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3-D SEISMIC EXPRESSION OF A CRYPTOEXPLOSION STRUCTURE[1]

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ABSTRACT

An enigmatic circular structure is observed on three-dimensional (3-D) seismic data from James River, Alberta. It has an outer diameter of 4.8 km and a raised central uplift surrounded by a ring synform. The central uplift has a diameter of 2.4 km and its crest appears to be about 400 m above regional levels. The top of the structure is at a depth of about 4500 m and is below the zone of previous economic interest. Consequently, the feature has not been penetrated by any wells in the survey area. The seismic data interpretation indicates that the disturbed sediments are Cambrian in age. It is estimated that the structure was formed during the Late Cambrian to Middle Devonian time period and suffered severe erosion before the deposition of the overlying Middle and Upper Devonian carbonates. Rim faults, probably caused by slumping of material into the depression, are observed on the outer slope of the synform. Reverse faults are revealed by the seismic data underneath the feature. The central uplift appears to have coherent internal reflections and the amount of uplift is seen to decrease with increasing depth. The whole feature has the morphological characteristics of a meteorite impact structure.

INTRODUCTION

Several enigmatic circular structures have been described from observations on seismic data from the Western Canadian Sedimentary Basin (WCSB) (Sawatzky, 1976; Isaac and Stewart, 1993) and other parts of Canada (Scott and Hajnal, 1988; Jansa et al., 1989). These structures are often imaged well on seismic data. Cryptoexplosion structures have a characteristic circular to polygonal morphological outline and display evidence of violent disruption during their formation but lack evidence of volcanic material to confirm a volcanic origin. Cryptoexplosion structures can result from meteorite impact or diatreme intrusion (Nicolaysen and Ferguson, 1990). Diatreme structures are thought to be caused by abrupt and violent exsolution of deep gasses and fluids but are not well documented, geophysically. In contrast, the mechanics and morphology of impact craters have been studied and documented in great detail (e.g., Roddy et al., 1977; Melosh, 1989; Sharpton and Ward, 1990). Impact craters can be termed either simple or complex, the main difference being the presence of multiple ring structures and central uplift in a complex crater. The morphological change takes place at an excavation cavity diameter of about 2 km in sedimentary rocks and 4 km in crystalline rocks (Dence, 1972). The principal feature of a complex impact crater is a central peak, or group of peaks, surrounded by a flat floor inside a terraced rim (Dence, 1965). Complex crater central peaks are composed of deformed and fractured rocks which are often older than the country rock surrounding the structure. Partial collapse of the central peak may be the source of some of the breccia filling the surrounding rim synform.

Without geological evidence it is difficult to establish the origin of a structure observed on seismic data alone, since similarly shaped features can result from different causes. However, observed morphological and tectonic features such as central uplift, changes in structural uplift with depth or fault patterns, may provide compelling evidence for the origin of the structure.

Economic aspects of impact craters

Mineral deposits such as metals and hydrocarbons are associated with about twenty percent of all known impact craters and in some cases the economic implications are significant (Masaytis, 1989). In some structures, interpreted to be impact craters, commercial hydrocarbon accumulations have been found (Table 1: Sawatzky, 1972; Brenan et al., 1975; Carpenter and Carlson, 1992). The significance for the petroleum industry of impact craters as hydrocarbon-bearing was discussed in detail by Donofrio (1981).

The geophysical responses of impact structures were summarised by Pilkington and Grieve (1992). Several probable impact craters have been imaged with seismic data, use of which allows good estimates of a structure's size and age. 3-D seismic data, in particular, afford three-dimensional images unobtainable by other methods.

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Table 1. Tabulation of some commercial hydrocarbon accumulations associated with probable impact craters.

Name	Diam (km)	Age	Hydrocarbons
Viewfield, Saskatchewan	2.4	Triassic/ Jurassic	Commercial oil field discovered in 1968. Production of up to 65 m^3/d (400 bbl/d) from Mississippian carbonate breccia and in-situ Mississippian in the raised rim. Pay thicknesses from 4 m to 50 m. Estimated reserves: 3.2×10^6 m^3 (20 MMbbl) recoverable. $\emptyset = 14\%$, k = 400 md.
Red Wing Creek, North Dakota	10	Triassic/ Jurassic	Commercial oil field discovered in 1972. 870 m of pay in Mississippian carbonate breccia from a 1.6 km diameter area within the 6.5 km diameter central uplift. Reservoir rocks are steeply dipping and intensely faulted. Estimated reserves: 6.4×10^6-11×10^6 m^3 (40 -70 MMbbl) recoverable.
Newporte, North Dakota	3.2	end Cambrian	Oil shows found in 1977 in Cambro - Ordovician sands draped over the raised rim. Some production from highly-fractured Precambrian gneiss-schist.
Ames, Oklahoma	8	Lower Ordovician	Oil and gas production from dolomite on crater rim and from brecciated granite and dolomite on crater floor. Estimated potential reserves: over 7×10^6 m^3 (50 MMbbl).
Steen River, Alberta	22	pre - Late Cretaceous	Precambrian basement complex uplifted 760 m above regional levels. Producing 95 m^3/d (600 bbl/d) oil. Also gas present in the Slave Point.

Within the WCSB there are two widely known structures believed to be impact craters: Steen River (Winzer, 1972) and Eagle Butte (Sawatzky, 1976; Lawton et al., 1993). In addition, several other structures in Alberta can be identified on proprietary seismic data, including that at James River.

The subject of impact cratering has significance beyond current economic implications. The well-known extinctions at a number of geological boundaries (e.g., Permian/Triassic, Cretaceous/Tertiary) may be the result of meteorite impacts (Alvarez et al., 1980; Lampton, 1986; Raup, 1991). The meteorite impact theory for mass extinction has recently gained momentum with the possible impact crater discovered at Chicxulub, Mexico (Hildebrand et al., 1991). A proposal by Oberbeck et al. (1993) suggests that a giant asteroid impact could have caused the breakup of Gondwanaland and demonstrates the geological importance of this subject.

GEOLOGICAL SETTING

A 45-km^2 3-D seismic survey (Figure 1) was acquired in the James River area of Alberta (Twp. 34, Rge. 7, W5) in 1986 for Canterra Energy Ltd. (now Husky Oil Operations Ltd.). The survey was designed to image beneath the disturbed Cretaceous section and to delineate an Upper Devonian Leduc carbonate structure observed on 2-D seismic data. The Leduc structure is at a depth of about −2800 m subsea (4050 m below ground level). The main hydrocarbon reservoir at James River is the Upper Cretaceous Cardium Formation with the Leduc Formation

