3-D seismic characterization of a cryptoexplosion structure

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ABSTRACT

Three-quarters of a circular structure is observed on three-dimensional (3-D) seismic data from James River, Alberta. The structure has an outer diameter of 4.8 km and a raised central uplift surrounded by a rim synform. The central uplift has a diameter of 2.4 km and its crest appears to be uplifted about 400 m above regional levels.

The structure is at a depth of about 4500 m. This is below the zone of economic interest and the feature has not been penetrated by any wells. The disturbed sediments are interpreted to be Cambrian. We infer that the structure was formed in Late Cambrian to Middle Devonian time and suffered erosion before the deposition of the overlying Middle Devonian carbonates.

Rim faults, probably caused by slumping of material into the depression, are observed on the outside limb of the synform. Reverse faults are evident underneath the feature and the central uplift appears to have coherent internal reflections. The amount of uplift decreases with increasing depth in the section. The entire feature is interpreted to be a cryptoexplosion structure, possibly caused by a meteorite impact.

INTRODUCTION

Several enigmatic circular structures, of different sizes and ages, have been observed on seismic data from the Western Canadian sedimentary basin (WCSB) (e.g., Sawatzky, 1976; Isaac and Stewart, 1993) and other parts of Canada (Scott and Hajnal, 1988; Jansa et al., 1989). The structures present startling interruptions in otherwise planar seismic features. Their coherent but puzzling character challenges us to understand their morphology. They are interpreted to be cryptoexplosion structures: circular to polygonal geological features displaying evidence of violent disruption during their formation but having no evidence of volcanic material to confirm a volcanic origin. Cryptoexplosion structures with similar morphologies can be caused by both meteorite impacts and diatreme intrusions (Nicolaysen and Ferguson, 1990). Diatreme structures are thought to be caused by abrupt and violent exsolution of deep gasses and fluids from magmas.

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 are termed either simple or complex; the morphological change taking place at a cavity diameter of about 2 km in sedimentary rocks and 4 km in crystalline rocks (Dence, 1972). The principal features of a complex impact crater are a central peak, or group of peaks, surrounded by a flat floor inside a terraced rim (Dence, 1965). Complex crater central uplifts are composed of deformed and fractured rocks which are older than those filling the surrounding rim syncline and are often older than the country rock surrounding the structure.

Structures formed by meteorite impact or diatreme intrusion can be expected to demonstrate evidence of shock metamorphism. Such evidence may come in the form of, for example, breccia (suevite), the high pressure polymorphs of SiO_2 (coesite and stishovite), shatter cones and microscopic deformation textures. Although some authors believe that the stishovite and shock metamorphism sometimes found in cryptoexplosion structures can be caused only by the high pressures associated with meteorite impacts (e.g., Grieve, 1990), other authors have observed these attributes in structures interpreted to be of diatreme origin (e.g., Martini, 1978; Lilly, 1981). The stages of shock metamorphism can be expected to decrease with depth in meteorite impact structures, while in diatreme structures they should increase with depth. Evidence of diatreme breccia dikes indicates an internal origin. Shatter cones point towards the source of energy (Roddy and Davis, 1977), so a source interpreted to be above the present level of the central uplift of a structure would suggest an external origin.

Without such direct geological evidence it is difficult to prove the origin of a structure that is observed on seismic data alone. Similarly shaped features can result from different causes. However, observed internal structure in a central uplift, changes in structural uplift with depth or fault patterns may provide evidence for the structure's origin.

ECONOMIC ASPECTS

Mineral deposits of various kinds 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. A few of these are listed in Table 1 (Sawatzky, 1972; Brenan et al., 1975; Carpenter and Carlson, 1992). The significance to the petroleum industry of hydrocarbon-bearing impact craters was discussed in detail by Donofrio (1981). The geophysical responses to 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.

Within the WCSB there are two widely known structures that are believed by some researchers to be impact craters: Steen River (Winzer, 1972) and Eagle Butte (Sawatzky, 1976; Lawton, 1993). Several other anomalous circular structures are currently under our analysis.

The subject of impact cratering is of interest for scientific as well as economic reasons. Hildebrand et al. (1991) recently proposed that a massive meteorite impact at Chicxulub, Mexico, was responsible for a mass extinction at the Cretaceous/Tertiary boundary and Oberbeck et al. (1993) proposed that a giant asteroid impact could have caused the break-up of Gondwanaland.

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 in the raised rim. Pay thicknesses from 4 m to 50 m. Estimated reserves: 3.2 x 10^6 m^3 (20 MMbbl) recoverable. Ø = 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 x 10^6-11 x 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 recoverable reserves: over 6 x 10^5 m^3 (4 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 in the Slave Point.

TABLE 1. Some commercial hydrocarbon accumulations associated with probable impact craters.

CASE STUDY

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 Cretaceous triangle zone 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 being an additional target. In this area, structural and stratigraphic closures create traps 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.

