A SEISMIC REFLECTION STUDY OF A PROBABLE ASTROBLEME NEAR HARTNEY, MANITOBA

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ABSTRACT

Because of the similarity between the Hartney anomaly of southwestern Manitoba and certain other oil-bearing features in the Williston Basin, a 1200 percent seismic reflection survey was conducted over this anomaly. These data showed an extremely complex, circular structure set in a relatively undisturbed regional geologic setting. By utilizing both migrated sections and seismic velocity analysis, a structural model was developed for this feature. Its structural configuration indicates that the Hartney anomaly is probably an astrobleme, or meteorite impact crater, of Lower Cretaceous age. A possible sequence of events resulting in this structure was postulated from existing seismic control and well data.

INTRODUCTION

The Williston Basin of central North America is a gentle, bowl-shaped depression lying in western North Dakota, southeastern Saskatchewan and southwestern Manitoba, with extensions into eastern Montana and northern South Dakota. The basin was formed near the end of the Mississippian period and was subsequently truncated by post-Paleozoic erosion. The outline of this basin, as defined by post-Paleozoic erosion, is shown in Figure 1.

The geology of the Williston Basin is characterized by extreme uniformity of lithology and isopach, and the beds exhibit very gentle structural dip. The only major tectonic features within the basin are the Nesson anticline in North Dakota and the Cedar Creek anticline in Montana.

Figure 2 illustrates a simplified stratigraphic column for the southwestern Manitoba position of the Williston Basin. Gross lithologies are shown in the central column and the significant seismic markers are identified by their formation names on the right. These formation names are those in common usage in Manitoba.

Superimposed on this very regular geologic picture are several circular structural features, ranging in diameter from two to six miles, with which significant oil accumulations have been associated. The locations of these circular features within the Williston Basin are shown in Figure 1.

The first of these features to show an oil accumulation is located near Viewfield, Saskatchewan. The structure consists of a circular depression, approximately three miles in diameter, cut into Jurassic and Mississippian strata. This depression is surrounded by a raised rim made up of Mississippian debris removed from the depression, and lying on younger Jurassic sediments. It is believed that this structure is an astrobleme, or impact crater, caused by a meteorite impact during the Lower Jurassic. A commercial oil field was discovered in the raised rim of this feature in 1968. The feature has been described in some detail by Sawatzky (1972, 1975).

The second such feature to yield a commercial oil discovery is the Red Wing Creek structure of North Dakota. This extremely complex, circular structure is approximately six miles in diameter and is characterized by an uplifted,

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fractured central core. Although its genesis is not as straightforward as that of the Viewfield example, it also is thought to be an astrobleme. The oil field, discovered in 1972, is trapped in the central, uplifted core. This structure has been described by Sawatzky (1975) and Brennan *et al.* (1975).

At Newporte, North Dakota, another circular structure exists, consisting of a depression, two miles in diameter, surrounded by a raised rim. This feature is much older than the previous two examples, occurring some time near the end of Cambrian time. Whether this structure is an astrobleme or not is not clear; however, it does exhibit the circular nature common to the previous two examples and, in 1977, oil was discovered in basal Paleozoic sands draped over the raised rim.

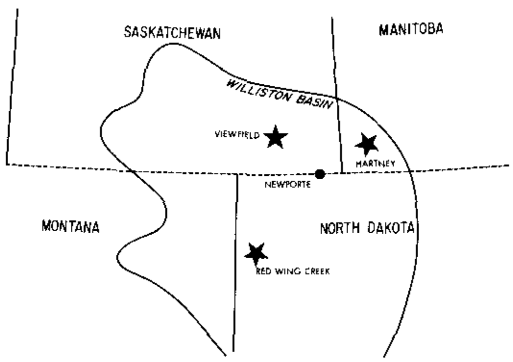

Fig. 1. Williston Basin location map.

Because of the occurrence of oil deposits in these unusual structural features within the Williston Basin, a seismic reflection survey was conducted over a similar anomaly, approximately six miles in diameter, near Hartney in southwestern Manitoba.

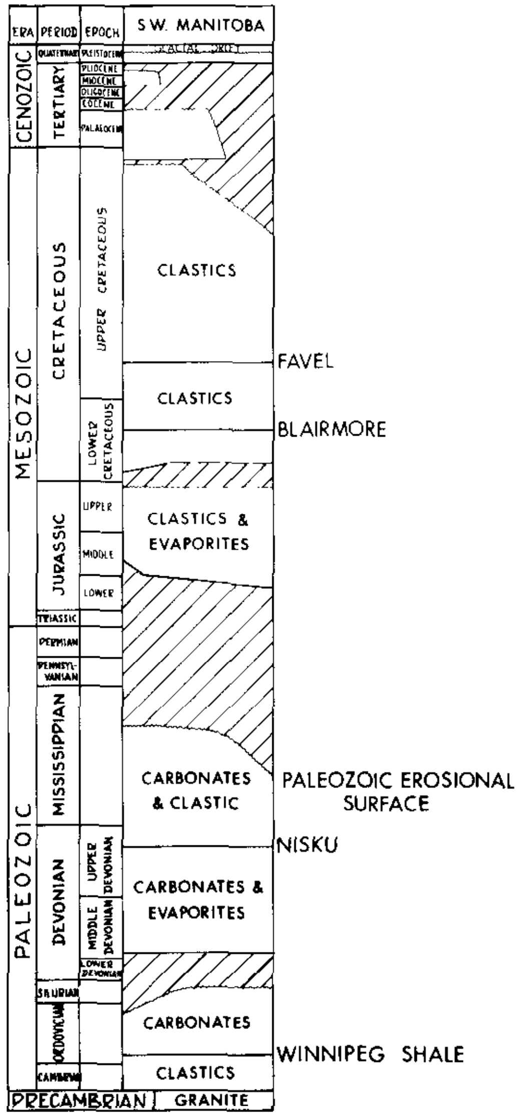

Fig. 2. Generalized stratigraphic column.