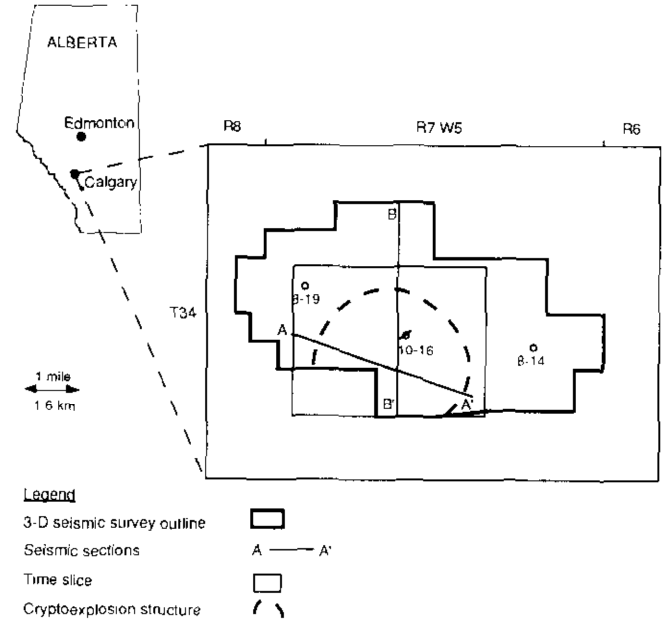

Fig. 1. Outline of James River 3-D seismic survey with locations of seismic lines and wells.

being an additional target. In this area, structural and stratigraphic traps exist and major reserves of oil and sour gas have been found nearby (e.g., Caroline, Harmattan). A generalised stratigraphic chart for this part of southwestern Alberta is shown in Figure 2.

Most of the wells in the area covered by the 3-D survey are shallow Cardium tests but three were drilled deeper. Mobil et al. James 8-14-34-07W5 was drilled in the project area in 1969 and penetrated 14 m of the Middle Devonian Elk Point Formation before T.D. at -3017 m subsea (4240 m log depth). Drillstem testing of the Ireton-Elk Point interval produced gas to surface from the Leduc Formation, which was subsequently cored. The gas discovery was not commercial. Canadian Hunter et al. Ricinus 8-19-34-07W5 was drilled in 1982 to test the Leduc Formation. It penetrated 29 m of the Elk Point Formation before T.D. at -3164 m subsea (4444 m log depth). The 8-19 well production tested gas from the Mississippian Pekisko Formation and oil from the Cardium Formation but was plugged and abandoned. Husky Caroline 10-16-34-07W5 was drilled in 1990 to test a structure interpreted to be a Leduc reef. The well drilled 28 m into the Swan Hills (Beaverhill Lake) Formation before T.D. at –3012.5 m subsea (4274 m TVD). A Leduc reef with 29 m of gross gas pay was encountered but the discovery was non-commercial.

Seismic Data Interpretation

The 3-D seismic survey was acquired and processed by Geophysical Services Inc. (now Halliburton Geophysical Services Inc.). Summaries of the acquisition and processing parameters are listed in Tables 2 and 3, respectively.

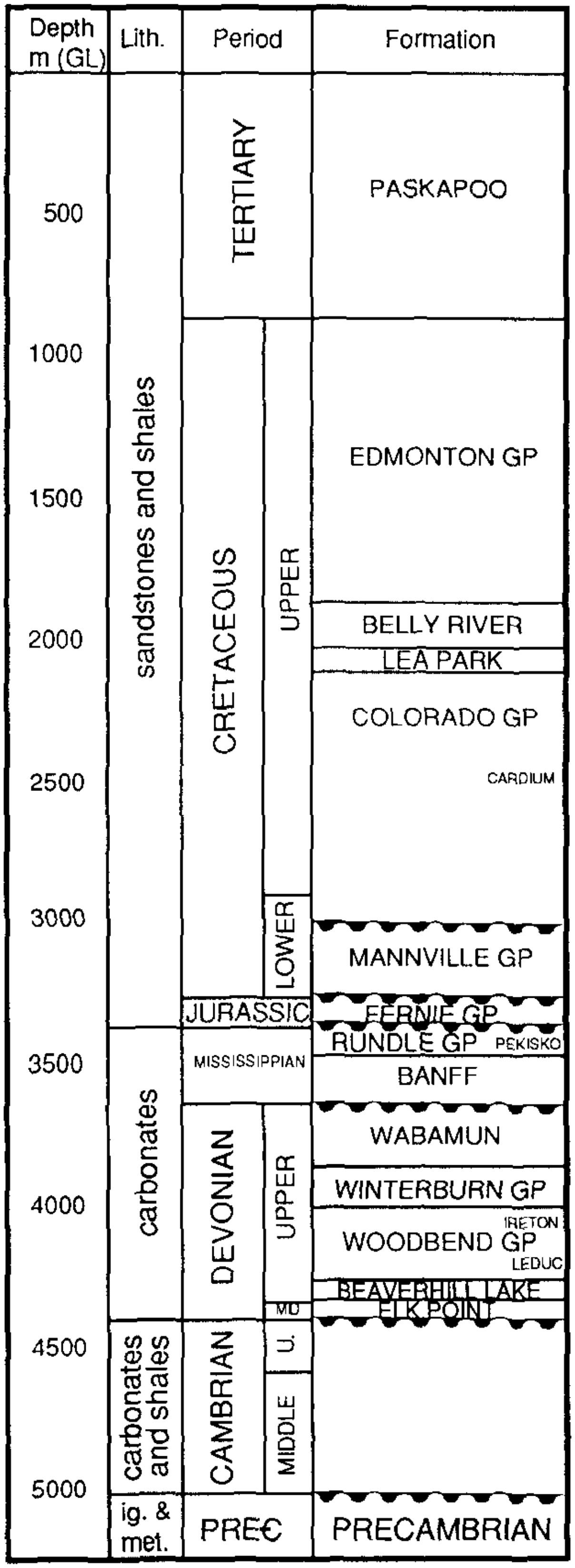

Fig. 2. Generalised stratigraphic column of southwestern Alberta.

Table 2. Acquisition parameters.

ACQUISITION PARAMETERS	
Source:	Vibroscis - 4 vibrators (TR4) sweep frequencies 10 - 70 Hz.
	17 east/west lines 500 m apart
	shotpoint interval 80 m
Receivers:	9 inline per group over 30 m
	27 north/south lines 320 m apart
	group interval 80 m

Table 3. Processing flow.

PROCESSING FLOW	
Rotation to zero phase	
Gapped deconvolution	operator length 80 ms
	gap 24 ms
CDP stack	15 fold
	40 x 40 m bin size
3-D *f-k* migration	
Filter	10/14 - 60/70 Hz.
Time-variant scaling	1000 ms gate

Although the high-cut trapezoidal filter frequency limits were 60/70 Hz, in the section of interest the highest signal frequency was about 40 Hz.

Three quarters of a circular feature about 4.8 km in diameter is observed deep in the section, below two seconds two-way time. Since the survey had been designed to delineate the shallower Leduc structure it does not entirely cover the deeper circular feature. This structure is below the zone of previous exploration interest and has not been drilled. Correlation of seismic markers with local geology indicates that the structure is in the Cambrian section.

Digitized sonic and density logs are available for the two deepest wells, which penetrated the Elk Point Formation, and are used to create synthetic seismograms. A Butterworth band-pass filter with frequency cutoffs of 15/20 - 35/40 Hz is applied to the synthetic seismogram. The synthetic seismogram from the well 8-19-34-07W5 and the seismic data around that location correlate quite well (Figure 3). The peak at 2145 ms is interpreted to represent the top of the Elk Point Formation (peak indicating a positive reflection coefficient).