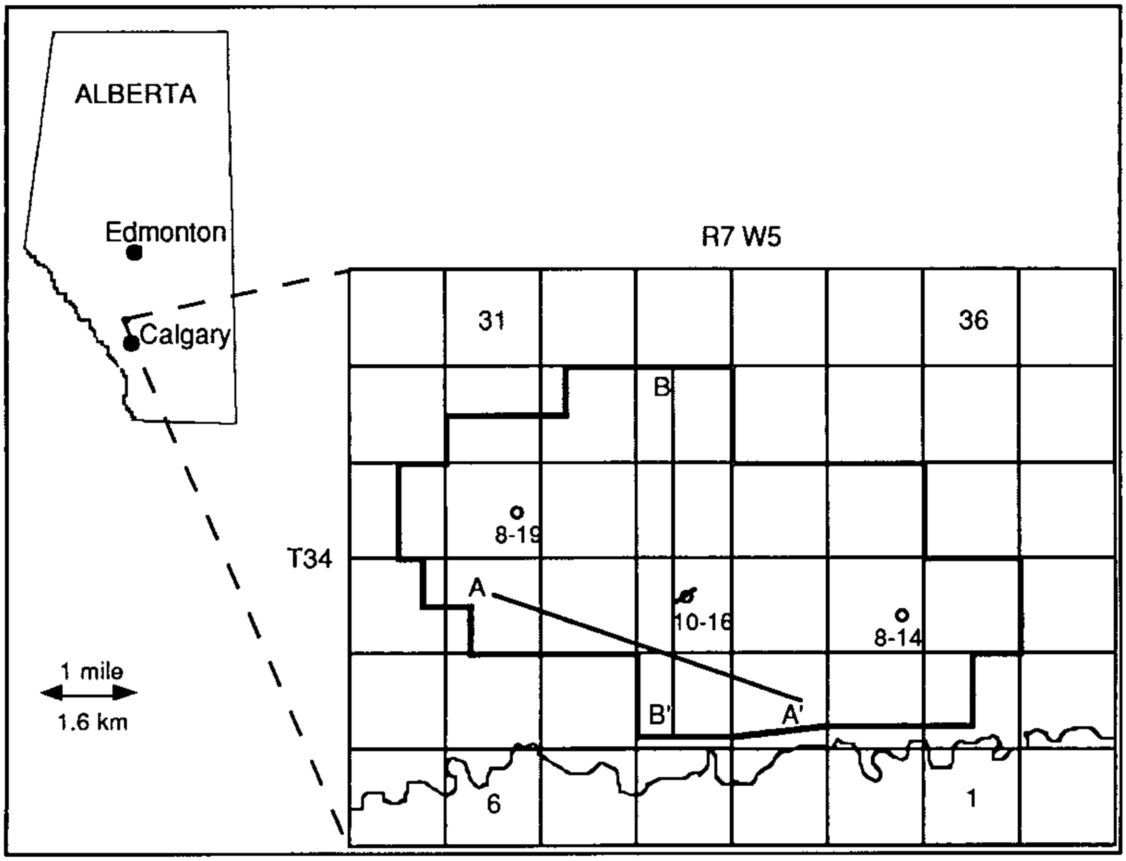


FIG. 1. Outline of James River 3-D survey with locations of displayed seismic lines.

The 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. 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.

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 Formation before T.D. at -3012.5 m subsea (4300 m log depth). A Leduc reef with 29 m of gross gas pay was encountered but the discovery was uncommercial due to the high sulphur content of the gas.

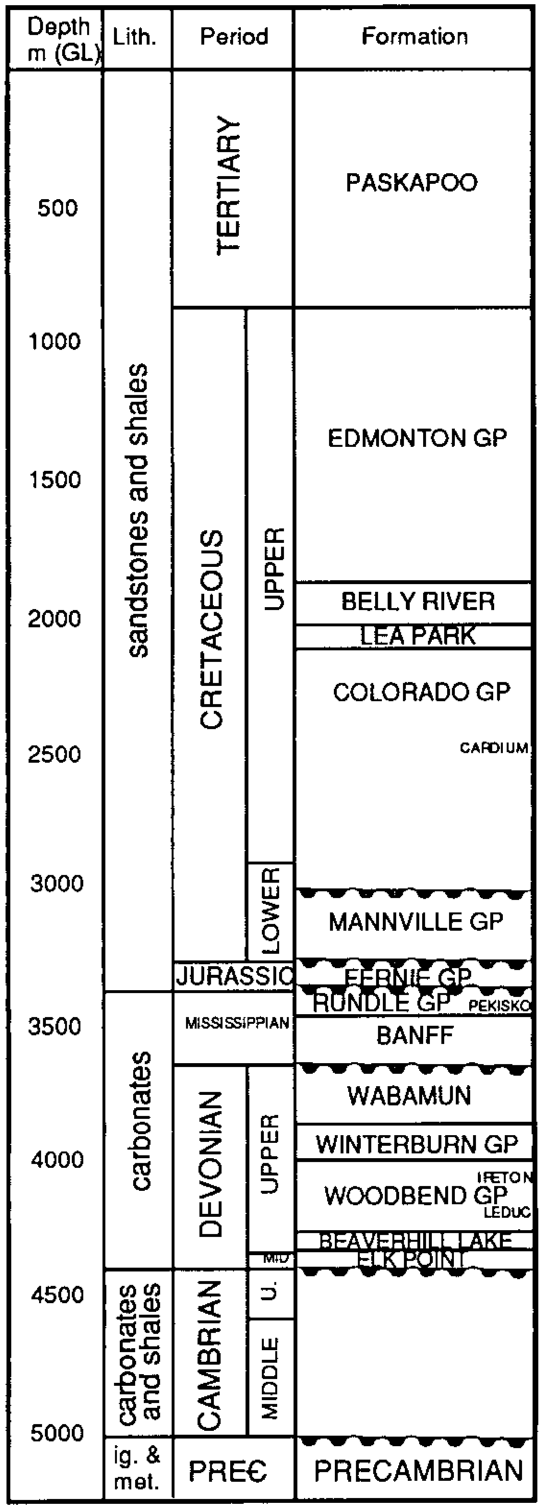


FIGURE 2. Generalised stratigraphic column of southwestern Alberta.

ACQUISITION PARAMETERS	
Source:	Vibroseis - 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 2. Acquisition parameters.

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

TABLE 3. Processing flow.

Seismic data interpretation

About 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 cover entirely the interesting circular feature. This structure is below the zone of original exploration interest and has not been drilled. It is interpreted to be 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 bandpass filter with frequency cut-offs 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 lie unconformably on 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. A nearby well, 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 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 travel time 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 Top Cambrian is picked, therefore, as the same peak as the Elk Point top, at 2145 ms on the seismic data.