Early Seismic Studies and Drilling

During the early 1950s, 100 percent seismic reflection data had been obtained over most of the Hartney area. These data showed continuous reflections only down to the Blairmore over the Hartney anomaly. Reflections below the Blairmore were either too discontinuous to map or absent altogether. The outer boundary of the anomaly could be determined, however, by mapping the termination of pre-Blairmore events such as the Paleozoic erosional surface, Nisku and Winnipeg Shale. The outline of the Hartney anomaly as mapped by this method is shown on Figure 3. Furthermore, the above-mentioned Paleozoic events appeared to turn upward before terminating.

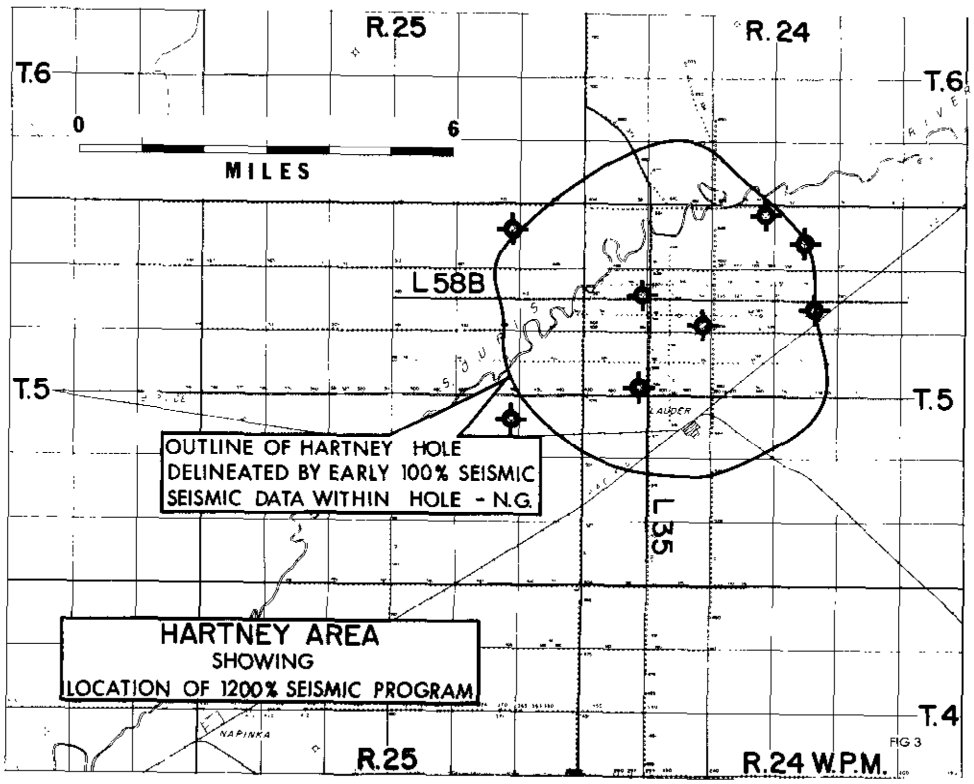

Fig. 3. Hartney area, showing location of 1200% seismic program.

A total of six wells had been drilled into or near to the Hartney anomaly previous to 1978. The results of this early drilling were confusing to say the least. The first well, Calstan Hartney 16-33-5-24 W1, was located just beyond the termination of the upturned Paleozoic markers and encountered the top of the Paleozoic over 600 ft below regional, with the Mississippian totally absent. Another well, Madison Lauder 1-19-5-24 W1, drilled further toward the centre, encountered the Paleozoic top over 200 ft above regional, with Mississippian sediments present. L-M Imperial Hartney 1-29-5-24 W1 drilled near the centre, encountered the Paleozoic top over 200 ft above regional, with Mississippian strata missing. No hydrocarbon shows were encountered in any of the early drilling. Furthermore, much of the Paleozoic porosity had been destroyed by anhydrite infilling. However, in view of the difficulty in interpreting the 100 percent seismic data, it was felt unlikely that any of the original wells had been drilled in a favourable position for hydrocarbon entrapment.

Current Seismic Reflection Program — Objectives and Methods

It was felt that modern seismic data-acquisition techniques would allow the interpreter to "see into" the Hartney anomaly in a fashion not possible for earlier workers in the area. This improved resolution would then permit the location of exploratory drilling in more structurally favourable positions. To achieve this end, approximately 110 mi of 1200 percent seismic program was laid out over the anomaly and shot in two stages. The location of this program is shown in Figure 3.

Texas Instruments DFS V recording instruments were used to record the reflection data, utilizing as a source 1 kg of dynamite buried at 12 m.

The interval between group centres was set at 16 m, with a 64 m shot-point interval. The 96-trace spread was arranged in a 24/72 asymmetric split spread. This particular spread geometry was felt to provide the optimum compromise between multiple attenuation and shallow-event retention. Record quality obtained was very good.

