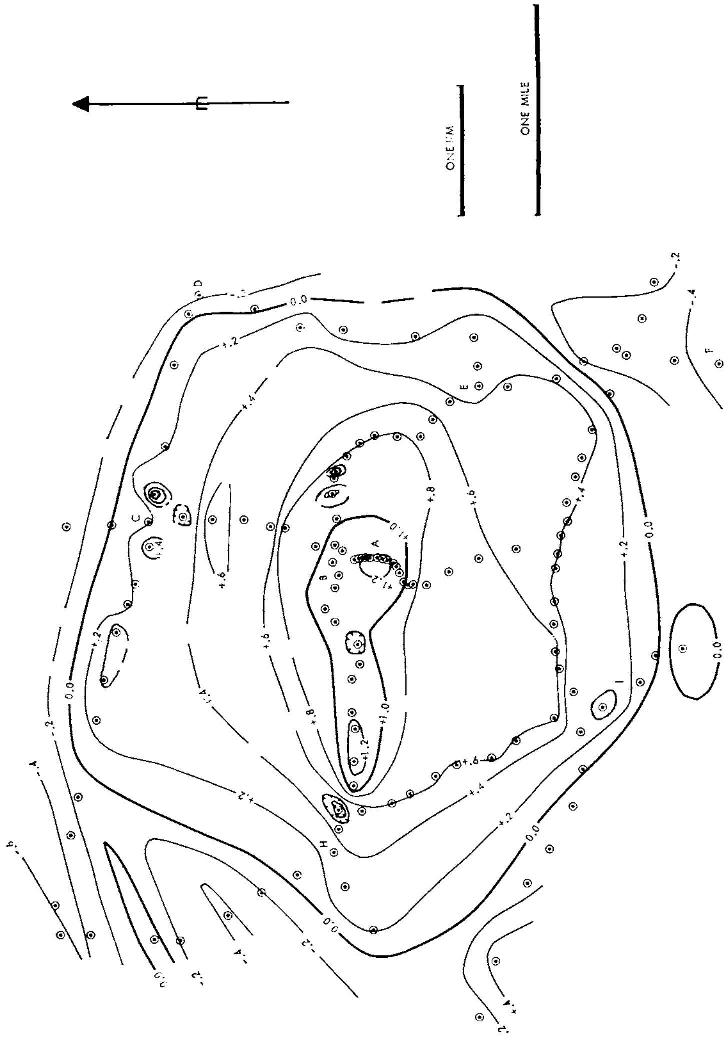


Fig. 4. Residual gravity map of the Jeptha Knob area, based on density 2.4 g/cm³. Contour interval 0.2 mgal.

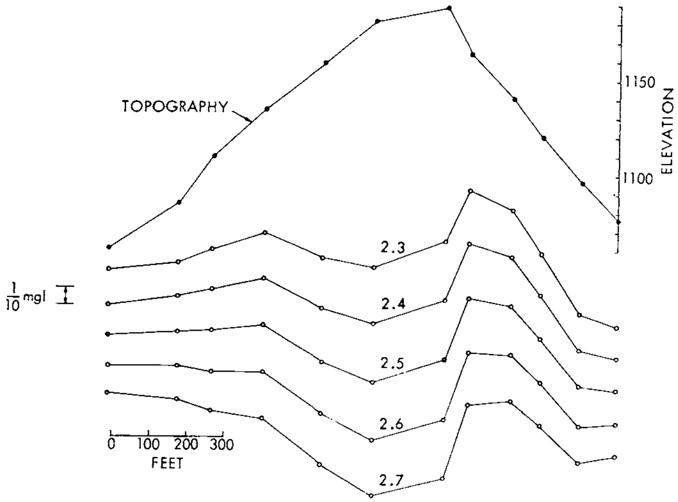


Fig. 5. Density profile at high elevations of the Jeptha Knob structure. Black dots are topography, elevations in ft above sea level. Curves, open circles, are based on data reduced at the labeled density in g/cm^3. The indicated density is 2.6 g/cm^3.

diameter. Also present are several small features with additional positive values of 0.2 to 0.6 mgal.

The density profile described above shows that the rocks in the region have a density of 2.4 g/cm^3. To see whether the rocks in the higher elevations of the central part of the structure have the same density, a closely spaced traverse was run over the tip of one of the knobs from 1060 ft to over 1185 ft elevation. Plotted as a density profile (fig. 5), it indicates an average density of 2.6 g/cm^3. The rock whose density was measured here was the Silurian dolomite, overlain by possibly 20 to 50 ft of chert, so that an average effective density of 2.6 g/cm^3 at this elevation is quite reasonable. Some rather pure dolomite is present in the structure, and dolomitization of the Ordovician rocks is more extensive than might be expected. The density of the dolomite is 2.7 g/cm^3 or higher, of the cherts 2.3 or 2.4 g/cm^3, so that 25 percent chert at 2.3 g/cm^3 and 75 percent dolomite at 2.7 g/cm^3 would give an average effective density of 2.6 g/cm^3.

This density profile shows a depression in the center, where the elevation is high, and high points on each side, especially on the northern side. These should correspond to the occurrence of the chert (and soil) on the top of the knob and to the top of the dolomitic beds, respectively. To test this interpretation, a few order of magnitude calculations were made using Dobrin's 1960 formulas and density measurements by the writer.

Bucher (1925) mapped 20 to 50 ft of chert on top of the structure. The writer has found cherts (density 2.3 g/cm^3) seemingly weathering in place in the soils at the high elevations and is convinced that considerable silica is present in these rocks. There is also a rather thick soil layer on the flat portions of the tops of the knobs. The calculations using these thicknesses show that this part of the gravity correlation seems justified.

Similarly the positive gravity feature was modeled, using known densities, as a horizontal cylinder of about 100 ft radius and as a flat plate of about 100 ft thickness. The latter would seem the best model, since the true geometry is between the two models, but probably closer to a flat plate. The dimensions modeled are consistent with the mapped thicknesses and lithologies. Thus the interpretation as stated above is considered justified. Depth calculations using Dobrin's (1960) methods verify that the feature is very shallow.

