The seismic expression and hydrocarbon potential of meteorite impact craters: Current research

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ABSTRACT

Nearly one quarter of all known terrestrial impact craters are associated with economic deposits of some kind. Ranging from mineral ores and hydrocarbons to evaporite minerals, these deposits often have significant economic importance. Imaged by seismic means, these craters often show characteristics that are diagnostic of crater morphology and impact mechanics. The University of Calgary has been fortunate to receive several seismic datasets showing possible impact structures. These datasets show simple craters, transitional craters, and complex craters. By characterizing and comparing these datasets a more thorough understanding of the morphology and mechanics of formation of impact structures is gained.

INTRODUCTION

More than 150 examples of impact craters are known to exist around the world (Figure 1). Approximately 25% of all known impact craters are associated with mineral or hydrocarbon deposits (Grieve, 1991). Scattered throughout the Western Canadian Sedimentary basin, several enigmatic circular structures are well imaged on seismic datasets. These structures have characteristic circular morphological outlines and often show evidence of violent disruption during their formation. Some are host to hydrocarbon accumulations.

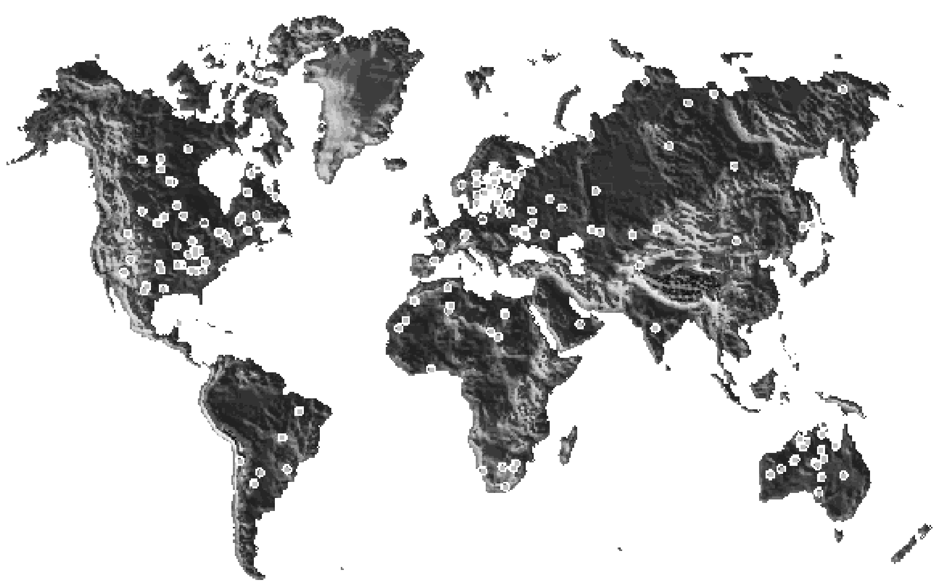

Figure 1. More than 150 impact craters have been identified and catalogued around the world. Each dot represents a known impact site.

Terrestrial impact craters are characterized by two basic forms: simple and complex (Figure 2a and 2b). Simple craters generally have diameters up to about 2 km in sedimentary rocks and 4 km in crystalline rocks (Melosh, 1989). Formed by lower-energy events, simple craters are relatively common. The morphology of a simple crater is characterized by a bowl-shaped profile. Filling the bottom of the 'transient cavity' is an allochthonous brecciated lens from the slumping of the transient crater walls (Pilkington and Grieve, 1992).

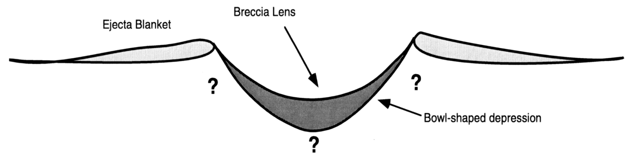

Figure 2a. Schematic of a simple crater (Westbroek and Stewart, 1995)

When a large, dense body enters the Earth's atmosphere, it is not slowed appreciably by the Earth's atmosphere (Grieve, 1991). The resultant impact involves very high shock pressures and the complete vapourization of the impactor. As in the simple case, a deep transient cavity forms. Gravitational effects, however, are great enough that the floor of the transient cavity rebounds to form a central uplift region. The central uplift region is generally characterized by shock metamorphic effects. An ejecta blanket is spread around the perimeter of the crater in a pattern dictated by the impact angle and the rim of the crater is often terraced due to rim faulting. The annular trough is characterized by an amalgam of allochthonous shocked materials and impact melts (Grieve, 1991; Melosh, 1989). This is the basic morphology of a complex crater.

