Seismic characterization of impact craters: A summary

Michael J. Mazur, Robert R. Stewart, Alan R. Hildebrand, Don C. Lawton, and Hans-Hendrik Westbroek[1]

ABSTRACT

Enigmatic circular features have been observed on seismic data collected at various locations worldwide. We have examined eight seismic datasets collected within the Western Canadian Sedimentary Basin (WCSB) and other parts of the world over circular subsurface features. In these structures, we have observed many characteristics diagnostic of impact craters such as raised rims, annular synforms, terraced regions, inferred breccia infill, and large-displacement faults. All of the WCSB structures either have hydrocarbon production or production potential.

INTRODUCTION

Over the past 40 years, large amounts of seismic data have been acquired within the WCSB in the quest for hydrocarbons. Some of these data show enigmatic circular features that are not easily explained as reefs, diatremes, or dissolution features (Sawatzky, 1976; Isaac and Stewart, 1993; Stewart, 1999). Indeed, these features are of interest to resource companies as they often prove to be productive in terms of hydrocarbons as discussed later. We might ask how many impacts would be expected in the sedimentary record – as an indicator of their importance as targets. This is estimated in the Table below and Figure 1.

Table 1. The cumulative number of impacts expected over the past 600 MY distributed over the Earth, within Alberta, and within the WCSB. *after* French (1998).

Diameter (km)	# craters (Earth)	# craters (Alberta)	# craters (WCSB)
>1	384000	494	988
>1.8	138000	177	354
>3.1	49800	64	128
>5	21000	27	54
>7.2	10800	14	28
>10	6000	8	16
>12.2	4260	5	10
>20	1740	2	4
>31	840	1	2
>50	132	0.2	0.4
>100	24	0.03	0.06

By using the large amounts of seismic data collected in the sedimentary basins around the world, we expect to find many new examples of buried impact features. We also expect that the use of seismic interpretation methods will help us improve

[1] Shell Canada Limited

our understanding of the formation mechanics and morphology of impact craters. An outline of the terminology used in the discussion of meteorite impact craters is provided in Appendix I.

ECONOMIC POTENTIAL OF IMPACT CRATERS

Of the more than 150 known terrestrial impact craters, at least 35 have been associated with economic deposits of some kind. Currently, more than 16 are being exploited. Revenues generated annually from the recovery of material related to impact craters is approximately $12 billion (Grieve and Masaytis, 1994). This figure includes the $7 billion generated from gold recovery at Vredefort, South Africa and the $5 billion generated from North American deposits but not the $200 million from hydroelectric generation at Manicouagan, Canada nor that from the extraction of cement and lime at Ries, Germany ($70 million annually).

North America is home to a number of hydrocarbon-producing impact structures. The Ames structure in Oklahoma is, by far, the most prolific with reserves of more than 50 million barrels of oil and 20-60 billion cubic feet of gas. Fifty-two of the 100 wells produce oil while one produces gas. The Gregory 1-20 well is one of the most productive at 1300 barrels of oil per day (BOPD) with a primary recovery of more than 10 million barrels. A well-known impact structure in the WCSB is the Steen River structure located on the Alberta-NWT border. The structure hosts seasonal production of about 1000 BOPD and 32 million cubic feet (MCF) of gas per day. The majority of the wells at Steen River have been drilled into structures around the rim with only a few early wells into the central uplift. Table 2 summarizes some of the world's hydrocarbon producing craters.

Table 2. Some of the known impact craters with hydrocarbon potential. (*after* Sawatzky, 1976; Isaac and Stewart, 1993; Mazur, 1999; Scott and Hajnal, 1988; Jansa et al., 1989)

Structure	Diameter (km)	Age (Ma)	Hydrocarbons
Ames, Oklahoma	14	450	50 MMbbl oil and 20-60 BCFG source rock controlled by structure
Avak, Alaska	12	3-100	37 BCFG - provided trap to migrating hydrocarbons
*Hotchkiss, Alberta	3.5	110-330	-gas production from draped sediments overlying the central uplift
Marquez, TX	22	58	- some gas production
*Muskingum, Ohio	1.3	~505	- gas in crater fill - too wet for production
Newporte, ND	3.2	500	- oil shows in Cambro-Ordovician sands
Red Wing Creek., ND	9	200	- 40-70 MMbbl oil and 100 BCFG - provided trap to migrating hydrocarbons
Steen River, Alberta	25	95	- 32 MCF gas per day - ~1000 BOPD - rim features provide structural traps
Tookoonooka,	55	?	- forms shadow zone to migrating