To process these data into stacked sections, a standard processing flow was employed, involving spiking deconvolution, initial and residual normal-moveout corrections, initial and residual static corrections, followed finally by CDP stacking. All stacked sections were migrated by using wave-equation methods. In addition, selected lines were given a detailed seismic velocity analysis, to aid in the development of an accurate structural-depth model.

The Hartney Anomaly

Structural Configuration

The line that best illustrates the major geometric elements of the Hartney anomaly is L.58B (Fig. 4). The location of this line is shown in Figure 3. The extreme structural variations on the various seismic events are immediately apparent, and are greatly out of character with typical Williston Basin structure. Because of the lack of parallelism between the various seismic markers, it is necessary initially to describe each marker separately.

The deepest event arising from the sedimentary section is the Winnipeg Shale event. This marker is a reflection from a carbonate/shale interface, approximately 200 ft above the Precambrian surface. Moving from the outside inward toward the centre of the anomaly, the event first appears to rise as it approaches the anomaly's edges. As overlying horizons terminate, the Winnipeg Shale event appears to plunge off into a syncline. Progressing inward, the event rises again, culminating in an inner anticline. Continuing inward, the Winnipeg Shale event drops off into a sharp central pit. In plan view, the outer and inner anticlines and the syncline between them are somewhat discontinuous; however, they are circular in nature and the terms 'ring anticline' and 'ring syncline' seem appropriate.

Moving upward in the section, the Nisku event appears to parallel the Winnipeg Shale event; however, at the boundary of the anomaly the event terminates and cannot be identified within the anomaly.

Immediately above the Nisku event lies the Top of Paleozoic marker. Outside the boundary of the anomaly, this seismic event arises from the velocity contrast between the Jurassic Red

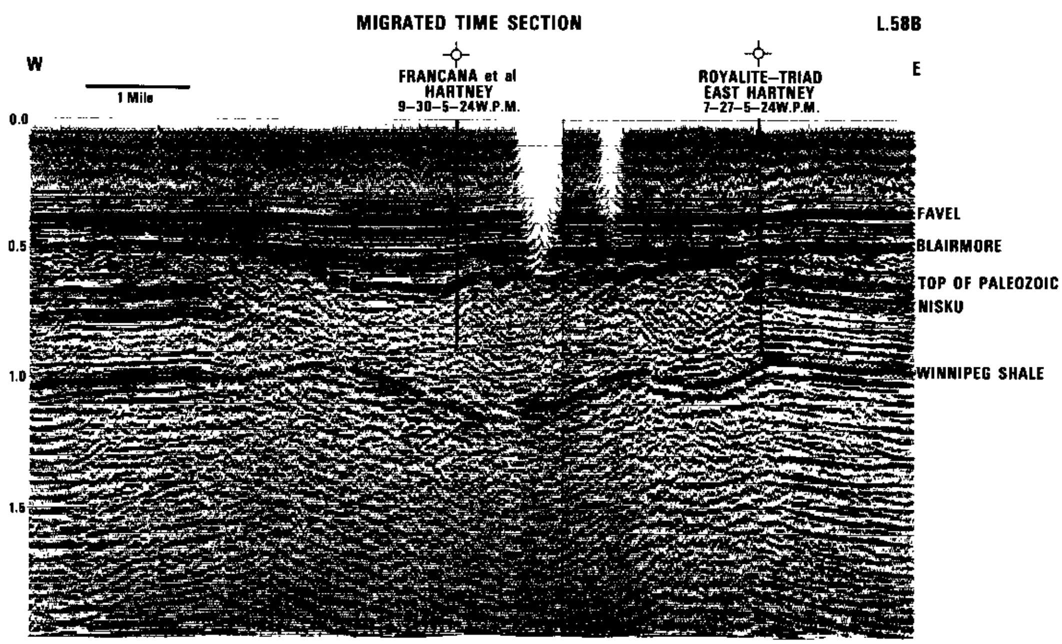

Fig. 4. Migrated time section, line L.58B.

Beds and the older, pre-erosion Mississippian carbonate. Although this horizon is an angular unconformity, the degree of angularity between Mississippian strata and overlying Jurassic beds is very low.

Moving inward toward the boundary of the anomaly, the Paleozoic unconformity turns upward, parallelling the outer ring anticline seen on the Winnipeg Shale event. At the boundary of the anomaly, however, this similarity ends, as the Top of Paleozoic event terminates against a jumble of uncorrelatable seismic energy. Moving inward across this confused zone of seismic energy, the Paleozoic top recurs at a much higher structural elevation. From this point inward, the event drops slightly and continues across the anomaly, forming an upraised, dish-shaped surface. Around the flanks of this upraised dish, Mississippian-age rocks are at the surface of the Paleozoic, but toward the centre, Mississippian rocks are absent and older Devonian strata are at the surface. It is believed, for reasons that will become apparent later, that this uplifted, dish-shaped surface was subaerially exposed immediately following the phenonema that caused this anomaly. At the very centre of the anomaly, the Top of Paleozoic event is forced up into a central uplift, directly above the central pit on the Winnipeg Shale.

The next correlatable seismic event above the Top of Paleozoic marker is generated by the top of the Blairmore. This is the first event to continue across the anomaly unbroken, and sets the age of formation of the anomaly as Lower Cretaceous. Between the Blairmore and Top of Paleozoic events, outside the anomaly itself, the seismic reflections are extremely contorted. This situation continues outward from the boundary of the anomaly for a distance of several miles. At this point, the chaotic seismic reflections merge back into their normal, flat-lying configuration. As this zone was near the ground surface at the time of formation of the Hartney anomaly, it can be inferred that the creation of this feature was accompanied by a great deal of surface destruction for a distance of several miles on all sides. Within the feature, the interval between the Blairmore and the Top of Paleozoic consists of easily correlatable, flat-lying events.