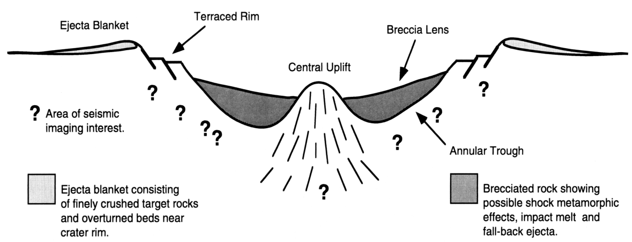

Figure 2b. Schematic of a complex crater (Westbroek and Stewart,1995)

At still larger impact energies, we see a further change in crater morphology. The central uplift no longer contains a single peak but is instead defined by a ring. As such, this type of crater is termed multi-ring. Due to the large energies required to create such a structure we see very few on the Earth. The 180 km crater at Chicxulub, Mexico is thought to be associated with the extinction of the dinosaurs and is probably the best known multi-ring terrestrial crater (Hildebrand, 1991).

Economic Importance of Impact Structures

Of the 150 known terrestrial craters, about 35 have been associated with economic deposits of some kind. Currently 17 are being exploited. Revenues generated annually from the recovery of material related to impact craters is approximately \$12 billion. This figure includes the \$7 billion generated from gold recovery at Vredefort, South Africa and the \$5 billion generated from North American deposits. It should be noted that the above figure does not include the revenues from the generation of hydroelectric power at Manicouagan (\$200 million annually) nor that from extraction of cement and lime products at Ries, Germany (\$70 million annually). These examples of the economic importance of impact structures have resulted in the inclusion of a session on hydrocarbons in meteorite impact craters at the 1998 AAPG Annual Meeting in Salt Lake City, Utah.

North America is home to a number of oil and gas producing impact structures. The Ames structure is, by far, the most prolific hydrocarbon producer. It is estimated that reserves at Ames total more than 50 million barrels of oil and 20-60 billion cubic feet of gas. Fifty-two of the 100 wells produce oil while 1 produces gas. The Gregory 1-20 well is one of the most productive at 1300 barrels of oil per day with a primary recovery of more than 10 million barrels. The best known impact structure in the WCSB is located on the Alberta-NWT border at Steen River. Known as the Steen River structure, this impact structure currently produces 600 barrels per day from several wells. The majority of the approximately 40 wells have been drilled into the rim of the structure with only a few wells drilled into the central uplift (Figure 3). Table 1 below summarizes some of the world's hydrocarbon producing craters.

Structure	Diameter (km)	Age (MA)	Hydrocarbon Accumulation
Ames, OK	14	450	50MMbbl oil 20-60 BCFG source rock controlled by structure
Red Wing Creek, ND	9	200	40-70MMbbl oil 100 BCFG provided trap to migrating hydrocarbons
Avak, Alaska	12	3-100	37 BCFG provided trap to migrating hydrocarbons
Marquez, TX.	22	58	some gas production
Newporte, ND	3.2	500	oil shows in Cambrian-Ordovician sands
Calvin, Mich.	?	?	600MMbbl oil
Steen, AB.	22	95	600bbl per day
Viewfield, Sask.	2.4	Triassic Jurassic	400bbl per day 20MMbbl oil formed trap to migrating hydrocarbons
Tookoonooka, Australia	55	?	forms shadow zone to migrating hydrocarbons

Table 1. Structures associated with hydrocarbon accumulation. (Sources: Isaac and Stewart, 1993; Westbroek and Stewart, 1996).