Australia			hydrocarbons
Viewfield, Saskatchewan	2.4	140-240	- 400 BOPD - 20 MMbbl oil reserves - provided trap to migrating hydrocarbons

*suspected impact origin

INTERPRETED DATASETS

Circular structures have been observed on seismic data obtained within the WCSB and throughout other parts of the world (Table 3). These features have seismic characteristics such as rim uplift, central uplifts (in complex cases), breccia fills, slump blocks, and structural pinch zones that are expected to be diagnostic of impact genesis. Many of these features also have associated hydrocarbons making them excellent exploration targets.

Table 3. Seismic datasets collected over possible and confirmed impact structures housed at the University of Calgary.

Structure	Diameter (km)	Type*	Seismic Data**	Age (MY)	Hydrocarbons
Eagle Butte, AB	15	C	2-D	<65	Yes
Hotchkiss, AB	3.5	C	3, 2-D	110-330	Yes
James River, AB	3.5	C	3-D, 60%	375-525	?
Muskingum, Ohio	1.3	S	2, 2-D	500	Yes
Puffin, Timor Sea	2	S	3-D, 100%	15	?
Purple Springs, AB	3	T	2-D	?	?
Steen River, AB	25	C	127, 2-D	95	Yes
White Valley, SK	5	C	4, 2-D	60	No

*Type refers to the observed morphology and is complex (C), simple (S), or transitional (T).
**The interpreted seismic data is given as the number of lines for 2-D and percent coverage for 3-D.

Muskingum, Ohio

Buried beneath approximately 1 km of sediments, the Muskingum structure (Figure 2) in Ohio, USA exhibits some of the characteristics of a buried impact crater. The structure is defined by two seismic lines over the feature and several others that border it. At nearly 1300 m in diameter, this feature lacks the diagnostic features of a diatreme intrusion crater. Evidence for rim faults and mounding at the center of the structure suggests that the Muskingum structure is an impact crater that was, at the time of formation, 1450 m in diameter and about 300 m deep. The transient cavity is estimated to have had a diameter of about 1215 m and a depth of 450 m. Correlation of the seismic data with well log data and the use of average erosion rates indicates that the structure is Cambrian-Ordovician in age (about 500 MY old). A more accurate estimation of the event timing is difficult to achieve, however, due to the erosion of the top 150-m of the structure during the Knox unconformity hiatus and a lack of core samples. Of exploration interest is the post-event sediment infill.

Puffin, Timor Sea

Approximately 250-km off the coast of northwestern Australia in the Timor Sea (Figure 3), a 3-D seismic survey images a small near-circular feature that exhibits some of the characteristics of a buried impact crater. The feature is approximately 2.0 km in diameter by about 150 m in depth. The depth of burial is about 1500 m in Tertiary carbonates. The seismic time structures and isochrons give evidence for rim uplift, an inner terrace and a broad, flat floor. The Puffin structure's elliptical shape and abnormally shallow profile can be explained by the impact of a clustered projectile about 75 m across travelling at 20 km/s (Mazur, 1999). Although the structure lies in close proximity to several kimberlite pipes, it is thought to be too large to be explained as such. Furthermore, there is no seismic evidence for a carrot-shaped root extending to great depths. The dissolution of limestone and subsequent collapse of overlying sediments has also been described as a possible mechanism for the formation of this structure. As there is no observed drape over the rim of the structure this explanation is thought to be incorrect. Sub-aerial or shallow marine dissolution also provides a possible mechanism for the formation of this structure. From the seismic reflection data, the age of the structure is estimated to be approximately 15 MY.

Purple Springs, Alberta

Located in south central Alberta, the Purple Springs structure is approximately 3 km in diameter and is within the simple-complex transition diameter. The structure is well imaged by several 2-D seismic lines and shows the basic bowl-shaped characteristics of a simple crater. Internally, reflectors are observed to truncate against the sides of the structure possibly representing post-impact crater infill.

Eagle Butte, Alberta

The Eagle Butte crater, situated near Cypress Hills in southeast Alberta is a complex impact structure approximately 15 km in diameter. The structure has an age of less than 65 million years and is well imaged by seismic lines.