Above the Blairmore event, a normal sequence of Lower and Upper Cretaceous seismic markers is observed, with only minor structural fluctuations over the region of the anomaly.

The above-described structural features appear to be roughly symmetrical about the centre of the anomaly in an east-west direction.

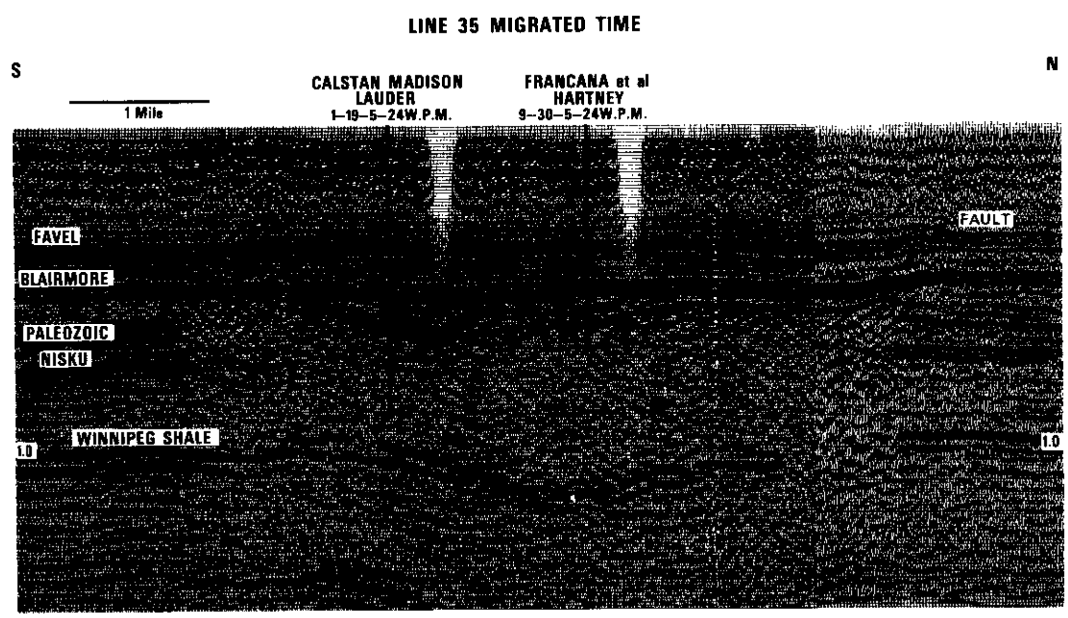

Fig. 5. Migrated time section, line L.35.

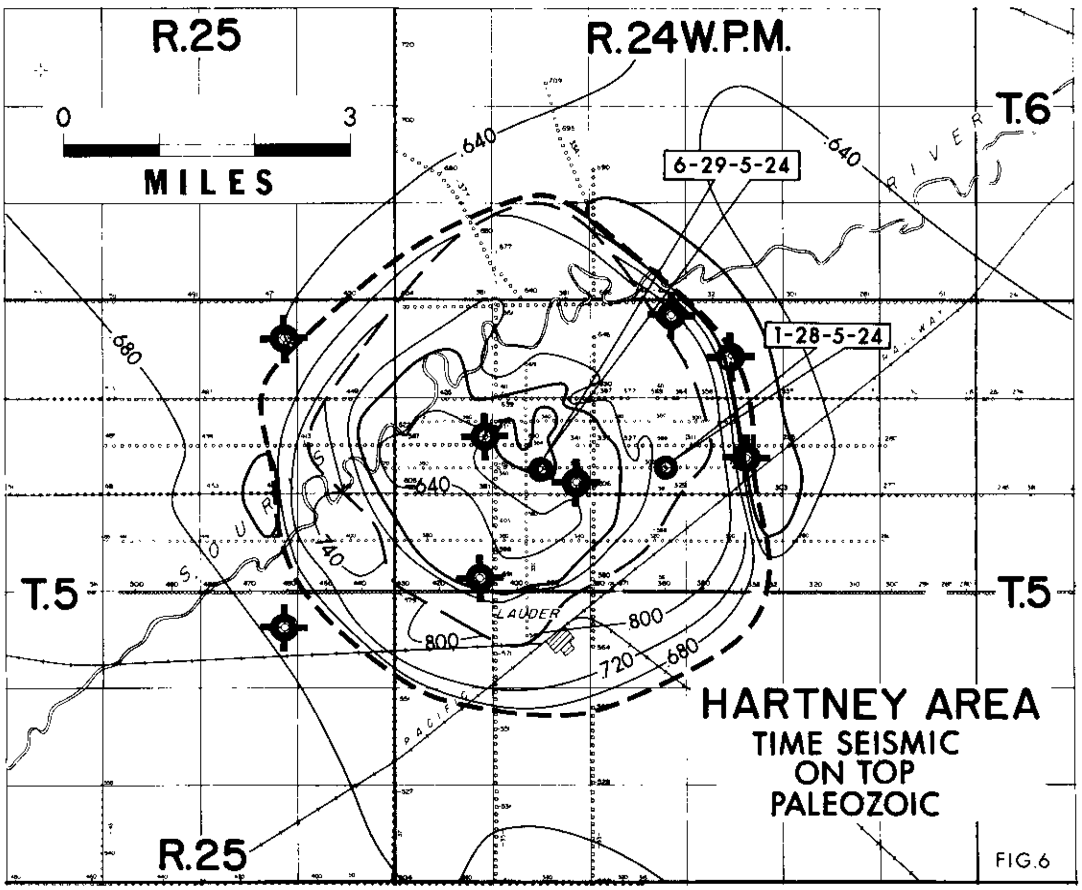

Fig. 6. Hartney area: time-structure map on Top of Paleozoic.