In order to identify the seismic reflectors beneath the Elk Point, it is necessary to estimate the thicknesses of the Elk Point and the underlying Cambrian sediments.

In this area of Alberta, the Middle Devonian Elk Point carbonates unconformably overlie clastic sediments of Upper Cambrian age (van Hees and North, 1964). James River is close to the western edge of deposition of the Elk Point which, consequently, is very thin here. Shell et al. Caroline 6-36-34-06W5, which was drilled about 10 km to the northeast of the project area, penetrated 22 m of Elk Point before encountering the Upper Cambrian. The sonic log from this well shows a sharp increase in velocity to about 7000 m/s at the top of the Cambrian, followed by a decrease in velocity to about 5500 m/s (Figure 4). The well 8-19-34-07W5 had penetrated 29 m of Elk Point, so the Elk Point Formation is assumed to be around 30 m thick here. An interval velocity of 6000 m/s is assumed, giving a two-way interval traveltime of 10 ms. At a depth of over 4000 m, a 30-m thick section is beyond the resolution of the seismic data so the Elk Point and Cambrian events cannot be identified separately. The

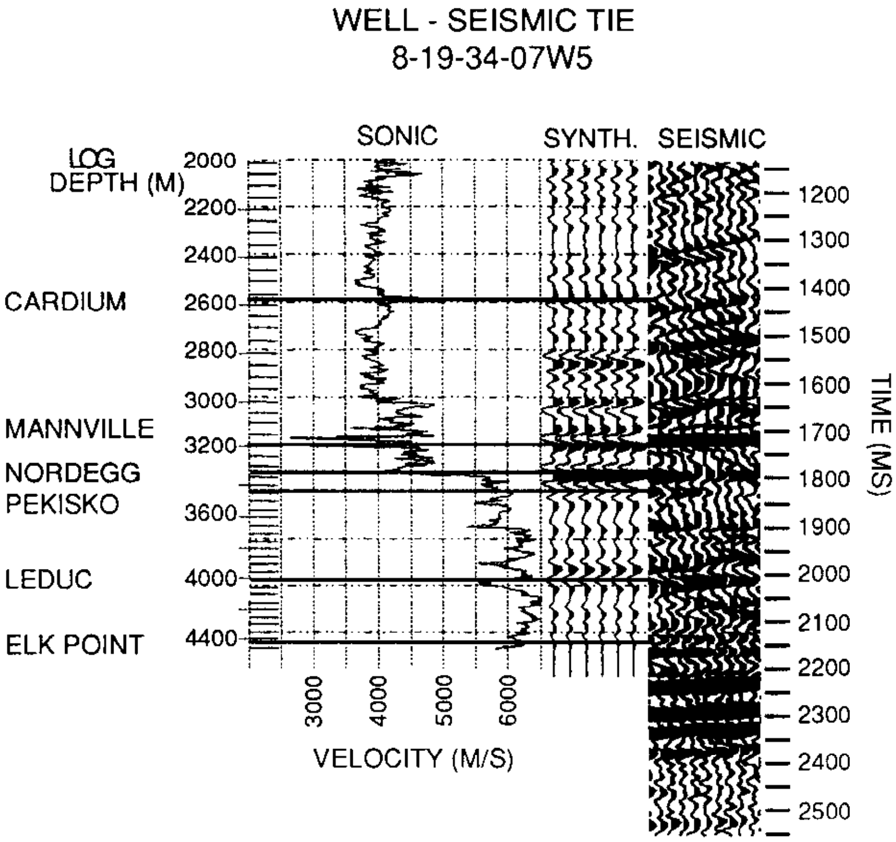

Fig. 3. Correlation of seismic data with synthetic seismogram for 8-19-34-07W5.

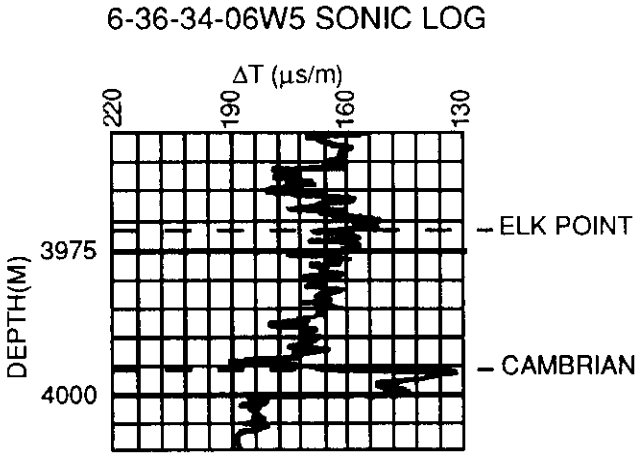

Fig. 4. Sonic log from the well 6-36-34-06W5 showing 23 m of Elk Point above the Cambrian section, which has a 5-m thick high-velocity zone at the top.

Top Cambrian is picked, therefore, as the same peak as the Elk Point top, at 2145 ms on the seismic data.

The Upper Cambrian sediments in the study area are predominantly siltstones and shales while the Middle Cambrian sediments are calcareous shales and argillaceous carbonates. Regional geological maps show the Upper Cambrian section at James River to be about 150 m thick and the Middle Cambrian section to be about 400 m thick (van Hees and North, 1964). Lower Cambrian sediments were not deposited here; the Middle Cambrian carbonates and shales were deposited directly on Precambrian igneous and metamorphic basement rocks.

Assuming interval velocities of 5500 m/s for the Upper Cambrian clastics and 6300 m/s for the Middle Cambrian carbonates and shales gives approximate two-way interval traveltimes of 55 ms and 125 ms, respectively, putting the top of the Precambrian as the peak at 2325 ms.

The 3-D seismic data are interpreted on a Landmark interactive workstation. The following events are correlated and mapped: Mannville event, Top Cambrian (base Devonian), Intra-Cambrian and Precambrian. The Mannville event is picked to observe structure in the section above the feature of interest, in this case about 2650 m shallower. It is the first strong, continuous reflector above the zone of interest that can be picked reliably across the survey area. The Intra-Cambrian is picked to demonstrate the morphology of the structure under investigation and is not intended to represent a continuous reflector. In places this reflector can be seen to be truncated by the unconformity representing the end Cambrian-Middle Devonian hiatus. Across the central uplift, the Intra-Cambrian event corresponds to the Top Cambrian unconformity event.