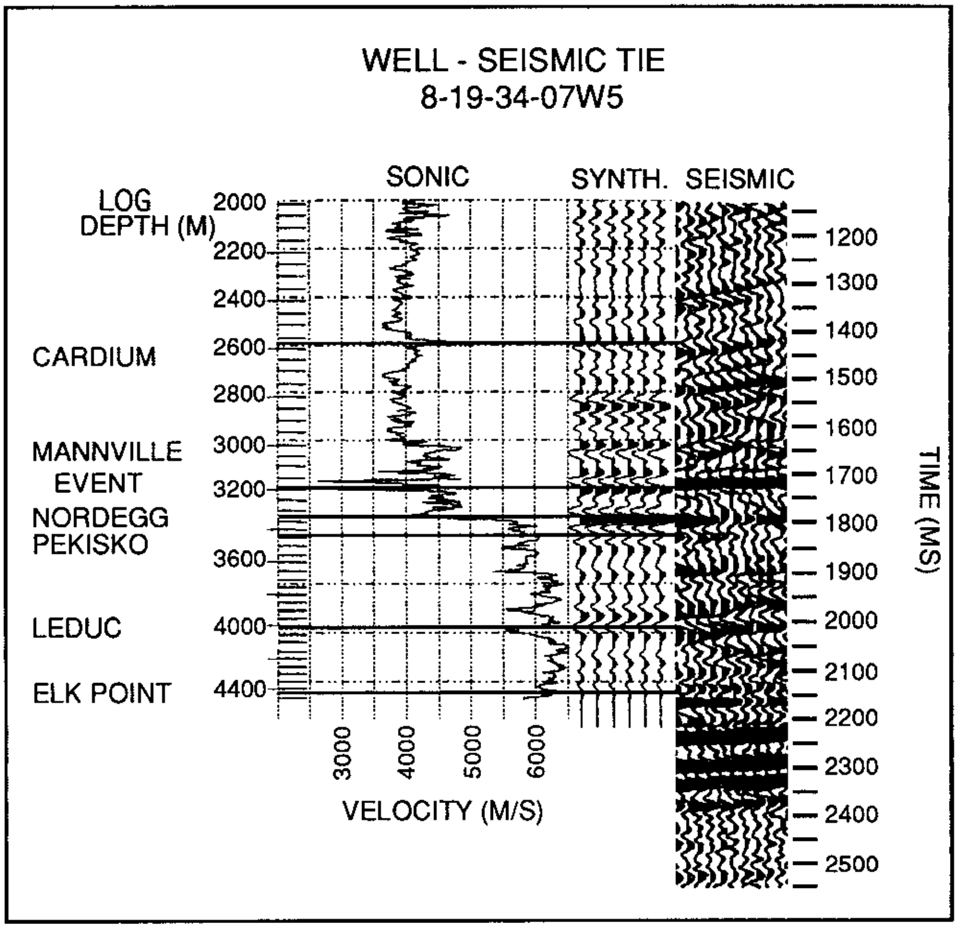


FIG. 3. Correlation of seismic data with synthetic seismogram for 8-19-34-07W5.

The Upper Cambrian sediments in this area are predominantly siltstones and shales and Middle Cambrian sediments are calcareous shales and argillaceous carbonates. Regional geological maps show the Upper Cambrian section at James River to be around 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 being 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 travel times of 55 ms and 125 ms respectively, putting the Precambrian pick at 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.

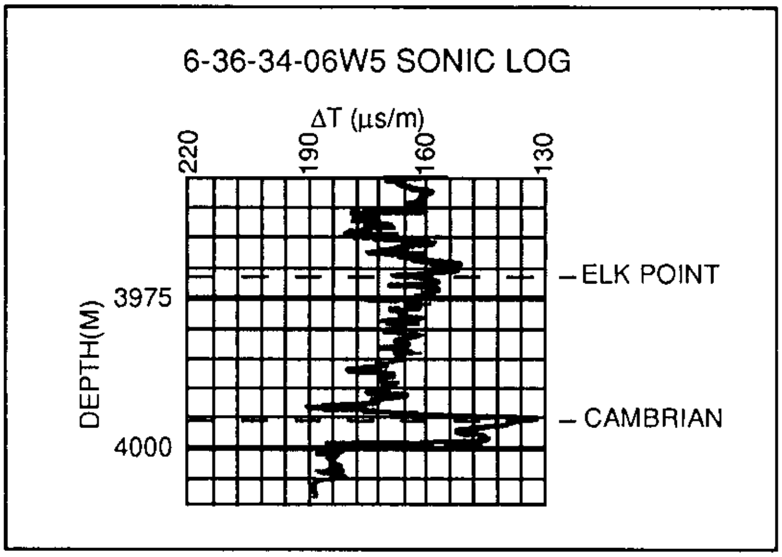


FIG. 4. Sonic log from the well 6-36-34-06W5, showing 23 m of Elk Point above the Cambrian section, which has a 5 m thick high velocity zone at the top.

A Northwest-Southeast seismic line A-A' (Figure 5) shows clearly the Top Cambrian unconformity surface and the truncation beneath it of dipping reflectors. The locations of seismic lines are shown in Figure 1. On the seismic data, blues represent peaks and reds troughs. 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 with increasing depth. 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 travel time). 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 normal 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 an arcuate pattern underneath the structure but are fairly discontinuous. 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.