Using all this information on densities it is possible to build up a stratigraphic section to explain the gravity features mapped.

Some rocks in the disturbed portion of the structure have densities up to 2.8 g/cm^3. First let us consider these rocks a minor portion of the total rocks from 800 to 1050 ft elevation and consider the density uniformly 2.5 g/cm^3 in order to set a lower limit in the first estimate. We will return to the consideration of these denser rocks. Using the "flat plate" formula (Dobrin, 1960, p. 175), from 80 to 1050 ft:

$$\begin{aligned}\Delta g_z &= 12.77\,(\Delta\rho)\,t & t &= 0.25\\ &= 12.77\,(0.1)\,0.25 & \Delta\rho &= 0.1\ \text{g/cm}^3\\ &= 0.32\ \text{mgal}\end{aligned}$$

and, from 1050 to 1180 ft, $\rho = 2.6$ g/cm^3

$$\begin{aligned}\Delta g_z &= 12.77\,(0.2)\,0.13 & t &= 0.13\\ &= 0.33\ \text{mgal} & \Delta\rho &= 0.2\ \text{g/cm}^3\end{aligned}$$

where: Δg_z is the gravitational anomaly in mgals, 12.77 is the combined geometrical and gravitational constants ($2\,\pi\gamma$), $\Delta\rho$ the density contrast, and t the thickness in kiloft.

Also present are the features that were previously modelel as horizontal cylinders or flat plates of density 2.8 g/cm^3. Again to set the lower limit, let us assume a horizontal cylinder:

$$\begin{aligned}\Delta g_z &= 12.77\,(\Delta\rho)\,R & R &= 60\ \text{ft}\\ &= 12.77\,(0.2)\,0.06 & \Delta\rho &= 0.2\ \text{g/cm}^3\\ &= 0.15\ \text{mgal}\end{aligned}$$

This means we expect a minimum of $0.32 + 0.33 + 0.15 = 0.80$ mgals anomaly as modeled above to be caused by the rocks above 800 ft elevation in the Jeptha Knob structure.

Similarly, the maximum expected anomaly may be determined, from 1050 to 1180 ft elevation:

$$\begin{aligned}\Delta g_z &= 12.77\,(\Delta\rho)\,t & t &= 130\ \text{ft}\\ &= 12.77\,(0.4)\,0.13 & \rho &= 2.8\ \text{g/cm}^3\\ &= 0.66\ \text{mgal}\end{aligned}$$

and, from 800 to 1050 ft elevation:

$$\begin{aligned}\Delta g_z &= 12.77\,(0.2)\,0.25 & t &= 250\ \text{ft}\\ &= 0.64\ \text{mgal} & \rho &= 2.6\ \text{g/cm}^3\end{aligned}$$

This shows that a 1.30 mgal maximum expected anomaly can be explained using the density contrasts modeled above.

In addition to the dense limestones found by the writer, the drilling information indicates a probable upward displacement of about 700 ft for a block of Tyrone limestone. This rock unit and the Lexington limestone are formations mostly of dense limestone and should be considerably denser than the Eden group shales. Therefore, taking just the average limestones density of 2.54 g/cm^3 (Dobrin, 1960, p. 251) we can set limits of this addition by estimating that the equivalent of a sphere (min) or a flat plate (max) of this material is also represented in the gravity survey. For a sphere:

$$\Delta g_z = 8.52 \frac{\Delta\rho R^3}{z^2}\left[1 - \left(\frac{x}{z}\right)^2\right]^{-3/2} \qquad z = 500 \text{ ft}$$

$$x = 0$$

$$R = 200 \text{ ft}$$

$$= 8.52 \frac{(0.14)\,(0.2)^3}{(0.5)^2}$$

$$= \mathbf{0.04} \text{ mgal (min effect)}$$

For a flat plate:

$$\Delta g_z = 12.77\,(\Delta\rho)\,t \qquad t = 400 \text{ ft}$$

$$= 12.77\,(0.14)\,0.4$$

$$= 0.72 \text{ mgal (max effect)}$$

That is, if a sphere or block of denser material is moved from a lower position to a higher one in the section it will cause a local increase in the relative force of gravity, and this effect will be between the two limits estimated above.

Allowing that the portion of the rocks above 800 ft elevation should be about half the total amount disturbed, the expected range of anomalies from all sources is from 0.82 mgals to 1.66 mgals, representing the sedimentary rock section. This section will explain most of the gravity features mapped in figure 4, and figure 6 is a diagrammatic density cross section which shows the distribution of densities as written above.

There are two types of gravity features which cannot be totally explained at this point. The first of these is a series of small positive anomalies.

Calculations show that these anomalies could be caused by slumped and slide blocks of the Silurian dolomitic limestone as described by Bucher (1925) and observed by the writer.

The maximum anomalous values occur in two places, in the highest parts of the structure, as has been explained above, and in Britton Run at elevations over 900 ft just west of the center of the structure. Bucher does not map the ring syncline in this sector, and it is probable that his *Cyphotrypa* Beds and the Upper Richmond Beds in the center of the syncline are buried here. It is mapped by the writer on figure 2. In other directions of the structures, that is, to the north, east, and south,

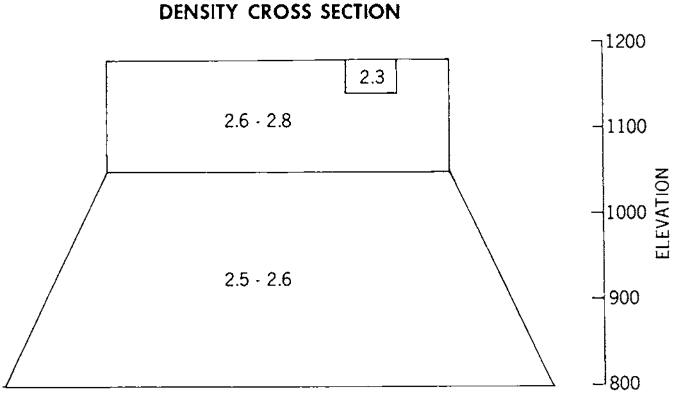


Fig. 6. Diagrammatic density cross section of Jeptha Knob above 800 ft elevation. Densities in g/cm^3. The regional density is 2.4 g/cm^3. The 2.3 g/cm^3 material at the top of the diagram is the chert; 2.6 to 2.8 g/cm^3 material from 1050 to 1180 ft elevation is the dolomite. The 2.5 to 2.6 material is the disturbed rocks of the area.