A northwest-southeast seismic line A-A' (Figure 5) shows clearly the Top Cambrian angular unconformity and the truncation beneath it of dipping reflectors. The locations of

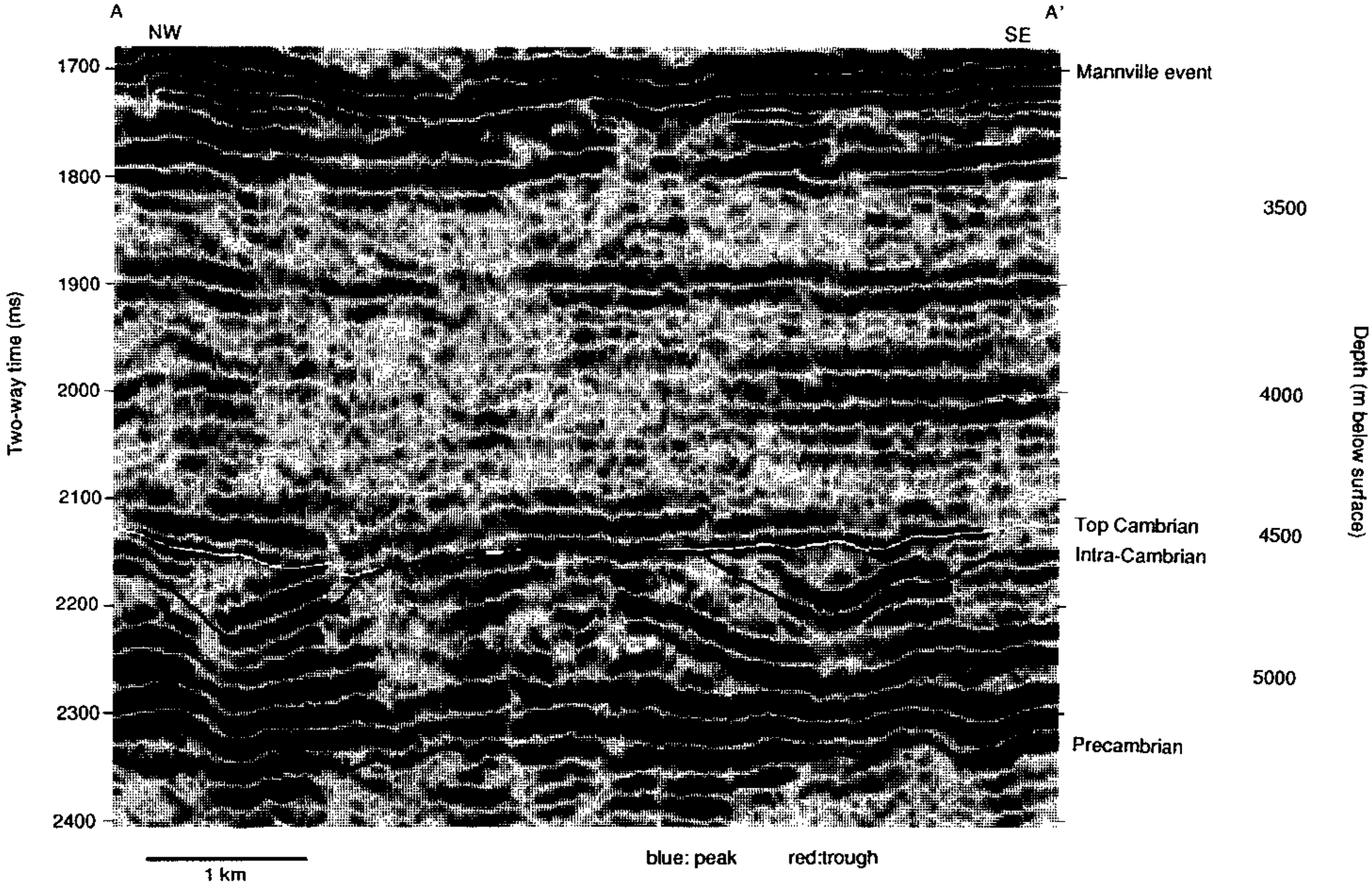

Fig. 5. NW-SE seismic line over the cryptoexplosion structure with interpreted horizons. The truncation of dipping events beneath the Top Cambrian unconformity and the eroded central uplift are seen clearly.

seismic lines are shown on Figure 1 and on the time structure and isochron maps (Figures 8, 9 and 10). The dipping reflectors form synforms on either side of the central part of the structure, which appears to be uplifted. The amount of uplift is seen to decrease to zero through the Top Cambrian to Precambrian interval. The Precambrian section appears to be relatively undisturbed underneath the central uplift, implying that Precambrian rocks have not been uplifted. The central uplift is interpreted to be composed of Cambrian rocks. The thickness of this uplifted central portion is estimated to be about 400 m (120 ms traveltime). The uplifted area appears to have coherent internal reflections and can be seen to have suffered erosion prior to the deposition of the overlying Middle Devonian carbonates of the Elk Point Formation.

On some lines in the survey, rim faults are evident. Examples are shown on a north/south line B-B' (Figure 6). These rim faults appear to be present only within the structure itself and do not affect the deeper section. Such faults are characteristic of complex impact craters and are probably caused by slumping of sediments into the cavity. On this line, reverse faults affecting the Middle Cambrian and Precambrian sections can also be seen. These faults map in a concentric pattern underneath the structure but are confined to the northwestern part. They are thought to be contemporaneous with the formation of the structure and indicate compressive forces, which could have been the result of the rebound of impacted material. There is a zone of very poor seismic reflectivity between the dipping reflectors of the ring depression and the Top Cambrian event. Such a seismic response might indicate a zone filled chaotically with breccia.

The circular nature of the structure is not immediately apparent on the seismic lines but is strikingly clear on the 2168 ms time slice (Figure 7). Successive time slices are used to observe the lateral movement of reflectors with depth and to aid in the interpretation of the structure.

After the horizons are correlated, several time structure maps are made. Some of the maps show clearly the circular shape of the structure and are illustrated here. At the Precambrian level there are indications of a circular structure but it is not known whether they are artifacts caused by anomalous interval velocities in the overlying central uplift. Stacking velocities indicate slightly higher interval velocities for the central uplift compared to the ring depression but the velocity data are not consistent. Lineations are seen in the southeast but they do not appear to reflect the major zones of deep Precambrian faulting that are often related to diatreme structures.

The Intra-Cambrian time structure map (Figure 8) and Intra-Cambrian-Precambrian isochron map (Figure 9) are the