Turning now to the north-south seismic section, L.35 (Fig. 5), it can be seen that this symmetry is not as apparent in a north-south direction. The south flank of the anomaly displays the same outer and inner ring anticlines and ring syncline on the Winnipeg Shale, while the Top of Paleozoic event behaves in a fashion similar to that seen on L.58B. However, on the north flank, the Winnipeg Shale marker climbs out of the central pit without forming the inner anticline or syncline. Instead, the event appears to be broken and pulled apart. On the other hand, the Top of Paleozoic event, where it forms the edge of the inner upraised bowl, seems to be thrust over the Top of Paleozoic event seen outside the anomaly.

Figure 6 is a time-structure map on the Top of Paleozoic event. The outer dashed line marks the apex of the outer ring anticline as mapped on this horizon. The inner dashed line marks the outer edge of the inner, upraised dish. The small structural high seen in the centre of the feature marks the location of the central uplift.

Because of the dramatic lateral variations in structure, and possible corresponding variations in average velocity below the Top of Paleozoic event, it was felt necessary to develop a velocity model for the anomaly. This was done in order to convert the Winnipeg Shale event from a time horizon to a depth marker before mapping, thus removing the effects of any lateral velocity variations. To accomplish this, detailed seismic velocity analyses were done on several lines. The results of the velocity study on a portion of L.35 are shown in Figure 7. This figure shows a plot of interval velocities versus time, determined between the major seismic horizons. From the surface to the Blairmore

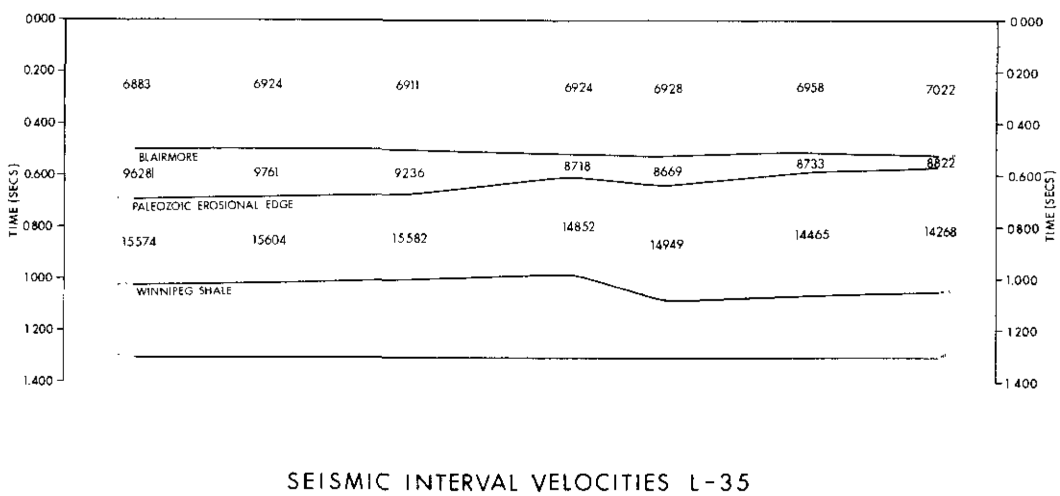

Fig. 7. Seismic interval velocities, line L.35.

event, the interval velocity appears to remain relatively constant. Between the Blairmore and the Paleozoic Top, the interval velocity appears to decrease by 1000 ft./sec. while moving from outside the anomaly to within it.

This apparent decrease in interval velocity between the Blairmore and the Top of Paleozoic within the inner, upraised dish is supported by known well control. The decrease in interval velocity, when combined with the dramatic change in reflection character in this interval going from within the anomaly to outside it, appears to indicate some basic change in depositional history for the area inside the inner dish. Furthermore, stratigraphy as determined from log character and chip samples from wells within this area cannot be satisfactorily correlated to wells outside the inner dish on the Top of Paleozoic. It is these observations that lead to the conclusion that the inner, upraised dish-shaped depression on the Top of Paleozoic was subaerially exposed immediately after formation of the Hartney anomaly. This exposed depression, or crater, was subsequently filled with either sea water or a crater lake, and a sequence of beds was laid down in the crater that was much younger than most of the surrounding sediments in this interval.

The interval velocities between the Paleozoic erosional surface and the Winnipeg Shale also appear to decrease toward the centre of the anomaly. This behaviour, however, is not reflected in the well control. Furthermore, the Winnipeg Shale event is discontinuous and steeply dipping. Consequently this reduction in seismic interval velocity cannot be considered reliable. Any reduction in velocity that may be present is probably minor and related to brecciation and fracturing within this interval in the centre of the anomaly.