SEISMIC DATASETS

Currently, CREWES has access to 8 seismic datasets acquired over possible meteorite impact craters (Table 2). These structures range from small simple craters (Purple Springs and Muskingum) to larger, more complex craters (James River and Steen River). Of these 8 structures, 2 have been imaged by 3-D seismic datasets (James River and Texaco's 3-D). The 3-D datasets tend to show details not evident in the 2-D datasets. Several examples of these datasets are given in Figures 4 through 10. The Hotchkiss structure (Figure 4), shows the morphological characteristics of a small (approximately 6 km in diameter) complex crater. The event surface is well defined as is the structural disturbance below the structure. Figure 5 illustrates the circular nature of the James River structure while Figure 6 gives an example of the quality of seismic data. Notice the high resolution and clear definition of the structure. Figure 7 shows the one line of the Muskingum dataset in Ohio. Morphologically, this dataset describes a simple crater approximately 3 km in diameter. This assertion is evidenced by the lack of a developed central uplift. The Purple Springs structure ,as shown in Figure 8, also illustrates the general characteristics of a simple crater. Figure 9 is an example of a seismic line acquired over the White Valley structure. It exhibits the general characteristics of a complex crater.

Structure	Size (km)	Survey Type	Morphology
Hotchkiss, AB	5 km	2-D, 1 line	Transitional
Hespero, AB	4 km	2-D	?
James River, AB	5 km	3-D	Complex
Muskingum, OH	3 km	2-D, 2 lines	Simple
Purple Springs, AB	3 km	2-D, 3 lines	Simple
Steen River, AB	25 km	2-D, >120 lines	Complex
Texaco 3-D, Illinois	5 km	3-D	Complex
White Valley, SK	6 km	2-D, 4 lines	Complex

Table 1. Numerous examples of impact structures as imaged on seismic data have been made available to the University of Calgary

CURRENT RESEARCH

Research into impact craters at the University of Calgary currently consists of the seismic characterization of impact structures. By characterizing and comparing these structures, a great deal can be learned about the morphology and formation mechanics of these structures.

The James River cryptoexplosion structure has been examined in detail (Isaac and Stewart, 1993). A thorough interpretation of the morphological characteristics of this structure has been initiated. As well, the complex nature of the faults related to the structure has been investigated. Results show the preferential placement of the various fault types, possibly indicating impact direction (Figure 10).

The Purple Springs and White Valley structures have been examined in detail (Westbroek, 1995).The Purple Springs structure has been observed to have the physical characteristics of a simple impact crater. The Muskingum and Hotchkiss structures show morphological characteristics consistent with Purple Springs and White Valley respectively. The similarities are being compared as thorough interpretations of the Muskingum and Hotchkiss datasets continue.

FUTURE RESEARCH

With the recent donation of several new datasets to the University of Calgary, research in the area of impact craters continues. In the coming year, we hope to build a physical model of a simple impact crater using the hypervelocity gun facility at the NASA-Ames Research Facility in California. Formed in epoxy impregnated sand, this layered model (Figures 10 and 11) will then be examined using the Seismic Modeling Facility at the University of Calgary. It is hoped that this research will lead to a better understanding of the seismic characteristics of terrestrial impact craters. Additionally, we anticipate compiling a database of the interpreted horizons of these structures that will be available via the World Wide Web. Using Virtual Reality Modeling Language (VRML) to describe seismic horizons (Bland, 1996) it is possible to provide real-time animated fly-throughs across the World Wide Web.

CONCLUSIONS

Approximately 25% of all known impact structures are associated with some sort of economic deposit. Many such structures have been imaged well on seismic datasets. Several these datasets have been made available to the University of Calgary for further study. Current research focuses on the seismic characterization of impact structures while future plans include the physical modeling of both simple and complex impact structures.