these rocks seem to produce about half a mgal positive feature, probably due to mainly to dolomitization. This valley, the portion of Britton Run that drains the center of the structure, is flanked by hills on each side. They are the remnants of the knobs which are in a higher state of erosional destruction than the higher portions. That is, the blocks (slump and slide features) are at lower levels than most of them in the other, less eroded parts and have been converged into the valley by gravitational gliding. The effect of this, plus the effect of the buried (or possibly down faulted) synclinal structure would account for the observed gravity in this location.

SUB-SURFACE GEOLOGY

There have been two drillings in the Jeptha Knob area, the J. B. Hayden No. 1 well just outside the deformed rocks and the T. D. Neal no. 1 well in the central portion, as shown on plate 1. Figure 7 is a columnar representation of the drillers' descriptions and depths aligned relative to sea level. Beds of 1 ft thickness or less are omitted from the Neal column.

Note the occurrence of "Pencil Cave" at about 900 ft elevation. This well know metabentonite is about 700 ft above its normal level. It occurs about 20 ft below the top of the Tyrone limestone in this area.

When the two wells are aligned by sea level elevation, a distinctive sequence of red beds is observed in the two columns at about the same elevation. This suggests that uplift markedly decreases with depth from 700 ft uplift to essentially no uplift within about 800 ft of the present land surface.

On this basis, one can restrict the structure of Jeptha Knob to only 50 ft of "uplift" at the top of the upper red bed and possibly none at the bottom of the reddish-brown bed. This would confirm the conclusions of the geophysical work that the rocks in the structure are un-

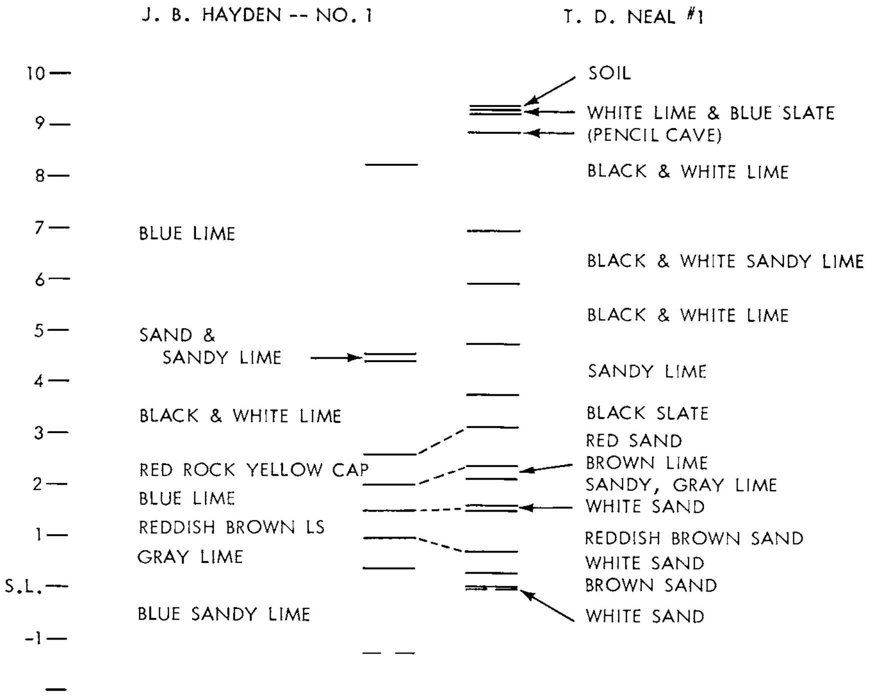


Fig. 7. Columnar representation of the drillings in the Jeptha Knob area. Elevations in ft x 100.

affected at depth, and the entire feature is confined to the surface and near surface rocks.

BRECCIAS

The breccias of Jeptha Knob may be divided into two general classes, autochthonous and allochthonous. The allochthonous breccias of Jeptha Knob are those in which the fragments and the matrix are dissimilar or in which the main constituents were clearly formed at a different place than now found. In this paper the term autochthonous breccias will be used for those in which the matrix material and the fragmental material are the same (essentially monomict). Whether the rocks, in the quantity being considered, were essentially ruptured in place or were moved in total as part of the process of formation cannot be determined. Unfortunately, there is no exposed contact between an autochthonous layer and an allochthonous layer. The autochthonous breccias are only exposed as blocks in the central area, except for some intraformational breccias in the folded rocks surrounding the central area.

Autochthonous breccias.—Large blocks of autochthonous breccia are present in upper Britton Run near the center of the structure at an elevation of about 900 ft. They are not in place and probably have weathered out and moved from a higher elevation, how far is not known. In the field the brecciated nature of the rock is quite apparent; individual angular fragments of a few inches on a side stand out because of subtle changes in color and weathering rate. However, all the interstices are filled and recrystallized, and the rock breaks as readily across fragments as between them.

In hand specimen and thin section the rock resembles a highly recrystallized and dolomitized "pseudospar" (Folk, 1965). It is composed of nearly equigranular euhedral intergrown sparry crystals of dolomite with some calcite, occasionally with slightly larger grains or small amounts of brown staining to mark probable fragment boundaries. No deformation features are found in the individual crystals. This rock is considered by the writer to have been brecciated as a unit and subsequently recrystallized.

Intraformational breccias are found in the deformed rocks of the area and cannot readily be distinguished from tectonic breccia. No distinctive single crystal deformation was observed in the section.