Figure 8 shows the final velocity model that was used to generate a depth map on the Winnipeg Shale. It was based on seismic velocity trends observed on several lines, including the one previously described, and strongly modified by information from wells in the area. This model was not intended as a detailed picture of interval velocity, but only as a means of computing approximate depth values to the Winnipeg Shale, with the aim of removing only the grossest velocity variations. Subsequent exploratory drilling demonstrated the model's basic validity.

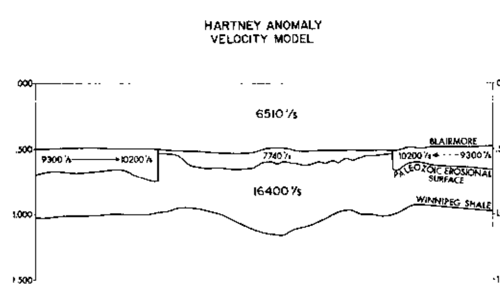

Fig. 8. Hartney anomaly velocity model.

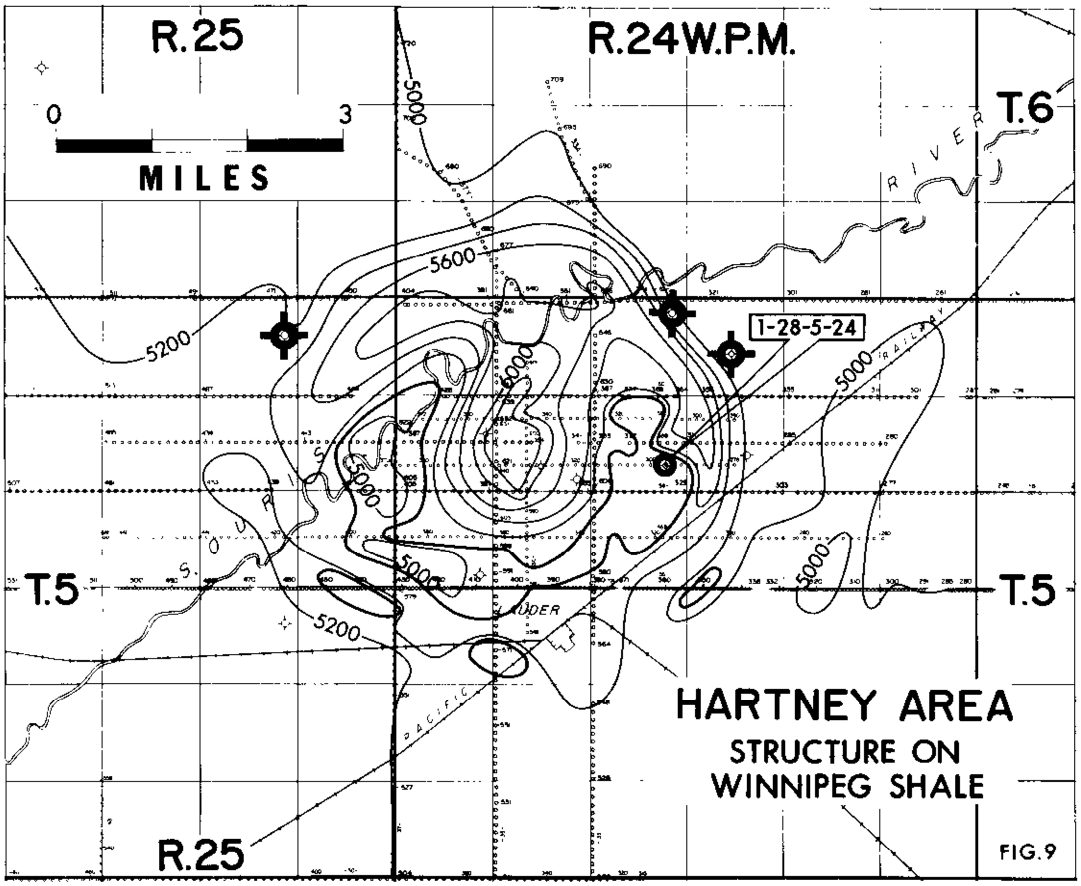

Fig. 9. Hartney area: structure on Winnipeg shale.

The structural depth map on the Winnipeg Shale developed from this velocity model is shown in Figure 9. On this map, the inner and outer ring anticlines, the ring syncline and the central pit can be seen. Highlighted wells are those that penetrate to the Winnipeg Shale.

Two exploratory wells were drilled by Chevron Standard Limited on this anomaly. The first well, Chevron *et al.* Hartney 1-28-5-24 W1, was drilled on the inner ring anticline. This location appeared to provide structural closure on all Paleozoic horizons within the anomaly. The well was drilled to Precambrian basement. Both the Top of Paleozoic and Winnipeg Shale horizons were structurally higher than in any surrounding wells. Mississippian rocks were present at the Top of the Paleozoic section.

The second well, Chevron *et al.* Hartney 6-29-5-24 W1, was located on the central uplift on the Top of Paleozoic and was abandoned 800 ft below the Top of Paleozoic. No Mississippian-age rocks were encountered in this well. There were no hydrocarbon shows encountered in either well.

Origin

The unusual nature of the Hartney anomaly suggests three possible origins for the formation of this feature: 1) normal tectonic forces, 2) volcanic explosion, or 3) meteorite impact.