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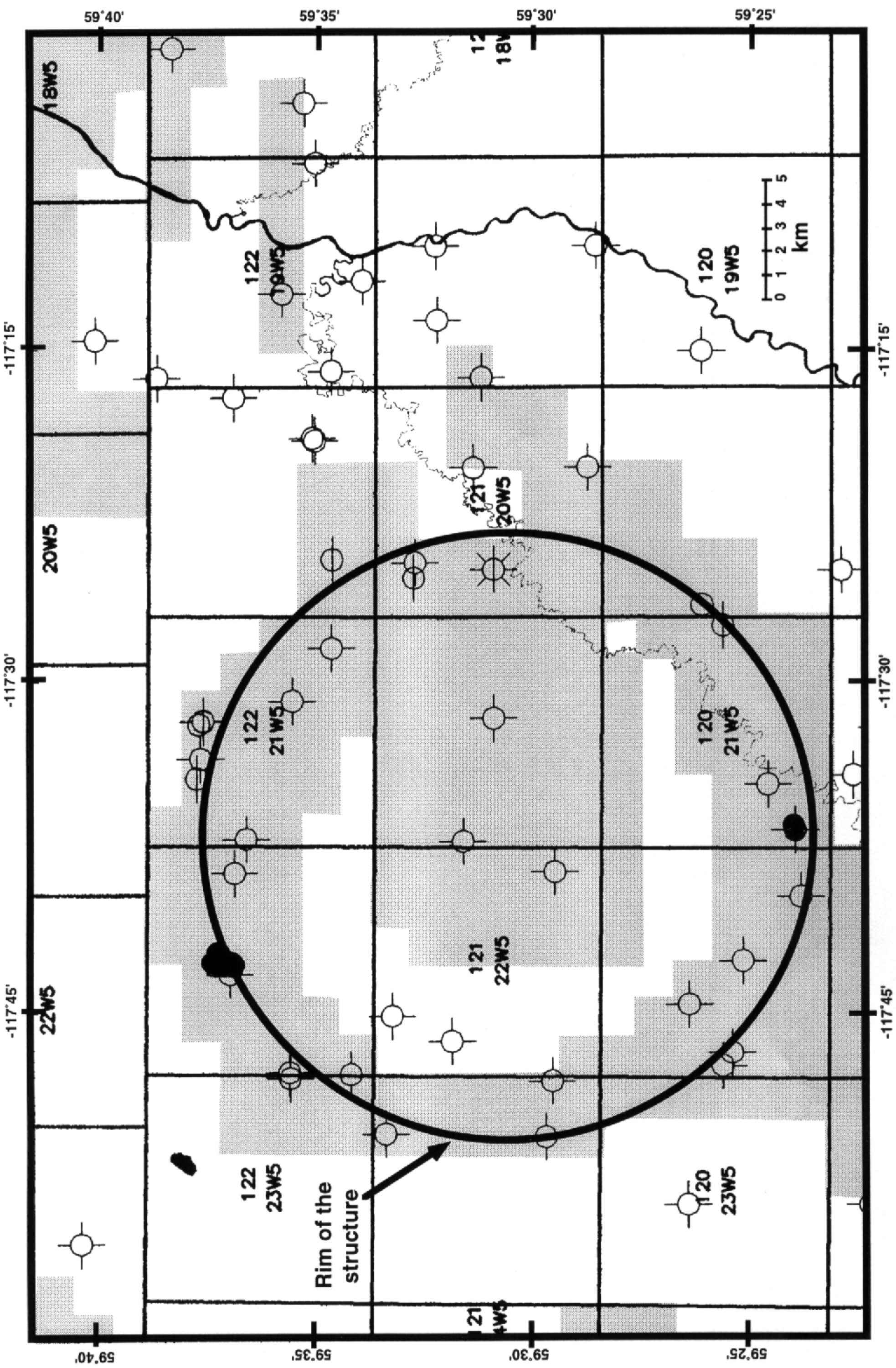

Figure 3. A map of the Steen River structure shows that exploration interest is concentrated on the rim of the structure. The solid circle outlines the approximate location of the rim and the shaded area represents land currently held or for sale. (Westbroek, 1997)