Allochthonous breccias.—These are more variable than the autochthonous ones and comprise three main types with variations within each type. The types are (1) the sedimentary breccias, (2) the flow breccias, and (3) the breccias in grabens and breccias associated with the folded and faulted plastically deformed zones.

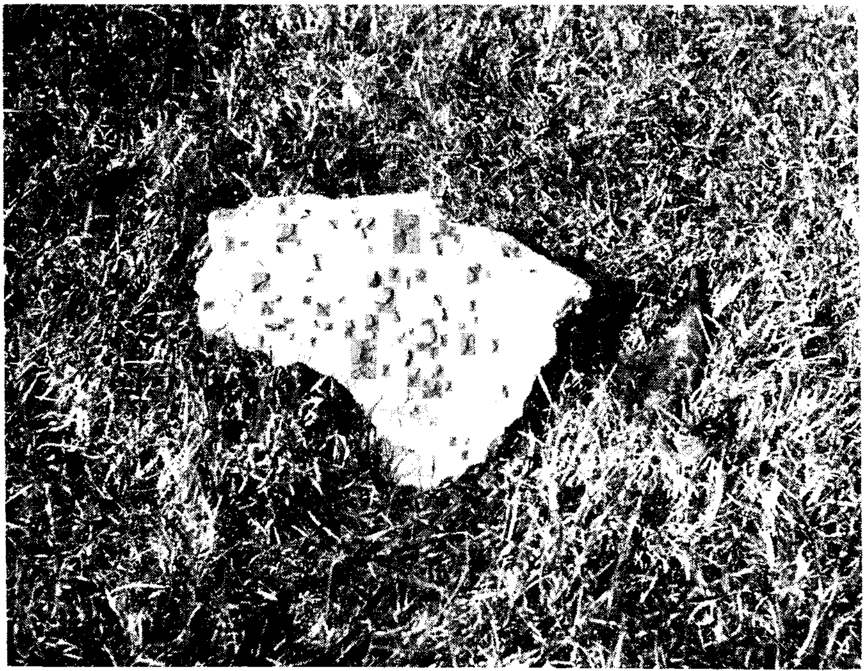
The sedimentary breccias are quite variable in both ratio of fragmental to matrix material and amount of rounding of the individual fragments, and a classification of three types based on the fragments characterizes them best:

	angular	rounded
closely packed	x	x
separated	x	

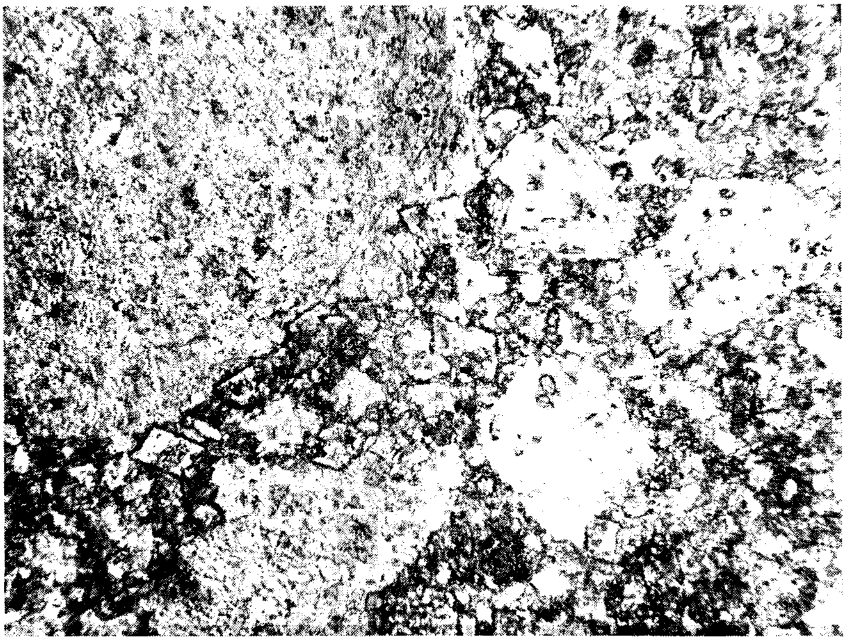
There are gradations between these classes, and they should be considered as end members.

Plate 3-A shows a large piece of the type with angular, closely packed fragments in the field. Such breccias are the most abundant of the sedimentary breccias. The fragments are ordinary Ordovician limestone, are of extremely variable size, and are very angular. Plate 3-B is a photomicrograph of the matrix material from between the fragments visible in plate 3-A. Even at this scale fragmental material can be seen. The matrix material is dolomitic, but the dolomitization has not proceeded nearly as far as in other sedimentary breccias. A euhedral grain of calcite visible in plate 3-B shows rather closely spaced fractures with no apparent displacement of the grain boundaries. This rock is interpreted as deposited very rapidly, with little if any sorting or transport of fragments and much better preservation of the fragmental nature of the rock than in the other sedimentary breccias. The dolomitic material is introduced into the interstices after deposition of the fragments; the full interpretation is given below.

PLATE 4



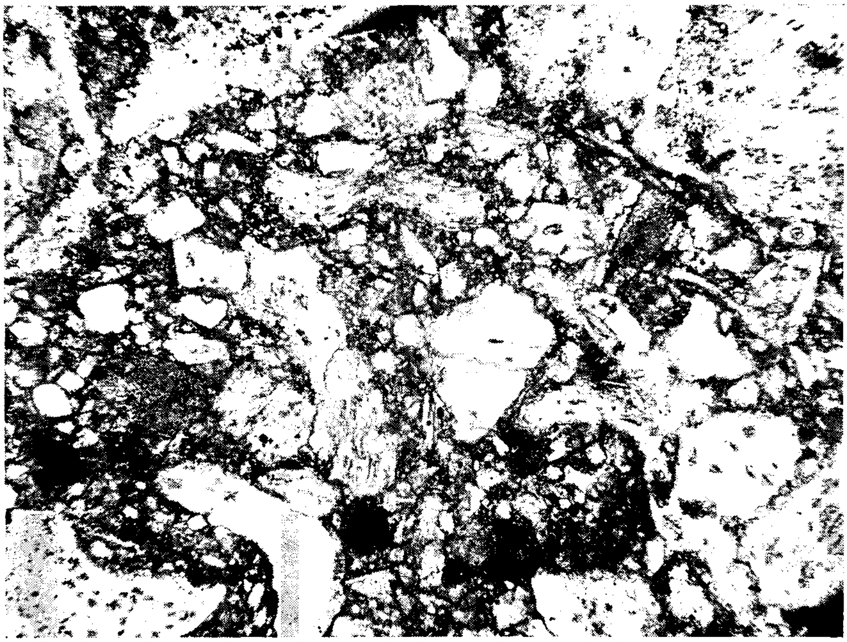
A. Sedimentary breccia from slide block of Silurian dolomite, Wolf Run, elevation approx. 1000 ft.