Hotchkiss, Alberta

The Hotchkiss structure in NW Alberta is an enigmatic feature imaged by several 2-D seismic lines (Figure 4). The appearance of the Hotchkiss structure on seismic data closely resembles that of a complex impact crater such as the White Valley structure in SW Sakatchewan (Figure 6). Using 2-D seismic data, this study interprets the current extent of the feature and its pre-erosional dimensions. The current size of the area of disturbance is 3.5 km across and 400 m thick. Using scaling relations, the Hotchkiss structure is estimated to have been 4.5 km in diameter and 500 m deep at the time of formation between 120 and 330 million years ago (Mazur, Stewart and Hildebrand, 1999). The transient cavity is estimated to have been about 2.6 km in diameter by about 730 m deep. Subsequent to its formation, the Hotchkiss structure experienced a large amount of erosion. The Gething-Debolt unconformity marks this period of erosion during which an estimated 500 m of the structure was eroded.

James River, Alberta

The James River structure (Figure 5) is located in southwestern Alberta and is consistent with complex crater morphology (Isaac and Stewart, 1993). The top of this structure is buried at a depth of nearly 4500 m and is truncated by an erosional unconformity marking the top of the Cambrian. This crater has a diameter of nearly 5 km, an annular moat, and a central uplift 2.4 km in diameter. The structure is estimated to have formed sometime during Middle Devonian to Late Cabrian time (Isaac and Stewart, 1993). Of exploration interest are structural traps formed by the terraces along the crater walls, the central uplift rocks, and the breccia infill.

White Valley, Saskatchewan

The White Valley structure (Figure 6) in southwestern Saskatchewan is a circular anomaly evident on four 2-D seismic lines. This structure has many of the morphological characteristics of a complex impact crater (Westbroek, 1997). The structure is interpreted to have a diameter of about 7 km with an annular trough and a raised central uplift. Also observed is an apparent asymmetry of the appearance of the Milk River formation across the central uplift.

Steen River, Alberta

The Steen River structure is located in northwestern Alberta and, at 25 km in diameter, is the largest known astrobleme in the WCSB. There are more than 130 seismic lines over the feature and more than 40 wells have been drilled around the rim. The crater's central structures show striking magnetic field anomalies, and ongoing gravity surveys reveal a series of concentric gravity anomalies that correlate to both the central magnetic anomalies and peripheral crater structure revealed by reflection seismic surveys. The Steen River structure is a classic example of an eroded complex crater and remains a site of active hydrocarbon exploration.

SUMMARY

Due to the large extent of the WCSB and other sedimentary basins worldwide many impact structures should be preserved within the sedimentary section. Impact craters have been shown to make excellent targets for hydrocarbon exploration and, as awareness is increased, we expect that many new seismic examples of impact craters will be brought to the public’s attention. The methods of seismic interpretation can aid in the identification of buried impact structures as we have seen that many diagnostic impact features are well imaged by seismic methods.

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APPENDIX I

IMPACT CRATER TERMINOLOGY

To better understand the morphometry and hydrocarbon potential of buried impact craters, we first outline the terminology used to describe impact structures.

Simple Crater – A simple crater (figure 7a) is bowl-shaped with an allochthonous breccia infill. Rim uplift is present and there may be extensive substructure fracturing and faulting. On Earth, simple craters typically have diameters smaller than 2 km in sedimentary rocks and diameters less than 4 km in crystalline rocks.

Complex Crater – At diameters larger than 2-4 km crater advances through a sudden transition (figure 7b). A central uplift forms along with rim faulting and down-slumped terraces. Rim uplift is observed and subcrater fracturing, faulting, and structural pinching can be significant.

Breccia – Hypervelocity impacts generate shock pressures far exceeding the Hugoniot Elastic Limits (HEL) of the impacted rocks. Rock in which the HEL has been exceeded that is neither vaporized nor melted is brecciated. In simple craters, an allochthonous breccia is found to form a lens at the bottom of the crater. In complex structures an annular breccia lens will be observed surrounding the central uplift. Due to the high porosity/permeability of many breccias they can make excellent hydrocarbon reservoirs when capped by an impermeable layer.

Disruption Cavity – The disruption cavity is the cavity defined by the boundary between the brecciated and competent rock. It exists transiently at the end of the excavation stage of crater formation. This is also the approximate volume beyond which the Hugoniot Elastic Limit for the target rock is no longer exceeded.