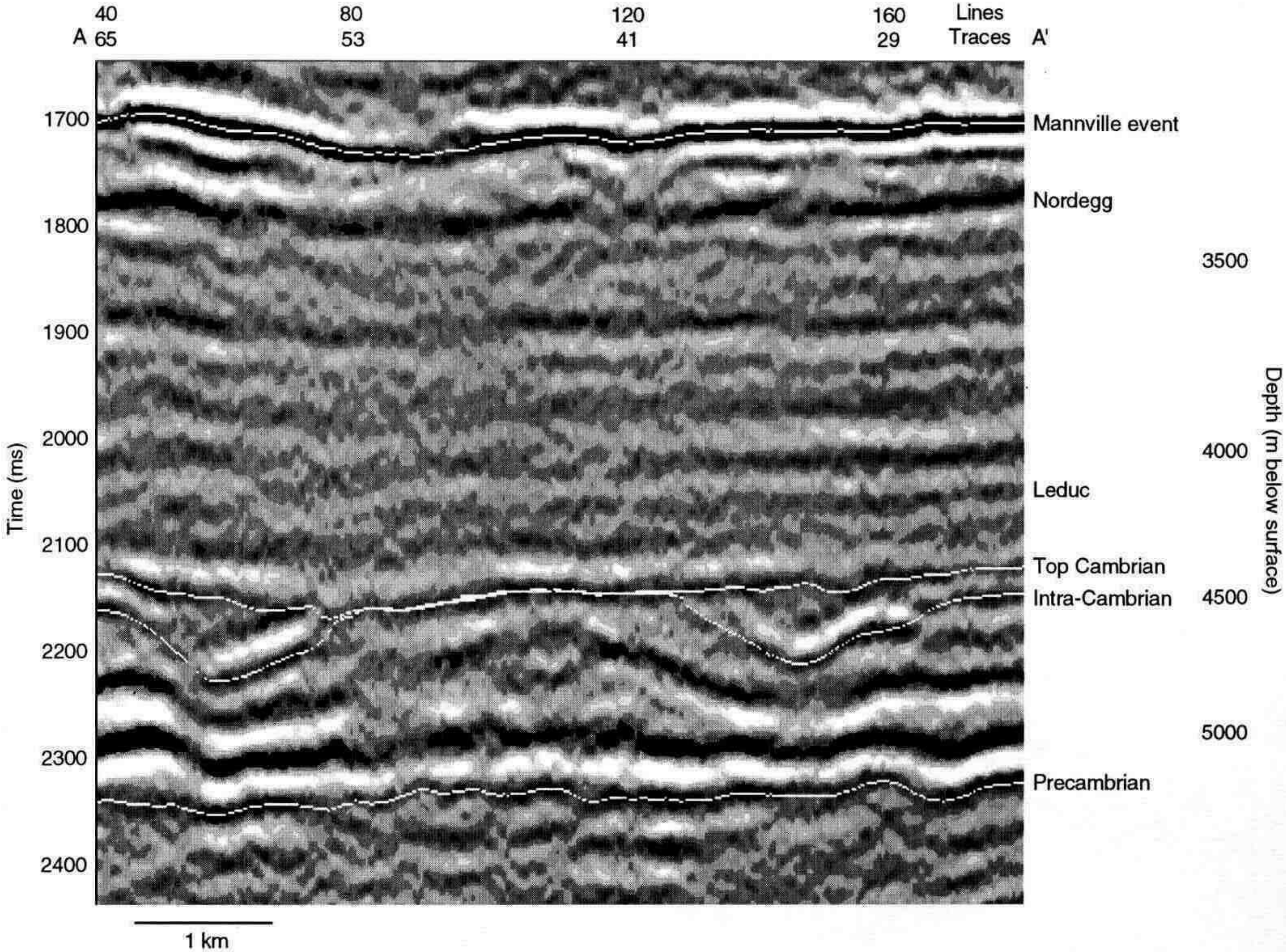
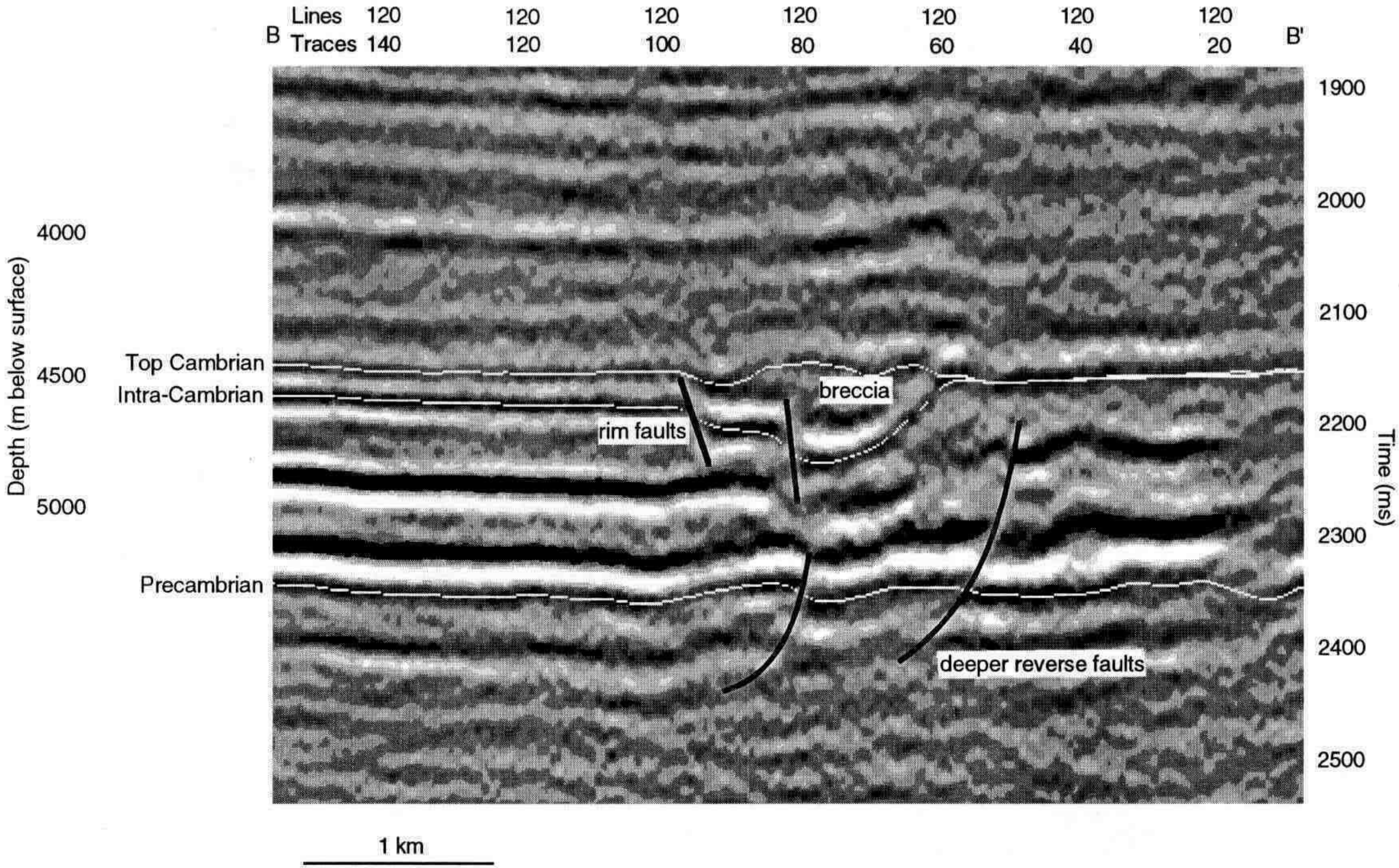


FIG. 5. NW-SW seismic line over the cryptoexplosion structure with interpreted horizons.
The truncation of dipping events beneath the Top Cambrian unconformity and the eroded central uplift are seen clearly.

FIG. 6. N-S seismic line showing normal rim faults, deeper reverse faults and the possible breccia zone.