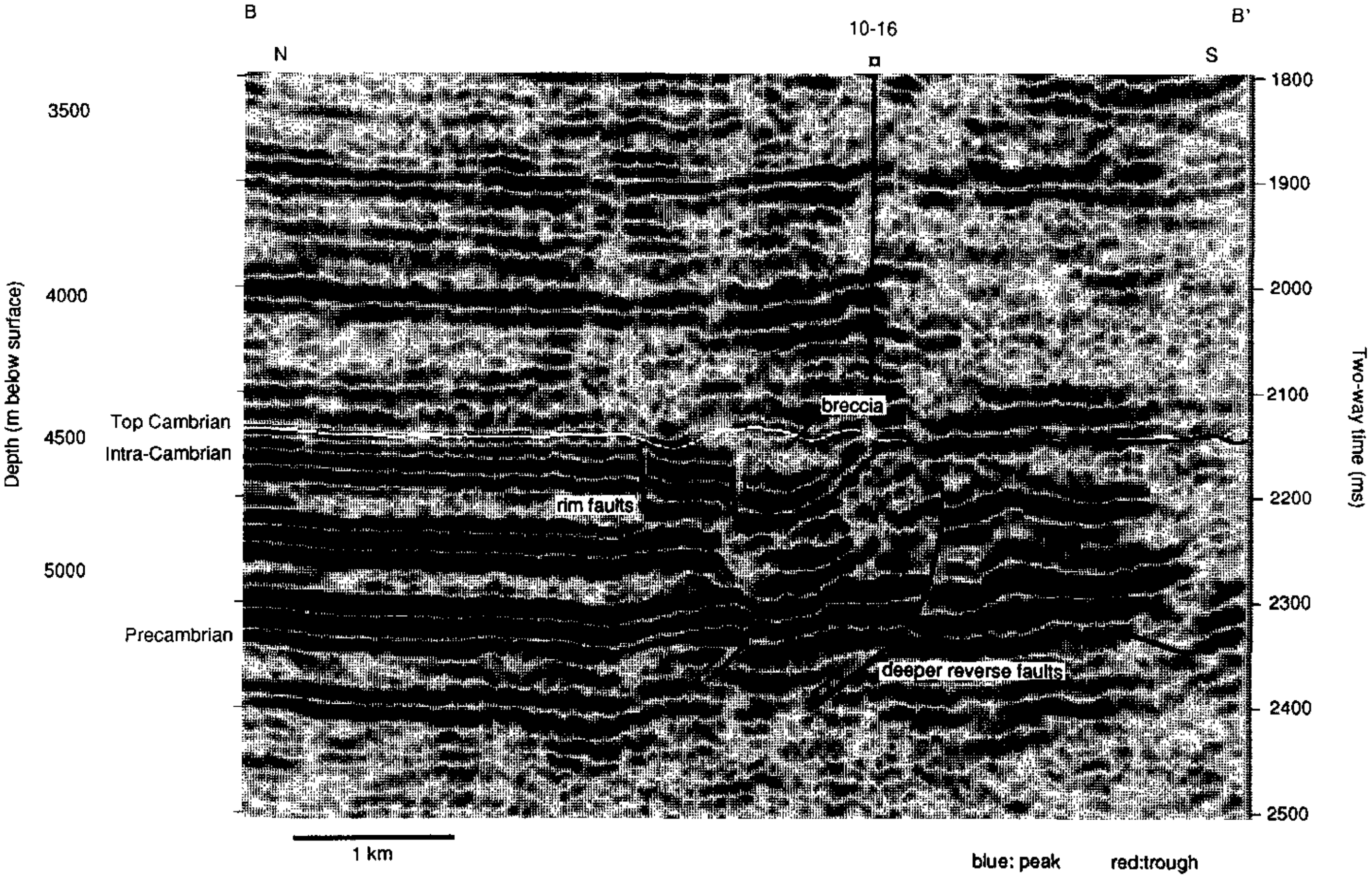

Fig. 6. N-S seismic line showing rim faults, deeper reverse faults and the possible breccia zone, as indicated by the poor seismic reflectivity.

most significant. The circular shape and annular rim synform are clearly visible. The diameter of the entire feature is 4.8 km and of the central uplift, 2.4 km. The circular shape evident on the Top Cambrian time structure map (Figure 10) might be a result of the selective resistances to erosion of the circular dipping strata beneath the unconformity surface or of differential compaction. At the Mannville level, later tectonic events with a strongly linear northwest/southeast orientation are superimposed on the preexisting structure.

Three-dimensional seismic data can be used to visualise a structure in different ways. The directions of dip of the Intra-Cambrian event are calculated with Landmark software and mapped (Figure 11) to give another three-dimensional image of the structure. The grey-scale image plots the dip directions of the surface from north (white) to south (black). This picture shows clearly the geometry of the structure, particularly the raised central uplift and the rim synform.

It is clear that the structure was eroded prior to the deposition of Devonian strata so an attempt is made to estimate its original dimensions. The maximum original size of the feature is estimated by extrapolation of the observed truncated dipping events of the central uplift to a maximum preerosion height, assuming no change in dip. This gives a maximum original uplift of 700 m and a maximum original overall diameter of 7 km. These values compare fairly well with estimates calculated such that scaling equations for complex impact craters are obeyed. The diameter of the central uplift of a complex impact crater, D_{su}, is related to the overall diameter, D, by $D_{su} \sim 0.22D$, for impact structures on all the terrestrial planets (Pike, 1985). Using these relationships and the extrapolated dips of the central uplift gives a preerosion overall diameter of 6 km, with a central uplift 1300 m in diameter and 600 m thick.

ORIGIN OF THE STRUCTURE

Let us review geological processes which can produce circular structures:

a) Impact

The morphology of the structure – its circular shape, ring depression, fault patterns and central uplift – is very similar to that observed at impact craters. The geometry corresponds reasonably well with the scaling equations for impact craters although, since there has been considerable erosion of the structure, its original dimensions can only be estimated. Regional gravity maps only show regional trends and the magnetic maps available to us do not cover this area. The observed decrease with depth of the structural uplift in the core of the feature and the coherent reflections in the uplift tend to suggest an explosive source from above rather than below.

The fall of a single meteorite is rare, since bodies entering the Earth's atmosphere usually break up due to aerodynamic