Transient Cavity – Often confused with the disruption cavity, the transient cavity is defined as the breccia and melt lined cavity which collapses into the final crater.

Ejecta – During an impact, large amounts of material are excavated and re-deposited outside of the transient cavity. In a complex crater-forming event, approximately one-half of the ejecta falls on the region that will later collapse to form slump blocks. In the case of a buried structure, the rim ejecta may be completely eroded away while that on the slump blocks preserved. The blocky, porous, and permeable nature of the ejecta makes it a good target for exploration.

Central Uplift – The central uplift of a complex crater is that region of near-vertical to vertical strata that have been uplifted from their original position a distance of about eight percent of the final crater diameter. Due to the highly inclined nature of central uplifts their internal structure is difficult to image by seismic means. As with the Ames structure, hydrocarbons can sometimes be found in the highly fractured rocks of the central uplift

Rim uplift – An important diagnostic feature of impact craters, rim uplift is that region surrounding the crater that is elevated above the regional elevation. Approximately one-half of the uplift is due to actual stratigraphic uplift while the rest is from the presence of the ejecta blanket. Crater rims often provide structural traps for migrating hydrocarbons. This, coupled with the relative ease of imaging them by seismic means, makes them excellent targets.

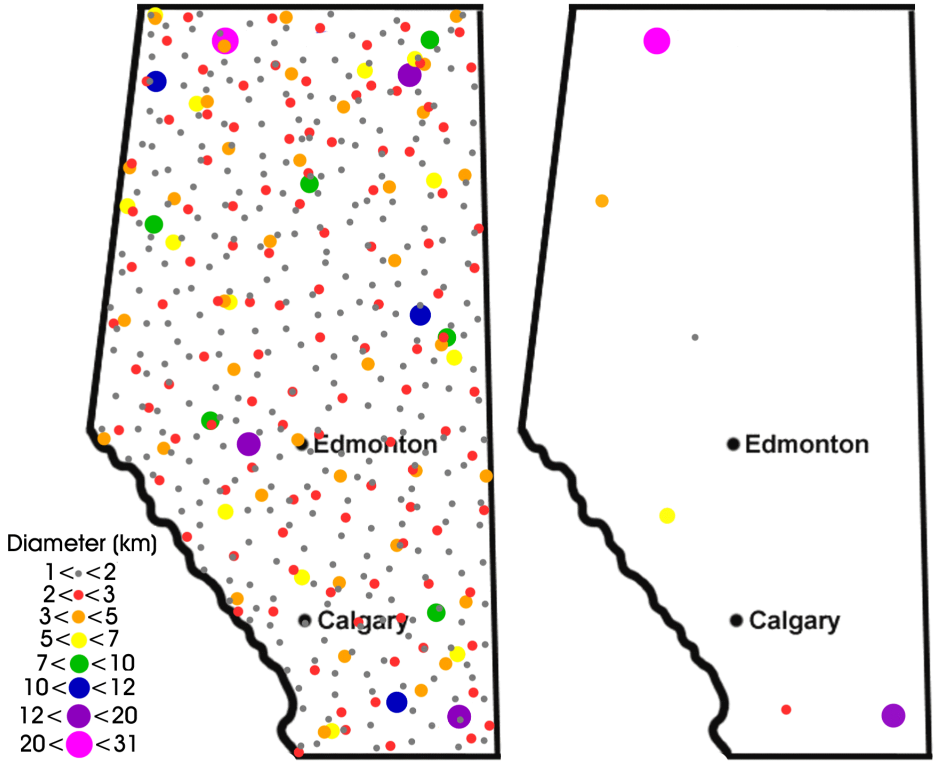

Figure 1. During the last 600My it is thought that nearly 500 craters larger than 1-km diameter have formed in Alberta. This figure shows a random distribution of ~500 events with their proper size distribution on the left with the known distribution of possible impact structures on the right.