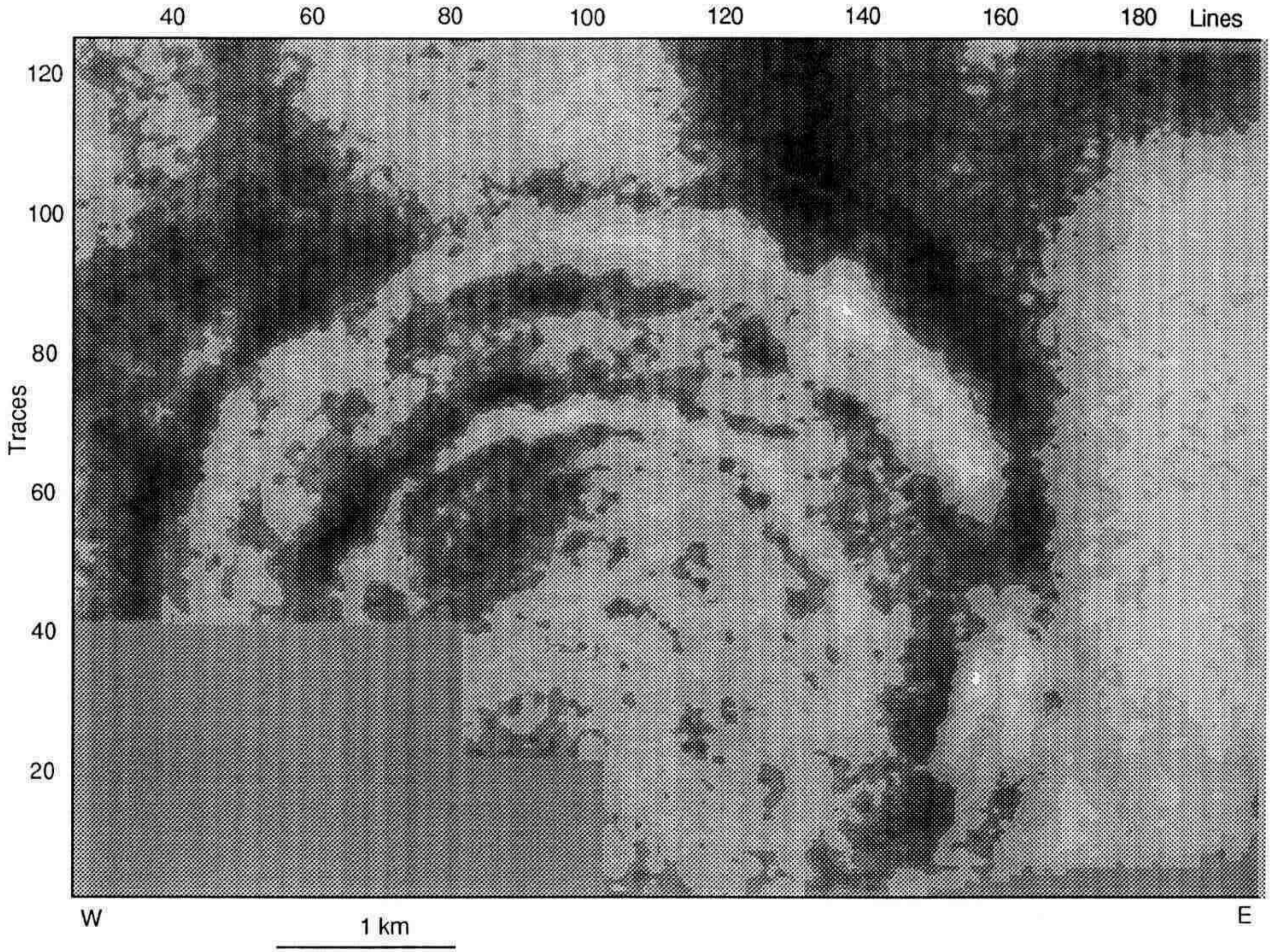
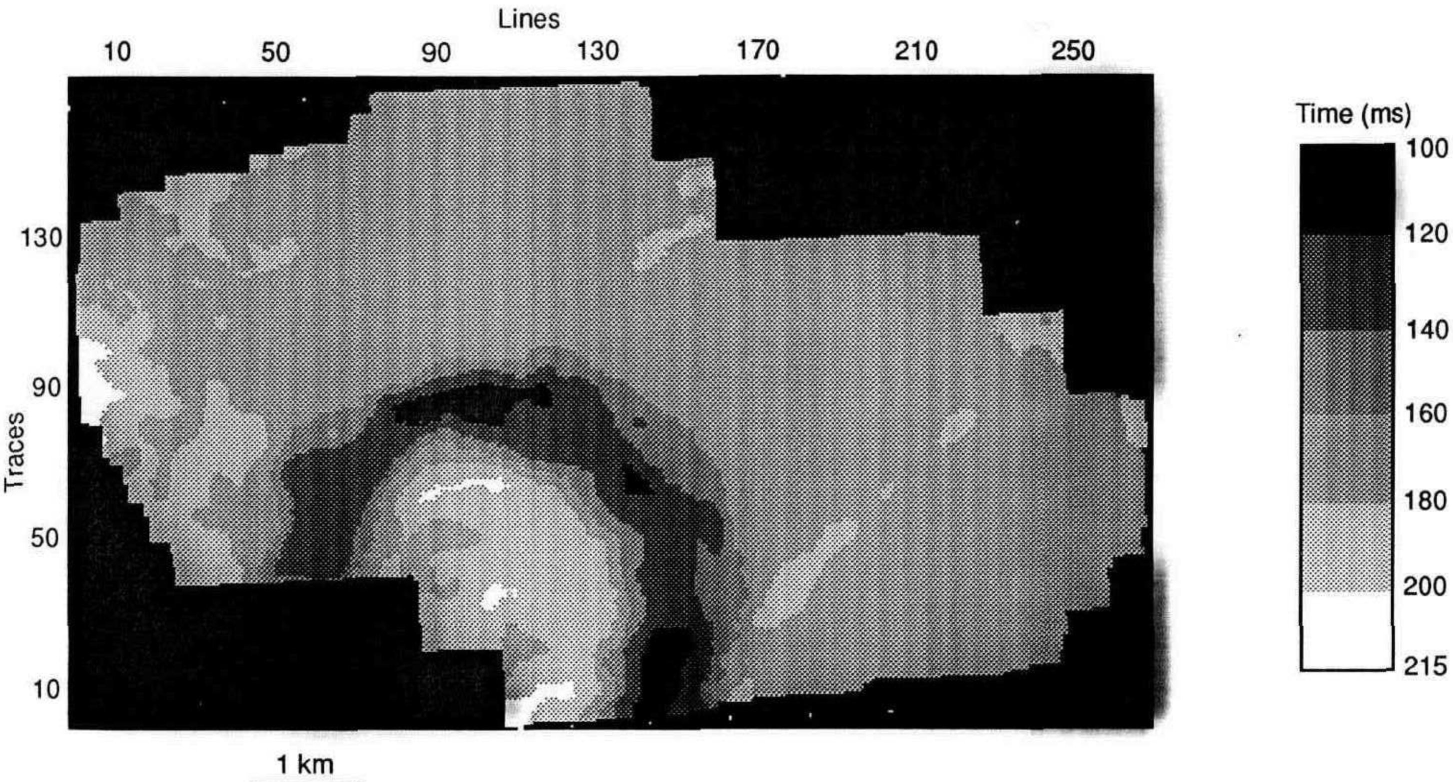


FIG. 7. Horizontal time slice at 2168 ms showing the circular plan of the beds.