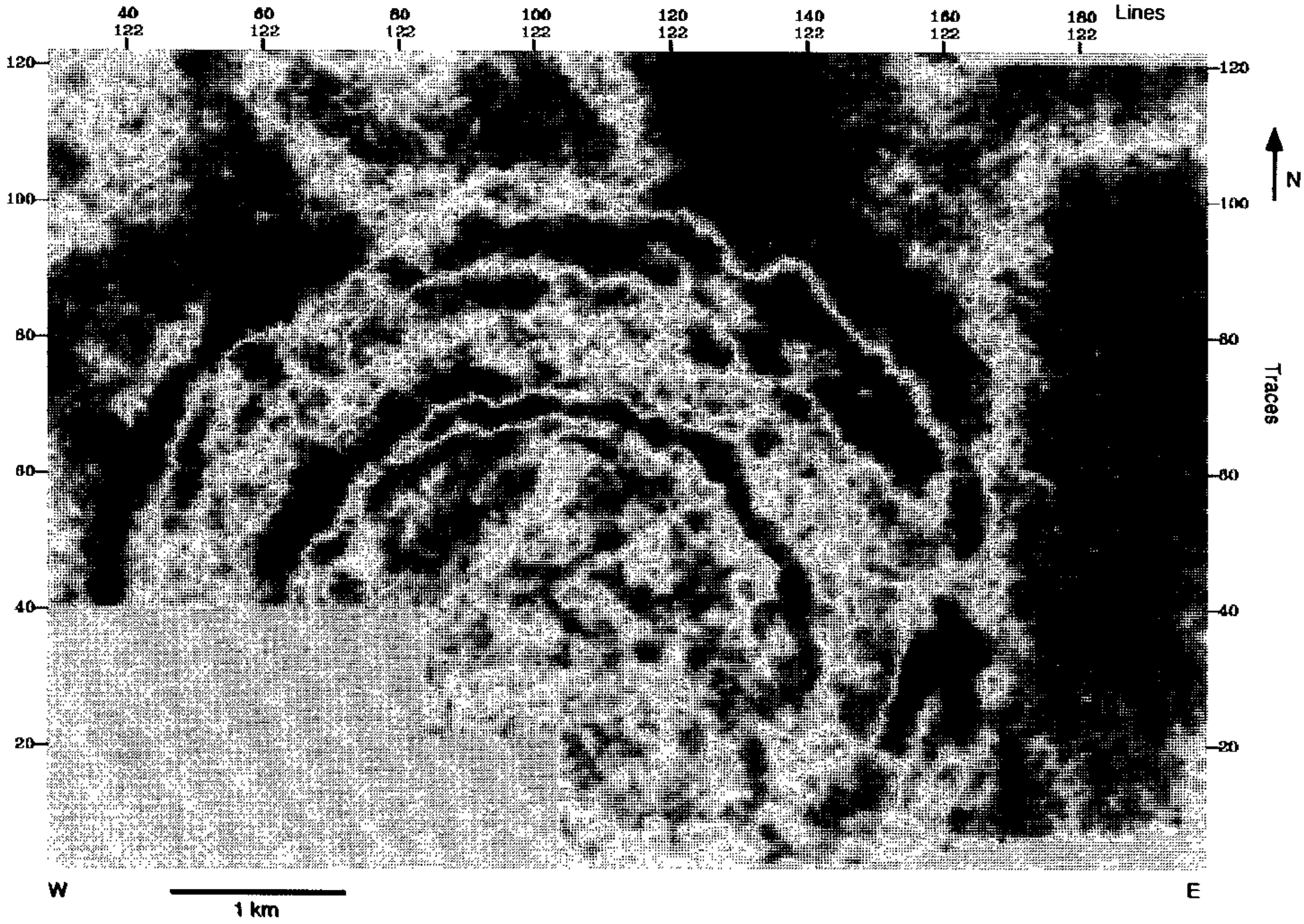

Fig. 7. Horizontal time slice at 2168 ms showing the circular plan of the beds.

stress, unless they burn up first (Melosh, 1989). Meteorite showers fall over an area known as the scattering ellipse, with the largest masses falling in the forepart of the ellipse and the smallest in the rear (Krinov, 1962). Observations on additional seismic data in the vicinity of the study area of more possible impact structures covering such an elliptical area would provide additional evidence for an impact origin.

b) Diatreme

Craters associated with diatremes are caused by the explosive release of highly compressed gasses and fluids by central venting. The proposed impact origin of such structures as Sudbury, Ontario and Manson, Iowa is disputed by some authors (e.g., Nicolaysen and Ferguson, 1990; Officer and Carter, 1991). Criteria for internally driven cryptoexplosion structures include the alignment of a few such structures on a lineament, since they are thought to be associated with the reactivation of preexisting deep linear zones of weakness (Nicolaysen and Ferguson, 1990). There are no obvious deep linear faults in the Precambrian on the James River 3-D survey. Also, there does not appear to be a large Precambrian basement uplift here, as seen on some structures interpreted as diatremes (Officer and Carter, 1991).

c) Volcano

The conical shape of the central uplift is similar to that of a volcano but the internal reflections observed in the central uplift would not be expected from the core of a volcano. There is no record in the literature of volcanic activity in Alberta during the Cambrian, Ordovician, Silurian or Lower Devonian Periods. If this structure were a volcano, one would expect the section to be disturbed below the structure to a considerable depth, something which is not seen here. A distinct, deep rim synform, as observed here on the seismic data, is not generally associated with a volcano.

d) Salt dissolution

During Upper and Middle Cambrian times, the environment of deposition varied between shallow marine, with clastic influx, and a submergent carbonate shelf. The sediments are predominantly siltstones, shales, calcareous shales and argillaceous carbonates with no evidence of salt (van Hees and North, 1964). Since there is no evidence for the existence of salt, salt dissolution is unlikely to be the cause of the structure. Furthermore, salt dissolution generally leads to funnel-shaped structures without a central uplift (Anderson and Brown, 1992).

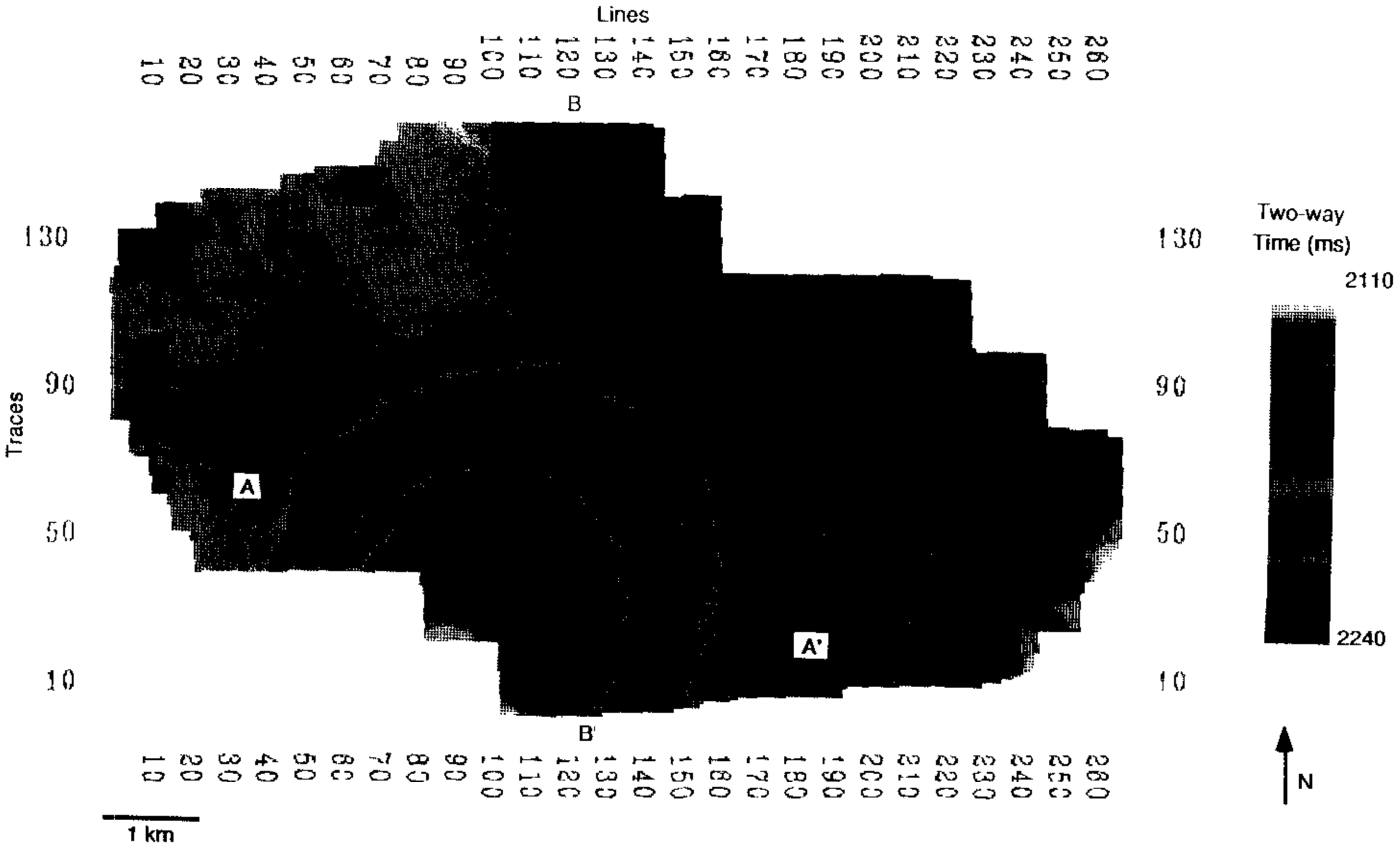

Fig. 8. Intra-Cambrian time-structure map, showing clearly the circular shape of the structure.