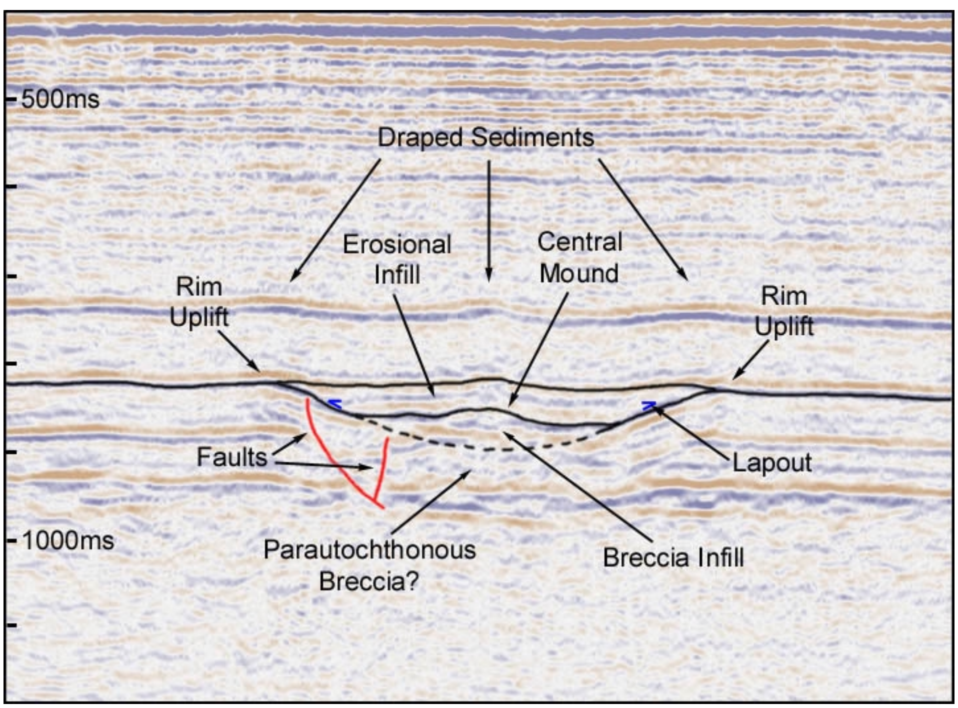

Figure 2. The Muskingum structure in Ohio is approximately 1.3 km across and shows evidence of a rim uplift, breccia infill, disturbed subcrater rocks, rim faulting, and an erosional infill. (Mazur, 1999)