FIG. 8. Intra-Cambrian - Precambrian isochron map.



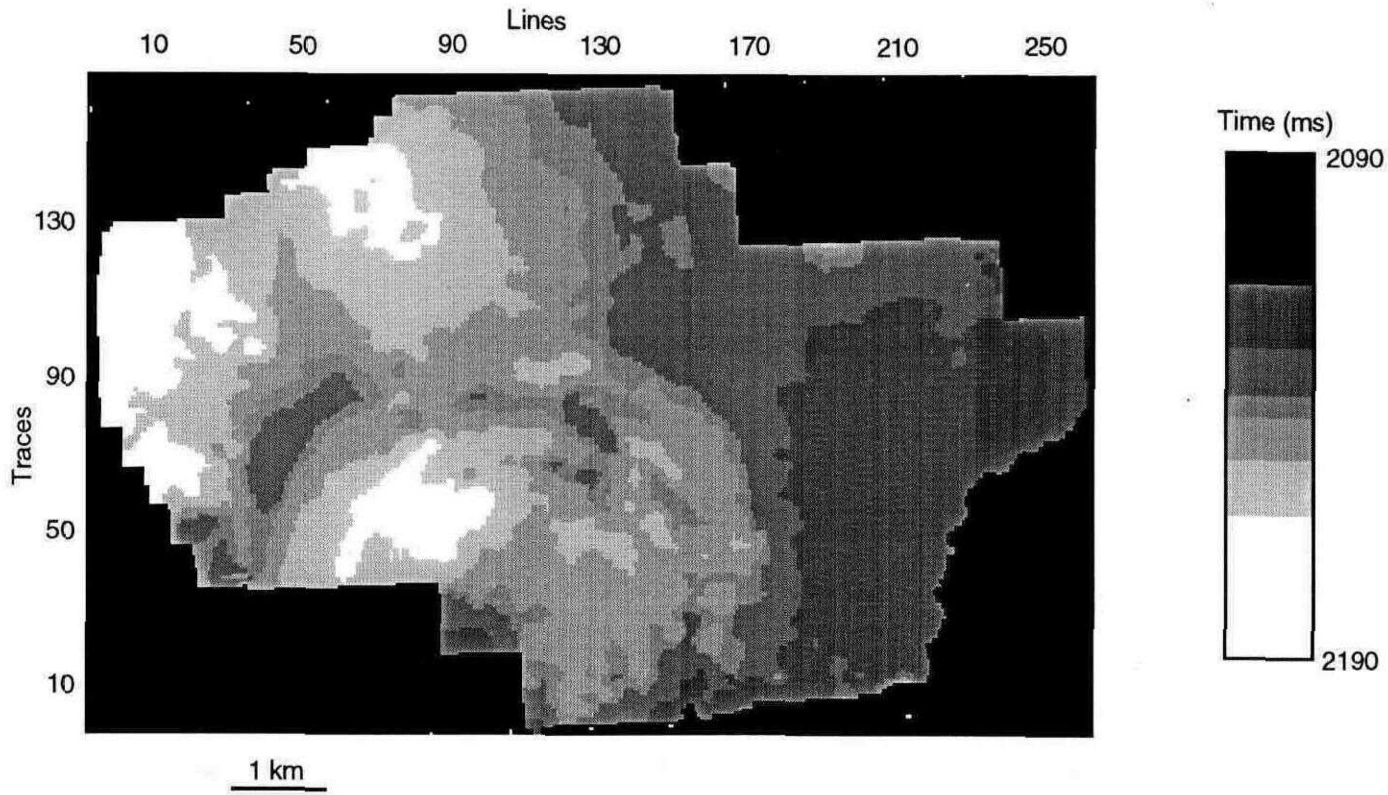
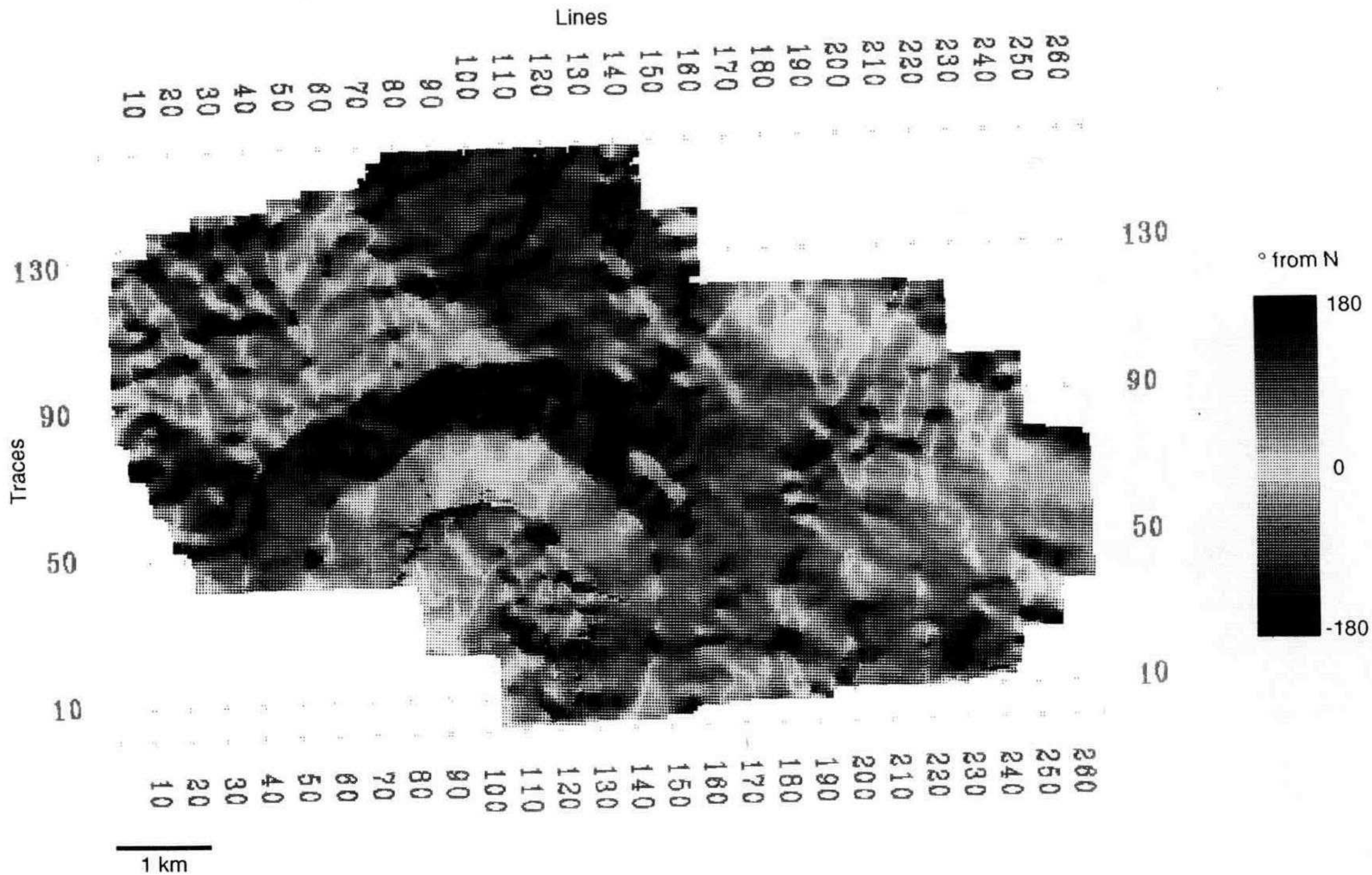