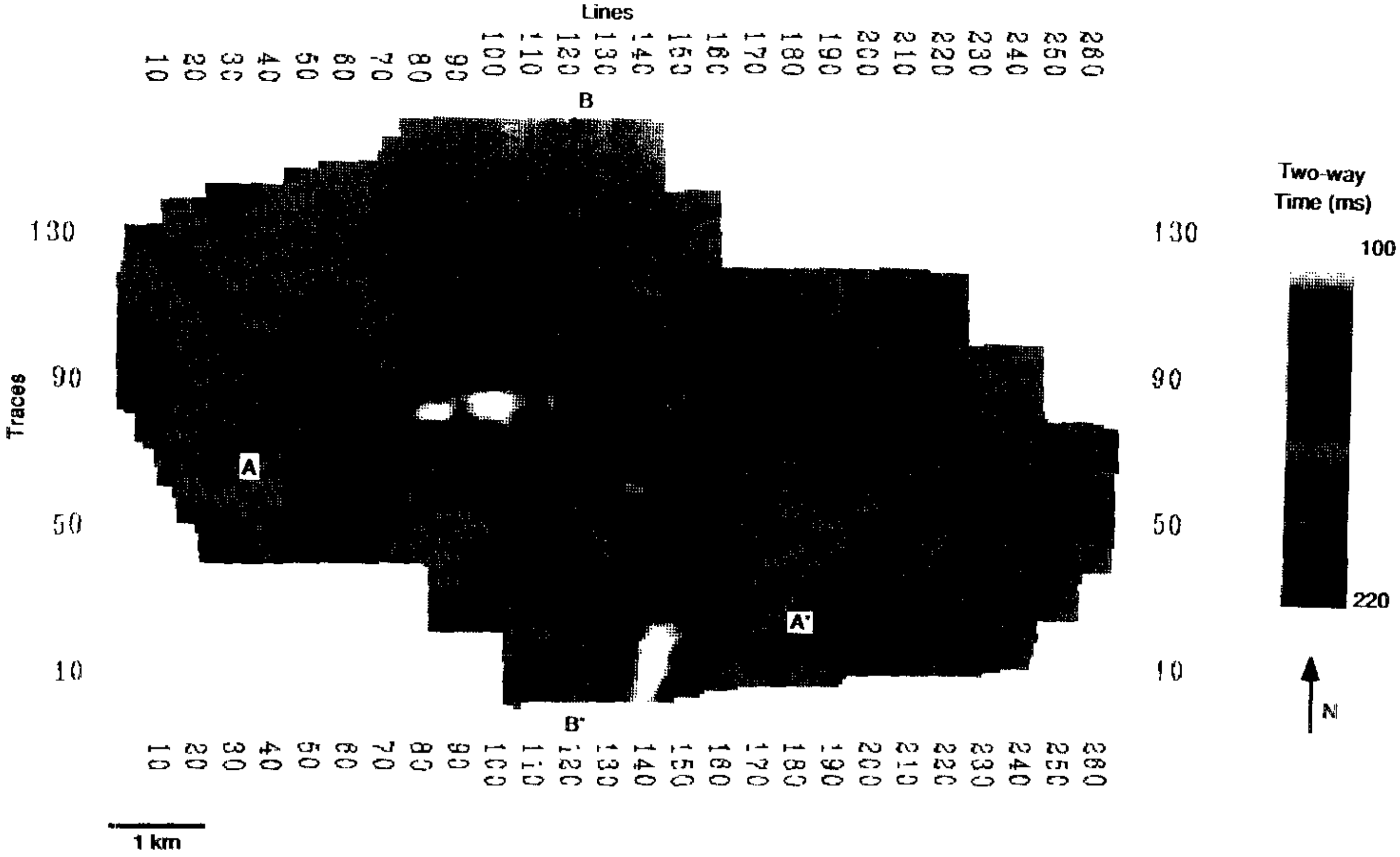

Fig. 9. Intra-Cambrian-Precambrian isochron map

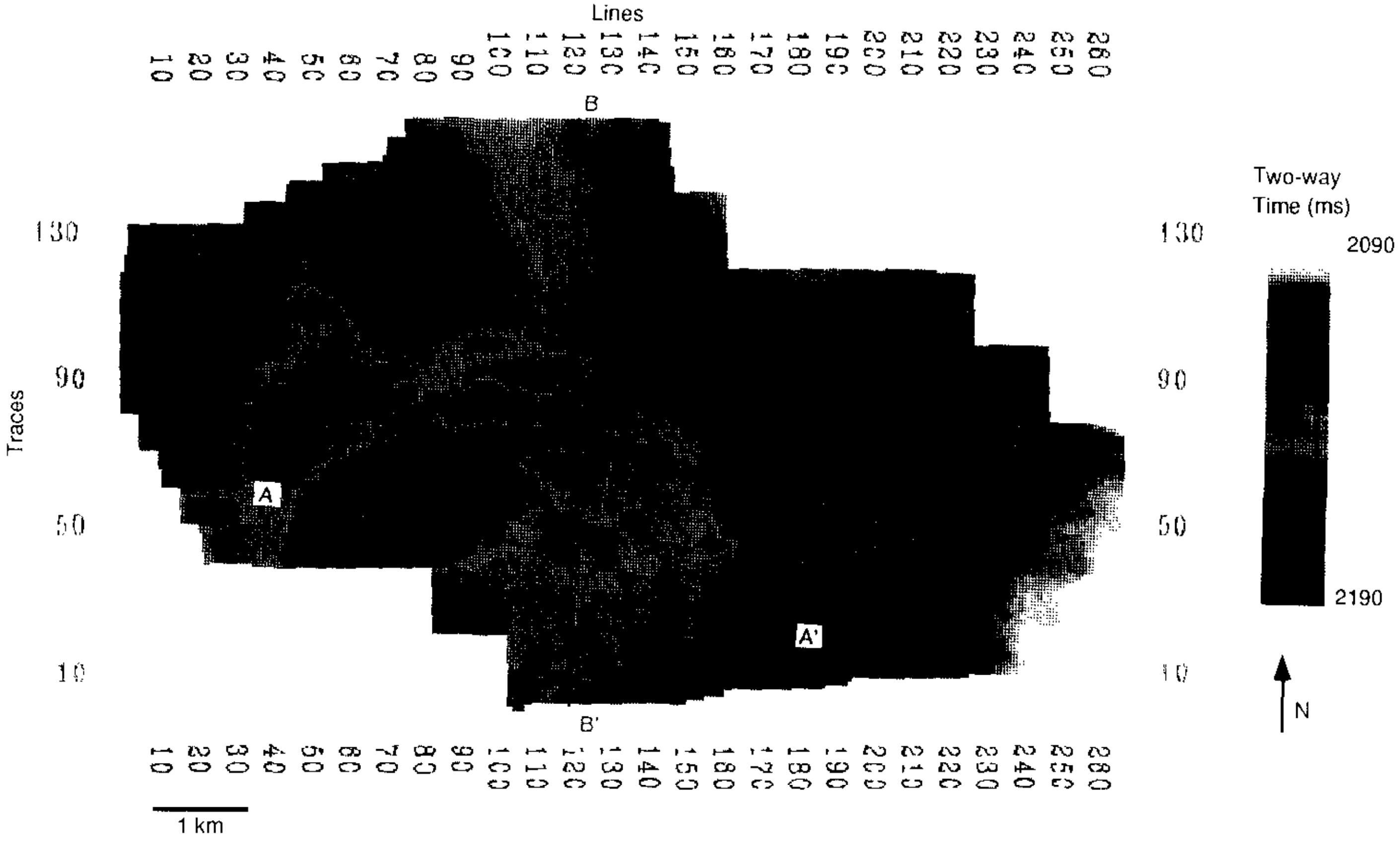

Fig. 10. Top Cambrian time-structure map. This unconformity surface reflects the selective resistances to erosion of the dipping strata beneath.

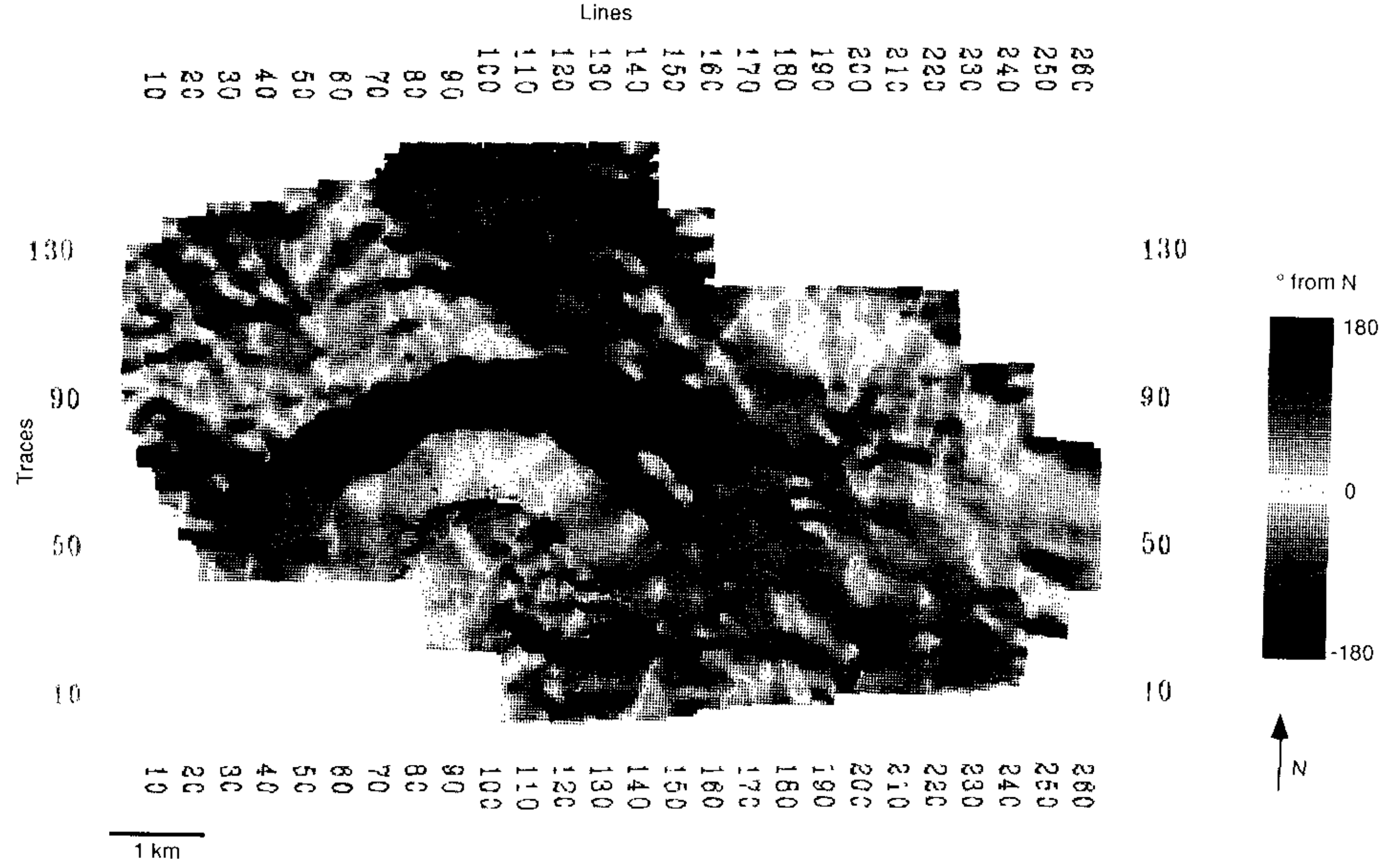

Fig. 11. Intra-Cambrian dip-azimuth map showing the directions of dip of the Intra-Cambrian event.

e) Shale plug

Shale plugs are upwellings of shale and can look similar to salt plugs, tending to be free of internal coherent reflections. The observed central uplift appears to have internal reflections. One would also expect to see a velocity pull-down beneath a shale plug, due to its lower velocity compared to the surrounding calcareous material, and that is not observed here.

f) Limestone dissolution

Limestone is present in the sedimentary section here but, as with salt dissolution, it is hard to find a model for dissolution in an annular shape with the observed faulting and coherent reflections in the central uplift. Most collapse structures associated with limestone dissolution are either sinkholes or linear features (Jenyon and Fitch, 1985).

CONCLUSIONS

The enigmatic anomaly observed on the 3-D seismic data at James River has the morphological characteristics of a meteorite impact structure. It has a circular shape, raised circular central uplift, annular rim synform and rim faults. The amount of central uplift is seen to decrease with depth and continuous reflections are seen within the uplift. The structure is confined to the interval between the Top Cambrian unconformity and the top of the Precambrian, leading to the conclusion that the central uplift is composed of Cambrian rocks. The structure is 4.8 km in diameter and has a central uplift 2.4 km in diameter which is raised about 400 m above regional levels. It is estimated that the structure was formed during Late Cambrian to Middle Devonian time and suffered severe erosion before the deposition of the overlying Middle and Upper Devonian carbonates. The disturbed, eroded rocks in the central uplift and the breccia-filled rim synform could be exploration targets for hydrocarbons. There is structural closure and there could be fracture porosity and permeability introduced into the central uplift due to deformation and erosion. The structure is estimated to extend from depths of 4500 m to 5000 m below ground level (3250 m to 3750 m subsea).

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