Of these three possibilities, the notion that the Hartney anomaly is a product of normal tectonic forces is probably the easiest to dispense with. It seems unlikely that, in a

16-33-5-24 W.1 M.
SOURIS RIVER FORMATION

FIG 10

16-33-5-24 W.1 M.
SOURIS RIVER FORMATION

FIG 11

Figs. 10, 11. Brecciation and faulting in Devonian rocks within the core.

sedimentary basin as devoid of significant structural features as the Williston Basin, any tectonic forces could have existed that would produce a local structure as violent as the Hartney anomaly. Furthermore, it is difficult to imagine a combination of tectonic forces in any kind of environment that would produce a high-amplitude circular structure, six miles in diameter, without disturbing the surrounding strata. Thus, a simple tectonic origin seems unlikely.

The possibility that the Hartney anomaly was a result of a volcanic explosion must be considered much more seriously. The dish-shaped depression on the Top of Paleozoic surface within the anomaly is reminiscent of a volcanic cauldera. Also, the location of the anomaly lies very close to the interpreted boundary between the Churchill and Superior Provinces in the Precambrian (Rankin *et al.*, 1978), a likely place to expect volcanic activity. There are, however, several arguments that dispute a volcanic origin for this feature. Evidence of volcanic activity within the Williston Basin is nonexistent to this author's knowledge, either along the Churchill-Superior boundary or anywhere else within the basin. Thus volcanic activity does not seem to have played a role in Williston Basin structural history. Furthermore, it seems likely that, if the Hartney area were the site of a catastrophic volcanic event, some evidence, such as beds of volcanic ash or igneous intrusions, would appear in chip samples taken from wells from the Hartney area. To date, no such evidence of volcanic activity has been reported in exploratory bore holes in the Hartney area. In addition, there is no magnetic anomaly and only a very minor gravity anomaly associated with this feature. It is difficult to imagine a deep-seated igneous source for this anomaly that did not also result in a magnetic anomaly.

The best clue to the genesis of the anomaly may lie in the geometry of the feature itself. When viewed in its entirety, the impression it creates is one of maximum destruction at the ancient Lower Cretaceous surface, with the amount of disturbance decreasing with increasing depth. Lower Cretaceous and Jurassic beds appear to be crumpled and broken for a distance of several miles beyond the immediate boundary of the anomaly. Within the anomaly itself these beds are absent. The Mississippian strata around the flanks of the anomaly are thrust over each other several times and in places are overturned. Mississippian-age rocks are missing from the centre of the anomaly. Devonian-age rocks are intensely brecciated and faulted (see Figs. 10, 11) but are present within the core. Finally, at the depth of the Ordovician Winnipeg Shale, the beds remain more or less continuous, although thrown into sharp folds. The continuous nature of Ordovician beds is indicated by the generally continuous Winnipeg Shale seismic event. The Nisku event, on the other hand, is unidentifiable within the anomaly, although Nisku-age rocks are present. If a deep-seated volcanic event were the cause of the Hartney anomaly, one would expect the disturbance in the sedimentary section to increase with increasing depth, or at least remain constant. Thus, one is left with the overwhelming impression that the force that created the Hartney anomaly was applied in a blow from above rather than below. This impression brings us to the third possible cause; namely, a meteorite impact.

A great deal of literature has been published on the subject of meteorite-impact craters, and it is beyond the scope of this paper to delve into this material in any detail. Several authors working in this field, however, have developed models for meteorite-impact craters (Dence, 1968; Dence *et al.*, 1977; Sweeney, 1978; Pike, 1971) that bear a striking resemblance to the Hartney anomaly. The arrangement of concentring ring structures, the formation of a crater with a central uplift, and the apparent net upward-and-inward particle motion of the centre combined with net downward-and-inward motion along the flanks are all characteristics of known astroblemes.

The two generally accepted diagnostic characteristics of meteorite-impact craters are the presence of meteorite fragments and the presence of shock metamorphism. Unfortunately these two criteria have not been observed in the Hartney anomaly. Generally, in astroblemes the size of Hartney, the meteorite has been completely destroyed on impact (Dence *et al.*, 1977). Hence, meteorite fragments would not be expected around or in the anomaly. The absence of evidence of shock metamorphism is probably more a result of the fact that the anomaly is hidden from view in the subsurface than an actual absence of shock metamorphism. The only view we have of the rock itself within the anomaly is through cores taken in wells drilled to evaluate the anomaly's hydrocarbon potential. These cores, therefore, were not taken from locations or horizons that might best display evidence of shock metamorphism. Furthermore, the cores have not been studied in sufficient detail to determine whether shock metamorphism is present. Therefore, in this case, the absence of evidence of shock metamorphism is not considered to be a significant factor in determining the origin of this anomaly.

From the preceding discussion, then, it is this author's conclusion that, although it cannot be proved conclusively, the Hartney anomaly is probably a meteorite-impact crater, or astrobleme, of Lower Cretaceous age. Dence (1965) has divided impact craters into two broad categories: i) simple craters consisting merely of a depression with or without a raised rim, and ii) complex craters having an uplifted central region. The upraised Paleozoic surface in the centre of the Hartney crater would place it in the latter category.

With meteorite impact in mind as the probable cause, the following sequence of events has been postulated in the formation of the Hartney crater:

I. *Pre-impact* — During the Lower Cretaceous, before impact, a normal sequence of flat-lying sediments had existed in the Hartney area, as shown in Figure 12.