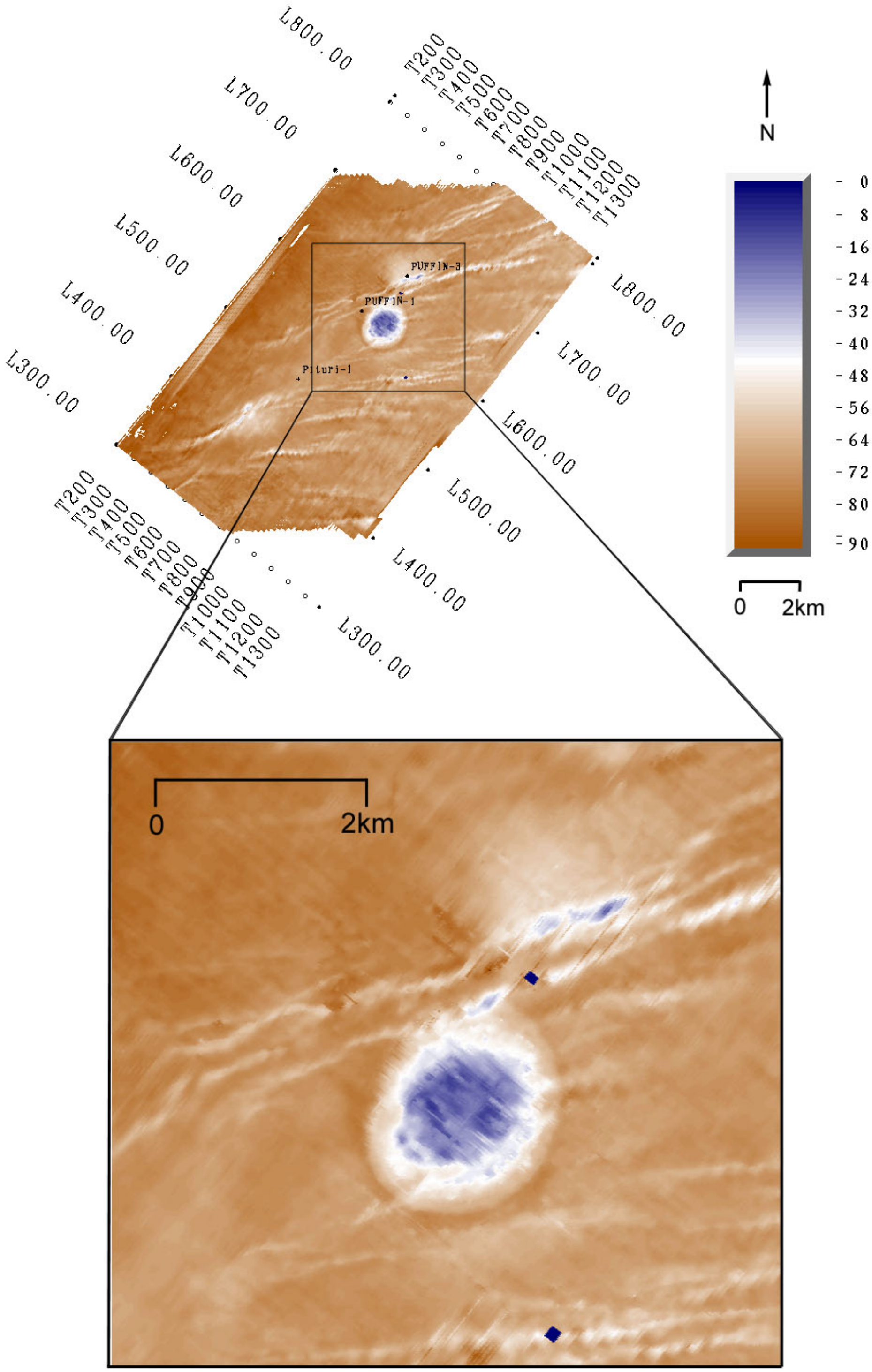

Figure 3. The structure-to-Oliver isochron shows the structure as it may have appeared at the time of formation. The structure structure can be broadly characterized as an elliptical, flat-floored crater-like feature with apparent rim uplift. Also note the slight raised region towards the NNW. (Mazur, 1999)