FIG. 9. Top Cambrian time structure map.
This unconformity surface probably reflects the selective resistances to erosion of the dipping strata beneath.

FIG. 10. Intra-Cambrian dip azimuth map showing the directions of dip of the Intra-Cambrian event.



The circular nature of the structure is not immediately apparent on the seismic lines but is strikingly clear on the time slice (Figure 7), which is a horizontal slice through the data at 2168 ms. Time slices are used to observe the lateral movement of reflectors in time and as an interpretation aid.

After the horizons are interpreted, a series of time structure maps is made. Some of the maps show clearly the circular shape of the structure and they are illustrated here. At the Precambrian level it is not known whether the observed hints of a circular structure 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 part of the map but they do not appear to reflect major zones of deep Precambrian faulting.

The Intra-Cambrian - Precambrian isochron map (Figure 8) is very striking. The circular shape and annular rim syncline 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 map (Figure 9) might be a result of the differing 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 pre-existing structure and the circular shape is not seen. Work is in progress to examine the relationship of the later fault trends to the earlier Cambrian structure and fault trends.

3-D seismic data can be used to visualise a structure in different ways. The directions of dip of the Intra-Cambrian event are calculated and mapped (Figure 10) to give another three-dimensional image of the structure. White areas indicate north dip and black south dip. This picture shows clearly the geometry of the structure, particularly the raised central uplift and the rim syncline.

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 original size of the feature is estimated by extrapolation of the observed truncated dipping events of the central uplift to a maximum pre-erosion height, assuming no change in dip. This gives a maximum original uplift of 700 m and a maximum original overall diameter of 7 km (Figure 11). These values compare 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, the original pre-erosion diameter of the James River structure is estimated to be 6 km, with a central uplift 1300 m in diameter and 600 m thick.

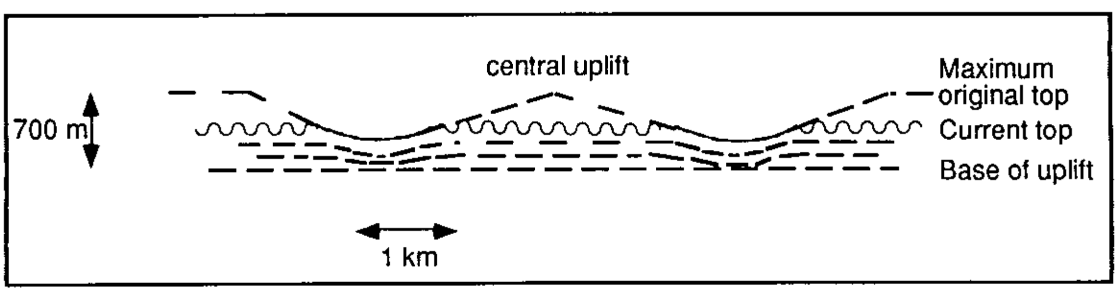


FIG. 11. Scaled diagram of the structure and its estimated maximum original dimensions.

Origin of the structure

Let us consider possible origins for this structure:

a) Impact

The morphology of the structure - its circular shape, ring depression, fault patterns and central uplift - is very similar to that observed at known or probable impact craters. The geometry fits 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 very rare, since bodies entering the Earth's atmosphere usually break up due to aerodynamic 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 in magmas by venting. They are capable of creating structures that look similar to impact craters. 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 of such structures on a lineament, since they are thought to be associated with the reactivation of pre-existing 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 syncline, 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.

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 and does not look like a shale plug. 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 and dissolution could have occurred. Most collapse structures associated with limestone dissolution are either sink-holes or linear features, as the fracturing which allows the circulation of waters is usually linear (Jenyon and Fitch, 1985). This James River structure is not well described by common dissolution features.

RESULTS

A 3-D seismic data set from James River, Alberta (Twp. 34, Rge. 7, W5) is interpreted, mapped and analysed using a Landmark interactive workstation. An unconformity surface, representing the end Cambrian-Middle Devonian hiatus, is seen on the data at about 2.1 s. Beneath the unconformity, steeply dipping events of Cambrian age form a ring depression between the outside rim of the circular structure and an inner circular area of apparently uplifted rocks. The amount of this uplift is seen to decrease with depth. The structure is confined to the interval between the top Cambrian unconformity and 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 syncline 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).

CONCLUSIONS

The feature observed on the 3-D seismic data at James River is a cryptoexplosion structure, interpreted to be the result of a meteorite impact. It has a circular shape, raised circular central uplift, annular rim syncline and rim faults. The amount of central uplift is seen to decrease with depth and continuous reflections are seen within the uplift. The age of the deformed rocks is Cambrian and the structure was formed during Late Cambrian to Middle Devonian time.