B. Photomicrograph of matrix from sedimentary breccia shown in A. Plane polarized light (× 125).

PLATE 5

A. Sedimentary breccia (pebble conglomerate) from slide block of Silurian dolomite, Wolf Run, elevation 1000 ft.



B. Photomicrograph, matrix material in breccia. Cataclastic nature. Outer folded zone. Plane polarized light (× 125).

Another type of sedimentary breccia is illustrated by plate 4-A; it is composed of angular fragments of typical Ordovician limestones rather widely dispersed in an extremely dolomitic matrix. Plate 4-B is a photomicrograph of this rock showing that the dolomitization of the matrix material is more advanced than in the rock discussed formerly. The dolomite rhombs seem to be developing into the boundaries of the fragments. Examination with the electron microprobe confirms this relationship; counts of Mg in the matrix are 25 times the counts in the fragments. Counts of Fe also increase in the matrix. These rocks are interpreted as formed by rapid deposition of the fragments within the matrix material. Most probably, the fragmental material slumped, churning up the sea bottom mud, and being redeposited with it. Density currents of short distance of transport could also account for such rocks. The fragments would have moved in suspension with the mud or ooze and would have been deposited in it when the velocity decreased, but graded bedding is poorly developed, if present.

The third type of sedimentary breccia is shown in plate 5-A. In this type the fragments are quite rounded; in fact, the proper name for this rock would be a pebble conglomerate (Pettijohn, 1957). It is the least abundant class of the sedimentary breccias. The rounding of the limestone fragments shows that they spent a considerably longer time in a high-energy environment than the other rocks discussed but obviously not long enough to erode or dissolve the limestone fragments completely. The fragments make up the major portion of this type rock and are of the typical Ordovician limestone; the matrix is fine-grained dolomite and fossil fragments. Wave action could produce such a rock, as could channels or streams.

Bucher (1925) writes of these sedimentary breccias: ". . . the lenses of fossil breccia in the Silurian dolomitic limestones and shales become more frequent and the fragments in them larger as one goes outward from the center of the structure. We must, therefore, look for the source of the fragmental material near the periphery of the structure". The subject of the source and origin of these rocks is discussed in the next section.

In the central portion of Jeptha Knob many rocks with obvious flow structures are found in the stream beds. They are argillaceous limestones, usually badly weathered, of the usual Ordovician type. The flow structures are lineations or rods of slightly different color or lithology, which pass through the rock in lines or eddy-like structures; they are quite apparent in cut specimens but not visible in thin section. They give the appearance of rock that was partially or mostly molten or soft and that flowed differentially, thus producing the flow structures common in volcanic and some plutonic rocks. Such features can be produced as compaction features in sedimentary rocks. The writer has called these flow breccias for lack of a better name. In thin section the rock, though quite weathered, shows very fine-grained recrystallization, mainly of dolomite. Some areas appear to have been pieces of fossil material rounded and recrystallized on a very fine scale. The primary structures of the original clastic fossil fragments have apparently been changed by the conditions at the time of the formation of the flow structures. Similar flow structures were observed by the writer in rocks from the Glassford structure, the Kentland structure, the Flynn Creek structure, Odessa Crater, and the Wells Creek structure. The latter were also reported by Stearns and others (1966).

The last type of allochthonous breccias is found in the matrix materials in the breccia along Route I-64. The breccia fragments are Ordovician limestones and shales. The matrix material is composed of very angular fragments of limestone and fossils, extremely unsorted in size but giving some appearance of flow structure in hand specimen or thin section. Plate 5-B is a photomicrograph of this rock. In hand specimen there is a hint of lineation, and in thin section there is some tendency of the fragments to be aligned. There is a very small amount, if any, of the recrystallized or dolomitized matrix that occurs in the other breccias; rather, the smallest pieces seem to be fragments. Only at a magnification of (800X) is any recrystallization evident. The extreme polymict character suggests a mylonite or impactite. These characteristics and the fact that this rock is itself the matrix material of a three-dimensional breccia, instead of occurring along planes or in zones, suggest that this material was injected into the breccia, filling the voids.

ORIGIN OF THE JEPTHA KNOB STRUCTURE

The foregoing information should permit us to determine the mode of origin of the Jeptha Knob structure. The first step is to choose between an endogenetic or exogenetic origin.

Endogenetic or exogenetic origin.—Using the method of multiple hypotheses, let us consider the endogenetic mechanisms that could be responsible for the Jeptha Knob structure as it is now exposed.

First of all, there is no reason to consider any that do not conform to the most obvious feature of the Jeptha Knob structure, its circularity (see fig. 2). Thus a mechanism such as vertical uplift due to early Silurian transcurrent faulting of intersection of fault systems can be excluded on the regional geology (McFarlan and Withers, 1950). Transcurrent faulting can produce circular vertical displacements (Chinnery, 1965), but it would require about 40,000 ft of net displacement of the two sides of the fault to produce the more than 400 ft of uplift required to move the block of Cynthiana limestone to an elevation of over 1000 ft as was observed. Clearly no such feature is present in the region.