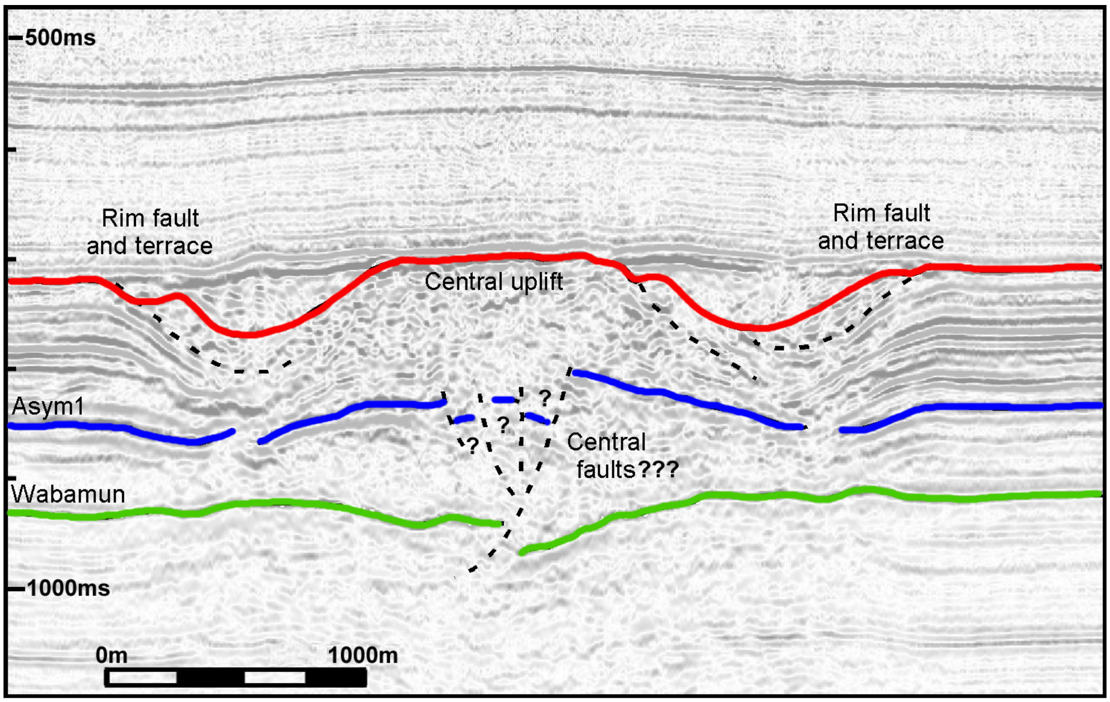

Figure 4. The Hotchkiss structure in NW Alberta shows many of the diagnostic characteristics of a complex impact crater. A central uplift, a faulted rim, structurally pinched areas, and possible central faults are apparent. Also notice the large amount of drape in the overlying sediments. (Mazur, 1999)

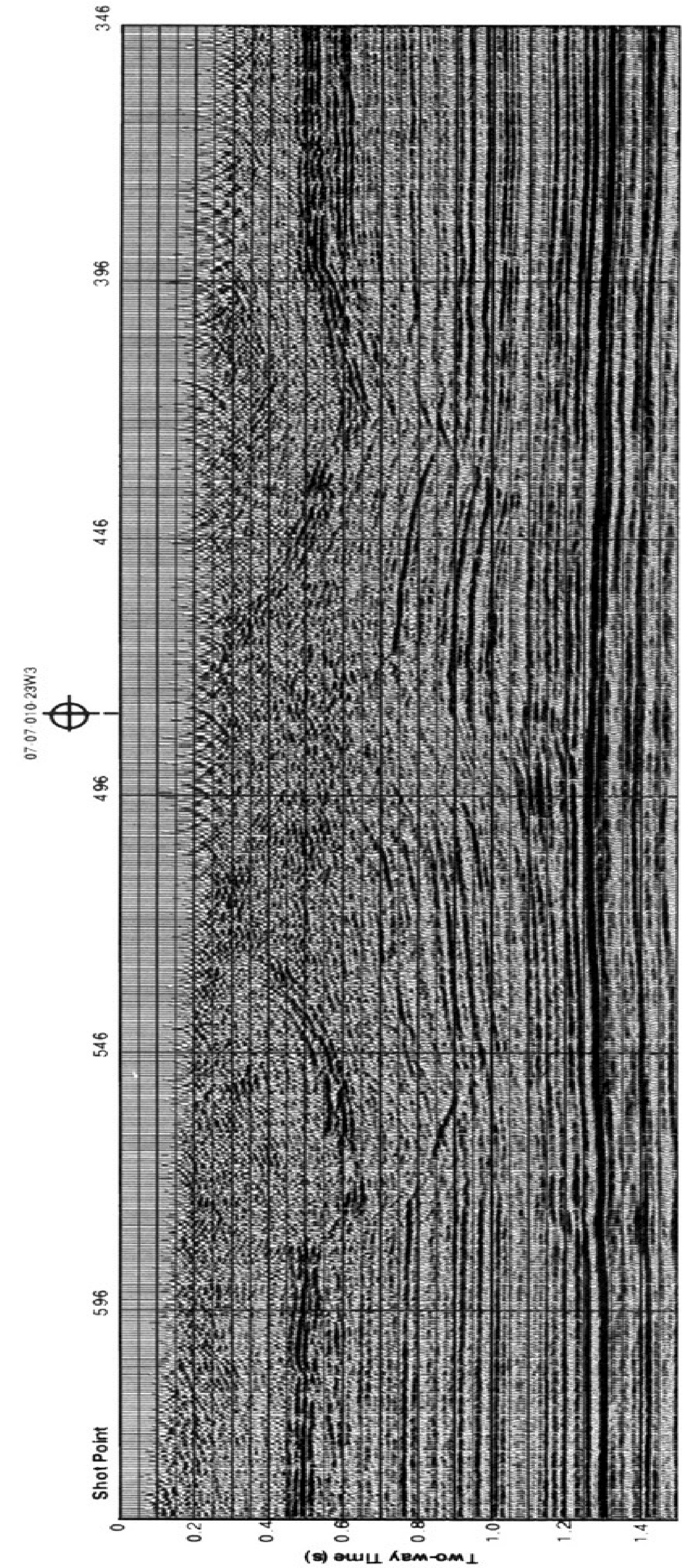

Figure 5. The White Valley structure in southwestern Saskatchewan has been interpreted as a <75 Ma old impact feature. (Westbroek, 1997)