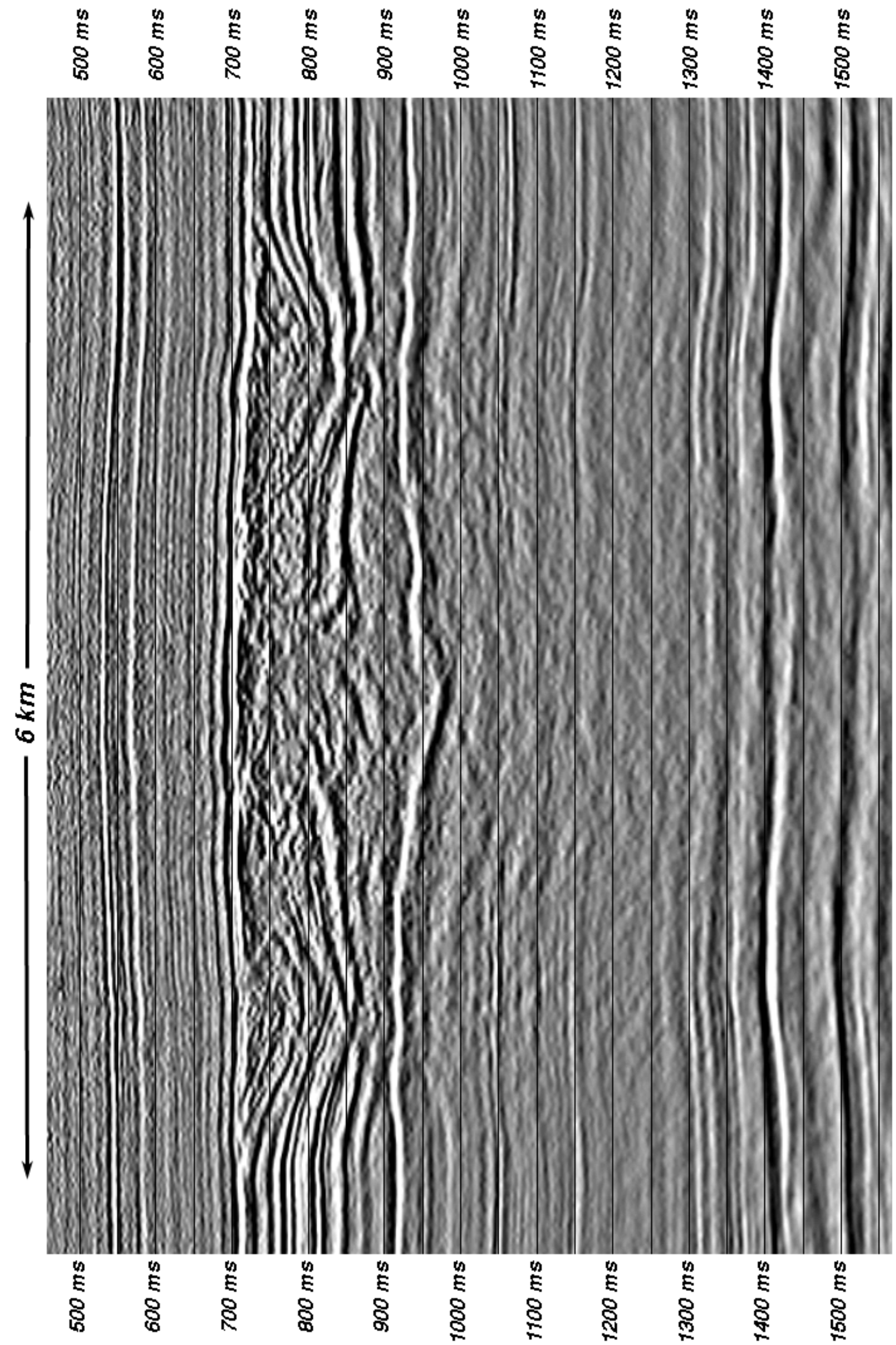

Figure 4. The Hotchkiss structure in northern Alberta shows many of the morphological characteristics that are diagnostic of a small complex impact crater. The structure has a diameter of about 6 km and is similar in appearance to the White Valley structure (Figure 8).