II. *Transient Crater* — At the instant of collision between the incoming meteorite and the earth's surface, a large, deep crater was excavated in the earth's surface to the depth of the Devonian (Fig. 13). Both the colliding meteorite and a portion of the earth's crust were completely disintegrated. The Mississippian section near the centre was thrown out to the flanks in a series of thrust sheets and overturned beds. This sequence of repeated and overturned Mississippian beds is well displayed in Chevron *et al.*

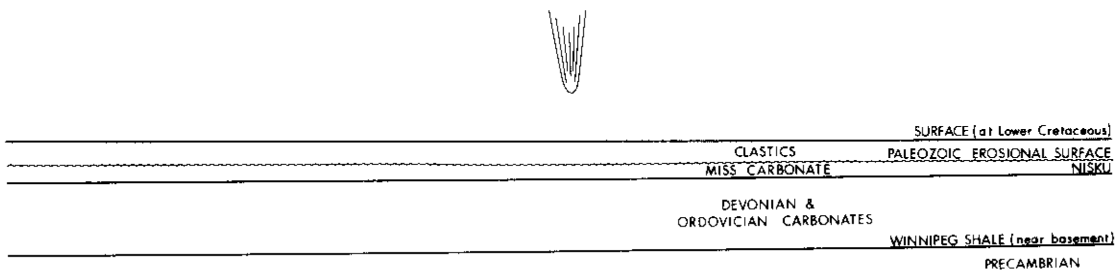

Fig. 12. Pre-impact state of Hartney sediments.

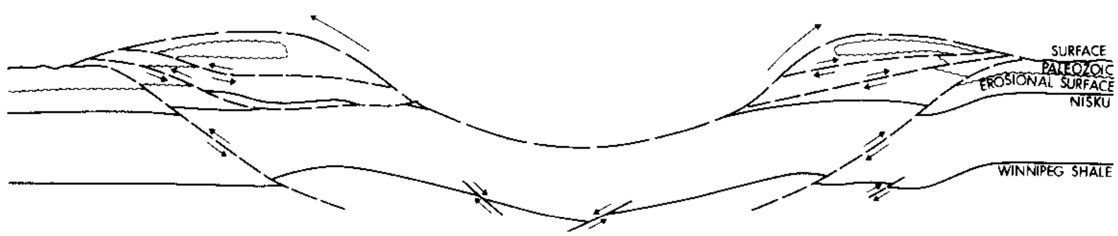

Fig. 13. Transient crater resulting from collision.

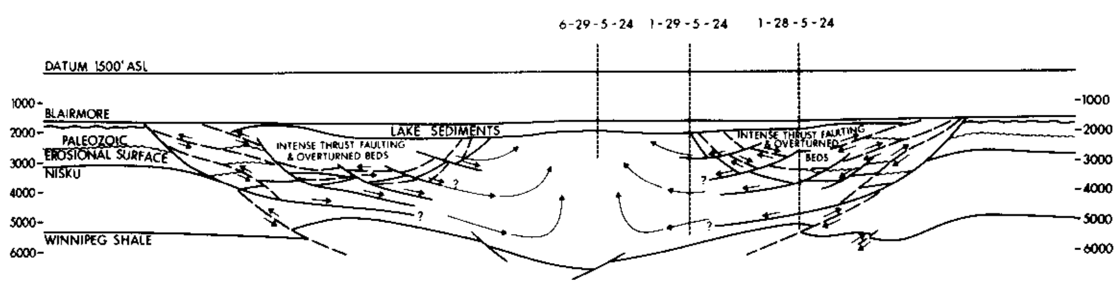

Fig. 14. Post-slump appearance of Hartney sediments.

Hartney 1-28-5-24 W1. The absence of Mississippian rocks in the centre of the crater is documented in Chevron *et al.* Hartney 6-29-5-24 W1 and L-M Imperial Hartney 1-29-5-24 W1.

The compressional wave that caused these thrusts travelled deeper into the section, depressing the Winnipeg Shale horizon beneath the point of impact and forcing the Winnipeg Shale marker, surrounding the point of impact, into the ring anticlines seen in Figure 4. The asymmetry about the centre, seen on the Winnipeg Shale event in Figure 5, may provide a clue to the meteorite's angle of impact. The meteorite may have angled in from the north, ridging up the Winnipeg Shale horizon to the south, west and east, while pulling it apart along the northern flank of the crater.

III. *Post-slump* — The steep-sided crater walls and high relief created by the impact were too much for the highly brecciated rock to support, and the raised flanks of the transient crater slumped back into the centre (Fig. 14). This slumping occurred along one major normal fault and numerous smaller ones. The major normal fault is seen in 1-28-5-24, where almost 1000 ft of Devonian, Silurian and Ordovician rocks are removed, placing the Devonian Winnipegosis Formation directly on top of the lower portion of the Ordovician Red River Formation. The many minor normal faults can also be seen in this well. As the flanks of the transient crater slumped inward, the bottom of the crater was raised to its present configuration and the central uplift was formed. The crater filled with water and normal deposition of sediment resumed. Most of the slumping probably occurred fairly rapidly, as indicated by the lack of major structure on younger beds. However, some minor post-Favel settling seems to have occurred, as shown by the minor structure on this horizon in Figures 4 and 5.

Conclusion

Exploratory drilling, which now numbers ten wells, seems to indicate that the Hartney astrobleme does not harbour significant hydrocarbon accumulations. The process of exploration, however, has resulted in the accumulation of a large mass of seismic and well data over this anomaly. The nature of oil exploration does not justify further work on this feature but, from an academic point of view, much more could be done. In particular, a thorough and detailed analysis of cores taken during exploratory drilling could cast more light on the genesis of the anomaly.

It is felt, however, that on the basis of existing work, the meteorite-impact hypothesis is the most reasonable explanation for this most unusual feature.

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