It is possible to eliminate most forms of igneous activity because igneous rocks or even hydrothermal alteration are completely absent at the surface. If igneous material were buried, it should have a geophysical counterpart, and none is present. Ring dikes, for instance, are characterized by strong magnetic and Bouguer anomalies. The mechanism proposed by Bucher, which is, in reality, much closer to a variation of the ring dike mechanism than to cryptovolcanism, can be eliminated on the same grounds. Computations by the writer have shown that the piston pushing up from the basement in Bucher's mechanism should be characterized by a circular magnetic anomaly and a positive Bouguer gravity anomaly about 1½ mgal. No such features were found; the required magnetic anomaly is not present, and the gravity anomaly is explained by the sedimentary lithologies.

This leaves only some sort of collapse mechanism as an endogenetic possibility, and we have shown that the central portion of the Jeptha Knob structure is characterized by substantial quantities of rocks in uplifted positions.

Since the deformation of the rocks of the structure seems to decrease with depth, essentially disappearing at about 700 ft below the present surface it is clear that the source of the energy which disrupted the rocks of the Jeptha Knob structure must have come from above. That is, an exogenetic origin is indicated.

The hypervelocity impact theory of origin of the Jeptha Knob structure.— The only exogenetic mechanism likely to have produced the Jeptha Knob structure is the hypervelocity impact of a meteorite, asteroid, or comet. That events of this type must have taken place on the surface of the Earth many times during geological history can be considered established beyond reasonable doubt (see Baldwin, 1963, for example).

The original Jeptha Knob structure.—We will now model the original Jeptha Knob feature and outline its evolution into its present form. Figure 8A is a diagrammatic representation of a crater defining the terms used in the descriptions and in the calculations. It also shows the probable original shape and size of the Jeptha Knob structure based on the dimensional information now available. Figure 8B superimposes the initial configuration data derived as follows on the structural cross section of figure 2. The initial ground level of the model crater in figure 8B was determined to correspond to a present elevation of 1125 feet, using average stratigraphic thicknesses in the region.

The only dimension available, with the present exposure of the Jeptha Knob structure, that can be related to the initial crater is the horizontal extent of the undisturbed Silurian rocks capping the topographic feature. This was measured by the writer as about 6000 ft. Exactly what original dimension this represents is open to consideration. First of all the environment, we recall, was neritic. Gault, Quaide, and Overbeck (1966) have found that impacts in loose materials and water can produce central uplifts. Dence (1966) confirms that they occur in "soft materials", as in Canadian experiments, which also seem to show that comet impact could produce them (Roddy, personal commun.). Dence (1965) also inteprets a sizable layer in the drill cores from Brent crater (about 1/10 the diam) as fallout, fallback, and material slumped from sides. Thus the crater floor and the limit of brecciation may be shown too deep in figure 8. But let us first assume that the 6000 ft of undisturbed Silurian rocks represent a layer at about the level of the

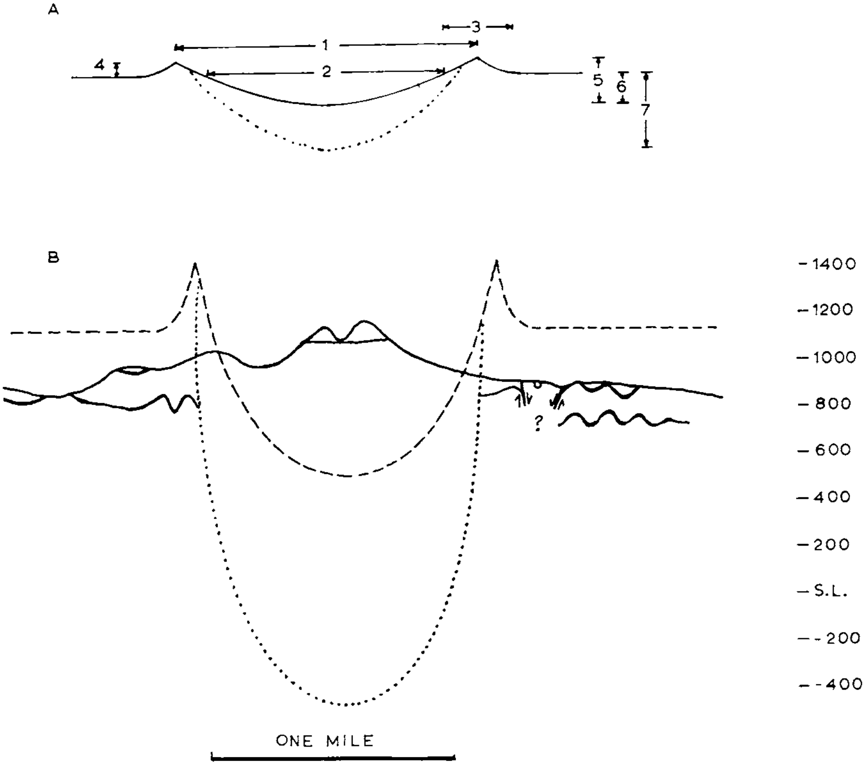


Fig. 8A. Diagrammatic representation of a crater showing terms used in descriptions and in calculations using Baldwin's (1963) formulas. It is approximately the shape of the original Jeptha Knob structure without vertical exaggeration: 1 is the apparent diameter; 2 is the true diameter; 3 is the rim width; 4 is the rim height; 5 is the apparent depth; 6 is the true depth; 7 is the depth to the limit of major brecciation.

B. The probable initial configuration of the Jeptha Knob structure based on the results of the investigations in this work, the previous work on the Jeptha Knob structure, and the known characteristics of hypervelocity impact craters. Vertical exaggeration, 5X. The solid lines are from the cross section X-Y in figure 2, the dashed line is the probable initial ground surface, the dotted line is the probable maximum limit of major brecciation. Elevations in ft based on present sea level.

true diameter. It could represent as much as the apparent diameter, but it is unlikely that the rim could be preserved long enough for this to be the case. The top of the rim should have been eroded very quickly.