3-D seismic data and the tools provided by an interactive workstation provide powerful new ways of analysing and displaying subsurface structures in three dimensions. The circular shape of a cryptoexplosion structure becomes apparent immediately on time slices and in map view. The structure itself is seen in striking fashion in perspective views and on azimuth maps.

Although we do not have enough geological evidence to establish definitively the origin of the feature, we suggest that the morphology of the structure, the internal structure of the uplift and the decrease in uplift with depth strongly indicate an impact origin.

We intend to investigate the possibility of relationships between the Cambrian structure or Top Cambrian unconformity surface and consequent Devonian carbonate developments. Cretaceous fault patterns will also be studied.

ACKNOWLEDGMENTS

The authors would like to acknowledge Husky Oil Operations Ltd., Calgary, who generously donated the 3-D seismic data and made borehole data and computer facilities available. In particular, we would like to thank Mr. Murray Watts, Mr. Lawrence Mewhort and Mr. David Emery of Husky Oil for their assistance. We also express our appreciation to Mr. Raymond Probst and Mr. Dean Sinnott, who previously interpreted this interesting feature on the 3-D data and shared their knowledge with us. We also thank Ms. Susan Miller for the many hours she spent on data management. The several anonymous reviewers are thanked for their constructive ideas.This work was partially supported by the CREWES Project.

REFERENCES

Brenan, R. L., Peterson, B. L. and Smith, H. J., 1975, The origin of Red Wing Creek structure: McKenzie County, North Dakota: Wyoming Geol. Assoc. Earth Sci. Bull. 8, 1 - 41.

Carpenter, B. N. and Carlson, R., 1992, The Ames impact crater: Okla. Geol. Notes 52, 6, 208 - 223.

Dence, M. R., 1965, The extraterrestrial origin of Canadian craters: N.Y. Acad. Sci. Ann. 123, 941 - 969.

Dence, M. R., 1972, The nature and significance of terrestrial impact structures: Proc. 24th Internat. Geol. Cong., sect 15, 77 - 89.

Donofrio, R. R., 1981, Impact craters: Implications for basement hydrocarbon production: J. Petr. Geol. 3, 279 - 302.

Grieve, R. A. F., 1990, Impact cratering on the Earth: Sci. Am. 262, no. 4, 66 - 73.

Hildebrand, A. R., Penfield, G. T., Kring, D. A., Pilkington, M., Camargo Z., A., Jacobsen, S. B. and Boynton, W. V., 1991, Chicxulub crater: A possible Cretaceous - Tertiary boundary impact crater on the Yucutan peninsular, Mexico: Geology 19, 867 - 871.

Isaac, J. H. and Stewart, R. R., 1993, 3-D seismic characterization of possible meteorite impact craters: Presented at the 19th Ann. Can. Geophys. Un. Nat. Mtg., Banff, Alberta.

Jansa, L. F., Pe-Piper, G., Robertson, P. B. and Friedenreich, O., 1989, Montagnais: a submarine impact structure on the Scotian Shelf, eastern Canada: Geol. Soc. Am. Bull. 101, 450 - 463.

Jenyon, M. K. and Fitch, A. A., 1985, Seismic Reflection Interpretation: Geoexploration Monographs 1 - no. 8.

Krinov, E. L., 1962, Giant Meteorites: Pergamon Press.

Lawton, D. C., Stewart, R. R. and Gault, R., 1993, The geophysical signature of the Eagle Butte impact crater: Presented at the 19th Ann. Can. Geophys. Un. Nat. Mtg., Banff, Alberta.

Lilly, P. A., 1981, Shock metamorphism in the Vredefort collar: evidence for internal shock sources: J. Geophys. Res. 86, 10689 - 10700.

Martini, J. E. J., 1978, Coesite and stishovite in the Vredefort dome, South Africa: Nature 272, 715 - 717.

Masaytis, V. L., 1989, The economic geology of impact craters: Internat. Geol. Rev. 31, 922 - 933.

Melosh, H. J., 1989, Impact cratering: a geologic process: Oxford Univ. Press.

Nicolaysen, L. O. and Ferguson, J., 1990, Cryptoexplosion structures, shock deformation and siderophile concentration related to explosive venting of fluids associated with alkaline ultramafic magmas: Tectonophysics 171, 303 - 335.

Oberbeck, V. R., Marshall, J. R. and Aggarwal, H., 1993, Impacts, tillites, and the breakup of Gondwanaland: J. Geol. 101, 1 - 19.

Pike, R. J., 1985, Some morphologic systematics of complex impact structures: Meteoritics 20, 49 - 68.

Pilkington, M. and Grieve, R. A. F., 1992, The geophysical signature of terrestrial impact craters: Reviews of Geophys. 30, 161 - 181.

Officer, C. B. and Carter, N. L., 1991, A review of the structure, petrology, and dynamic deformation characteristics of some enigmatic terrestrial structures: Earth Sci. Rev. 30, 1 - 49.

Roddy, D. J. and Davis, L. K., 1977, Shatter cones formed in large-scale experimental explosion craters *in* Roddy, D. J., Pepin, R. O. and Merrill, R. B., Eds., Impact and Explosion Cratering: Pergamon Press, 715 - 750.

Roddy, D. J., Pepin, R. O. and Merrill, R. B., 1977, Eds., Impact and Explosion Cratering: Pergamon Press.

Sawatzky, H. B., 1972, Viewfield - a producing fossil crater: J. Can. Soc. Expl. Geophys. 8, 22 - 40.

Sawatzky, H. B., 1976, Two probable late Cretaceous astroblemes in western Canada - Eagle Butte, Alberta and Dumas, Saskatchewan: Geophysics 41, 1261 - 1271.

Scott, D. and Hajnal, Z., 1988, Seismic signature of the Haughton structure: Meteoritics 23, 239 - 247.

Sharpton, V. L. and Ward, P. D., 1990, Eds., Global catastrophes in Earth history: an interdisciplinary conference on impacts, volcanism, and mass mortality: Geol. Soc. Am. Special Paper 247.

van Hees, H. and North, F. K., 1964, Cambrian *in* McCrossan, R. G. and Glaister, R. P , Eds., Geological history of western Canada: Alb. Soc. Petr. Geol., 20 - 33.

Winzer, S. R., 1972, The Steen River astrobleme, Alberta, Canada: Proc. 24th Internat. Geol. Cong., sect. 15, 148 - 156.