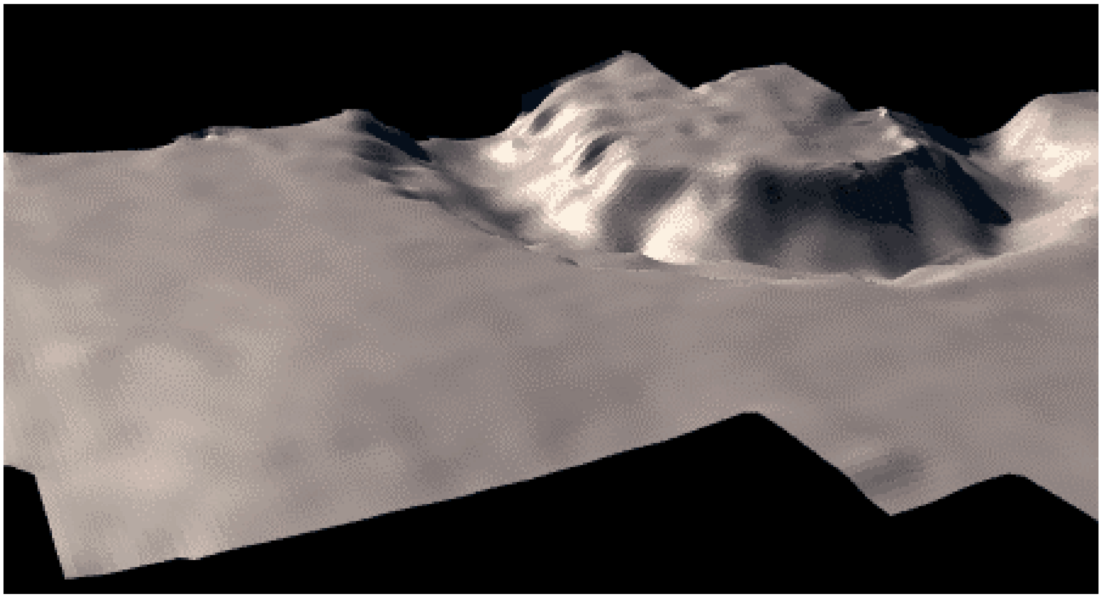

Figure 6. The James River structure in Alberta is approximately 4.8 km across and shows many of the morphological characteristics of a complex impact crater. This view is of the Cambrian 'event' horizon as described by Isaac and Stewart (1993). (image by Henry Bland)

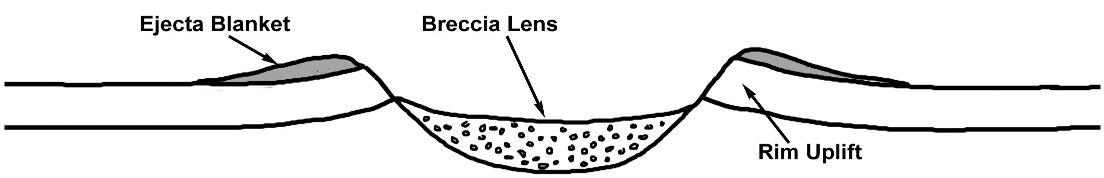

Figure 7a. A simple crater is described by a bowl-shaped cavity with a breccia infill and rim uplift.

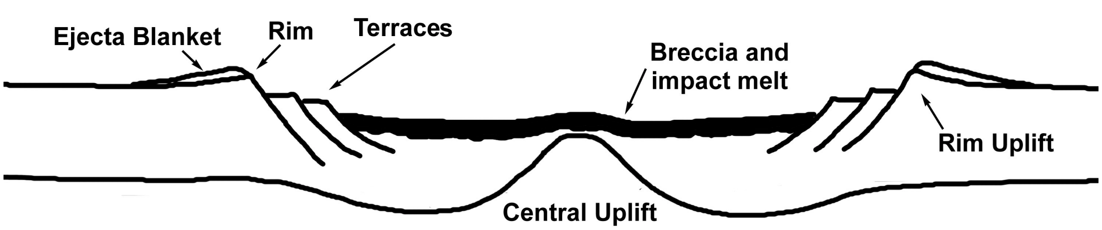

Figure 7b. Complex craters occur at diameters larger than simple craters and exhibit a central uplift and rim terraces in addition to the features of a simple crater.