We tabulate below (in ft) the parameters of the original crater, conconsidering 6000 ft to represent (1) the apparent diameter, (2) the true diameter, and (AVG) an average value of (1) and (2), which may be the best model.

	Apparent diameter	True diameter[a]	Depth to the limit of major brecciation[b]
(1)	6000	~5000	~1500
(2)	7200	6000	~1700
(AVG)	6600	~5500	~1600

[a] True diameter (at ground level) = 0.830 times apparent crater diameter (Baldwin, 1963).

[b] Interpolated between data for Arizona and Holleford craters from Baldwin (1963).

	Apparent depth[c]	Rim height[d]	Present elevation of original crater floor[e]
(1)	865	265	525
(2)	975	320	470
(AVG)	~920	~290	~500

[c] Interpolated between data for Arizona and New Quebec craters from Baldwin (1963).
[d] Interpolated between data for Arizona and New Quebec craters from Baldwin (1963).
[e] Equals original ground level (1125) — (apparent depth — rim height).

	Thickness of filling material[f]	Rim width[g]	Total diameter original crater[h]
(1)	525	1200	7400
(2)	580	1400	~8800
(AVG)	~550	~1300	8100

[f] Equals level of undisturbed rocks (1050) — present elevation of original crater floor.
[g] Logarithmic rim width = logarithmic apparent diameter — 0.70 (Baldwin, 1963).
[h] Equals 2 times rim width + true diameter.

The average (AVG) parameters determined as shown in the table above were used to draw figure 8. Figure 8B shows why the autochthonous breccias were found to be rarer than the allochthonous ones. The autochthonous breccias would only have been formed, in this model of the original crater, between the dashed line and the dotted line. Therefore, the exposure of them is quite small, and in real craters, it is quite variable as well. The figure also shows why the sedimentary breccias are so important in understanding the nature of Jeptha Knob. The entire area above the dashed line must have been filled since the event of formation of the original crater. As mentioned above, this line may be drawn too low in the center of the crater, but certainly there should be a considerable quantity of filling material up to the completely undisturbed rocks at about 1050 ft elevation. This material would consist of the fallback and fallout and slump and later erosion products from the sides and rim of the crater.

Innes (1961) has established the volumes of rock involved in the various portions of a crater structure using theoretical considerations of cratering and empirical information. Using Innes' formulas and the above given average dimensions of Jeptha Knob, the writer has computed the following volumes of material for the Jeptha Knob structure:

V_c: Crater volume below original ground level

$$\begin{aligned} V_c &= (\pi/8)\, D^2\, (d - E) \\ &= 1.08 \times 10^{10}\ \text{ft}^3 \end{aligned}$$

V_b: Volume of breccia left in the center

$$\begin{aligned} V_b &= (\pi/8)\, D^2\, (D/3 + E - d) \\ &= 2.69 \times 10^{10}\ \text{ft}^3 \end{aligned}$$

V_t: Total volume of country rock ruptured

$$\begin{aligned} V_t &= V_c + V_b = (\pi/24)\, D^3 \\ &= 3.77 \times 10^{10}\ \text{ft}^3 \end{aligned}$$

V_e: Volume of fragmental rock ejected

$$V_e = (\pi/8)\, D^2 \left[\frac{D}{3}\left(\frac{\rho_c}{\rho_b} - 1\right) + d - E\right]$$
$$= 2.69 \times 10^{10} \text{ ft}^3 \text{ (upper limit)}$$

where:

D is the apparent diameter,
d is the apparent depth,
E is the rim height,
ρ_c is the country rock density before rupture, and
ρ_b is the density of the rock after rupture.

The density values are clearly inaccessible for a crater formed in the early Silurian in a carbonate depositional environment, for reasons given above. It is possible, however, to set upper and lower limits on the volume of fragmental rock ejected. In the above estimate, the density decrease was considered small, and to find the upper limit the quantity ρ_c/ρ_b was taken as 1. In this case the volume of fragmental rock ejected is the same as the volume of breccia left in the crater. Based on densities, Innes (1961) has found that the volumes of fragmental rock ejected from Holleford, Brent, and Deep Bay craters are from 20 to 45 percent greater than the crater volume below the original level. He writes "As compaction and lithification would tend to have increased the density of the breccia since it was first fragmented, the estimates may be taken as lower limits . . .". Since it is a lower limit we now need, let us take the 20 percent increment:

$$V_e = V_c + 0.2V_c$$
$$= 1.30 \times 10^{10} \text{ ft}^3 \text{ (lower limit).}$$

Let us now estimate the volume of the original Jeptha Knob crater below the first known undisturbed sedimentary deposit, the Silurian caprock at 1050 ft elevation:

$$V_f = (\pi/8)\, D^2\, (d - E - t)$$
$$= 9.50 \times 10^9 \text{ ft}^3$$

where: t is the thickness of the undisturbed rocks below the original ground level (1125 ft − 1050 ft = 75 ft).

This means that even if we accept our lower limit of fragmental rock ejected from the crater (V_e) as the most appropriate, there was still adequate material available to fill the crater up to the level of the undisturbed rocks. There was, in fact, 3.5×10^9 ft ^{3} in excess of this requirement. This excess can be considered to represent that fraction of the fragmental rock ejected from the crater that was not redeposited in the crater by subsequent sedimentary processes.

The material filling the crater would have been composed of fallback material, material that slumped in from the sides and rim, or material that was transported in by streams or currents. The rim itself may well have been destroyed to some extent by erosion and have contributed sediments to the filling, especially if it projected above sea level where wave action would rather quickly destroy the poorly lithified and deformed rocks. Entire blocks of rock could have slid along thrust fault planes into the crater. Such faults have been shown to be present by several crater investigators: Shoemaker (1962, 1966) at Meteor (Arizona) Crater and Jangle U and Teapot ESS nuclear explosion craters, Milton (1966) at the Henbury craters, and Roddy (1966) at the Flynn Creek structure. These slide blocks and the rotated and uplifted blocks of the autochthonous zone of figure 8B comprise the large fragment portion of the megabreccia zone of plate 2. A substantial fraction of this filling could have been accomplished by the rush of water bringing ejecta, mainly, and other materials back into the crater following the excavation phase of the impact crater formation.

Of course, after the filling of the crater, the normal Silurian sedimentation of the region continued. The Silurian in the center of the crater would be thicker, with the beds draped over any of the rim remaining. This thickening would include the antecedent of the "Corniferous hornstone" of Linney (Bucher, 1925). This rock is now very resistant to erosion, with the result that present topographic form is a monadnock.

The types of sedimentary breccias can now be interpreted in terms of the filling of the crater in early Silurian times. It should be emphasized again that these types are to be considered end members of more or less continuous series. The type, those with closely spaced angular fragments (pl. 3-A, B), represents mainly the fallback materials, although materials that slumped into the crater early, during the fallback deposition, would be similar. The second type, composed of angular fragments widely dispersed (pl. 4-A, B), represents fallback material that slumped into the crater later, after the fallback phase, when normal sedimentary processes were operating, or were carried back into the crater by the rush of the returning water, as suggested above. The third type (pl. 5-A) represents a conglomerate, probably from the rim. Whether the fragments were originally fallback ejecta subsequently reworked by streams, waves, or currents, or fragments eroded out of the rim itself cannot be determined, because they are of the same rocks. This relationship explains the observations of Bucher, quoted previously, and of the writer that the source of the fragmental material seems to be near the periphery of the structure. Two of the three types have peripheral sources.

This interpretation compares well with the findings of Dence (1965) at the Brent crater. The first type found by the writer at Jeptha Knob corresponds to the "fallout or fallback" material of unit 2 of Dence, the second type corresponds to the "slumped" materials in unit 2 of Dence, and the third type of the writer corresponds to the "basal grits" of unit 1 of Dence.

It should be noted that the interlayering of the fallout and fallback materials with the material slumped in from the sides forms quite a thick unit. Unit 2 of Dence is 1120 ft thick at Brent Crater. Shoemaker (verbal commun.) cautions against "too much slumping in during the fallback deposition". The results of the study of Jeptha Knob by the writer would tend to confirm the findings at Brent Crater, for a considerable amount of filling material must be present. As can be seen in the table of parameters of Jeptha Knob, about 550 ft of this material is required, roughly 10 percent of the diameter as at Brent crater. The answer to this difference of opinion may be the environment. Shoemaker has worked on craters formed on dry land, while Jeptha Knob and Brent crater probably had a layer of water present at the time of formation. Thus, the materials swept in by the return of the water and the tendency toward formation of central uplifts in craters formed in water may explain the discrepancy.

Finally, an estimate of the energy involved in the deformation can be made. Innes (1961) gives a formula for the total energy of the body which impacted, forming a crater as:

$$E_{\text{meteorite}} = 5.08 \times 10^{11} D^3 \rho_c \text{ ergs.}$$

D and ρ_c are as in previous equations. As noted above, ρ_c is not known, but, considering that the country rocks were poorly lithified and probably fairly porous, a value of 2.0 g/cm^3 can be taken as reasonable. The above formula then gives 2.9×10^{23} ergs. The results based on Baldwin's work (1963) give about 5 times greater energy.

Using a table from Baldwin (1963) we can derive the size of a nickle-iron meteorite that could produce a crater of the size of the original Jeptha Knob structure if it exploded at a scaled depth of burst of $H/W_{1/3} = 0.10$ (pointsource model; H = height (−) or depth (+) of the burst center in ft, W = explosive energy in terms of pounds of TNT equivalent.) The following mass-velocity relationships hold:

	Velocity (miles per sec)			
	2	10	25	50
Mass (lb)	7.6×10^{11}	3.0×10^{10}	5.0×10^9	1.2×10^9

The choice of the proper velocity is left to the reader, but 2 miles per sec is probably just below the lowest velocity that could make an impact explosion crater and 50 miles per sec about the highest impact velocity to be expected.

SUMMARY AND CONCLUSIONS

The Jeptha Knob structure is the result of a violently disruptive process which occurred in its entirely during a very brief period of the early Silurian. The formation of the Jeptha Knob structure was extremely rapid, and all the deformation seems to have been contemporaneous.

To determine the shape of this disturbance in three dimensions, geophysical methods, a magnetic and gravity survey, were used to supplement the rather meager subsurface information. Such methods would be very likely to reveal a buried structure caused by a volcanic or tectonic event. The magnetic survey shows that there is not likely to be a basement counterpart to the Jeptha Knob structure. The gravity features observed can be totally explained by the densities of the near-surface sedimentary rocks. Furthermore, the drilling information seems to show that the disturbance decreases with depth and at rather shallow depth.

The above findings, along with complete absence of any other indication of endogenetic activity, volcanism, or tectonism of any type, force us to conclude an exogenetic origin for Jeptha Knob. Hypervelocity impact of a meteorite or comet is the most likely exogenetic mechanism, and therefore, the original structure of Jeptha Knob was modeled using the known characteristics of such craters. The model was based on the best known parameter presently available, the extent of the capping undisturbed Silurian rocks. The original crater was found to have the following probable dimensions:

Apparent diameter	6600 ft
Apparent depth	920 ft
Rim height	290 ft
Rim width	1300 ft
Depth to the limit of major brecciation	1600 ft

Jeptha Knob has the following features *especially* suggestive of an impact origin:

1. Approximate circularity.
2. Intense brecciation of the country rock.
3. Folding beyond the central zone, decreasing rapidly outwardly (damped).
4. Short period of time of formation and contemporaneousness of all features.
5. Geophysical and drilling evidence that the structure is confined to near surface rocks.

Also present are the following features considered indicative of an impact origin:

6. Distinctive sedimentary breccias.
7. General uplift of the folded and crushed zones, decreasing outward.
8. Chaos breccias in the central zone containing units from several horizons including surface beds.

No criterion for the recognition of impact structures that could be expected to be present was found to be absent.

In view of all of the above, the writer concludes that the Jeptha Knob structure is indeed the result of hypervelocity impact of a meteorite or comet.

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