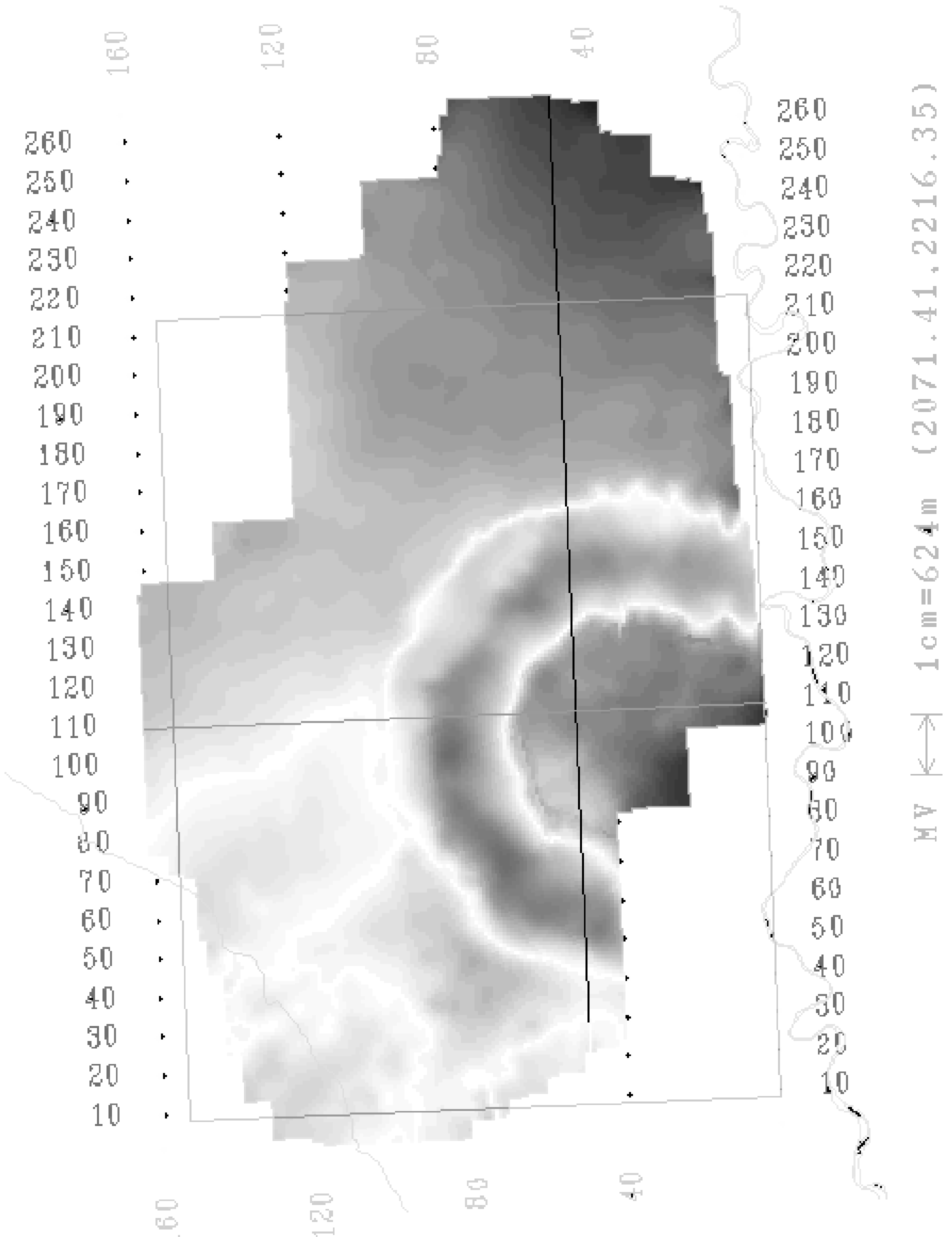

Figure 5. The James River impact structure in south-central Alberta is imaged well on a 3-D seismic dataset. This map of the Cambrian 'event' horizon illustrates the circular nature of the structure. Also evidenced, is an annular synform and a central uplift.

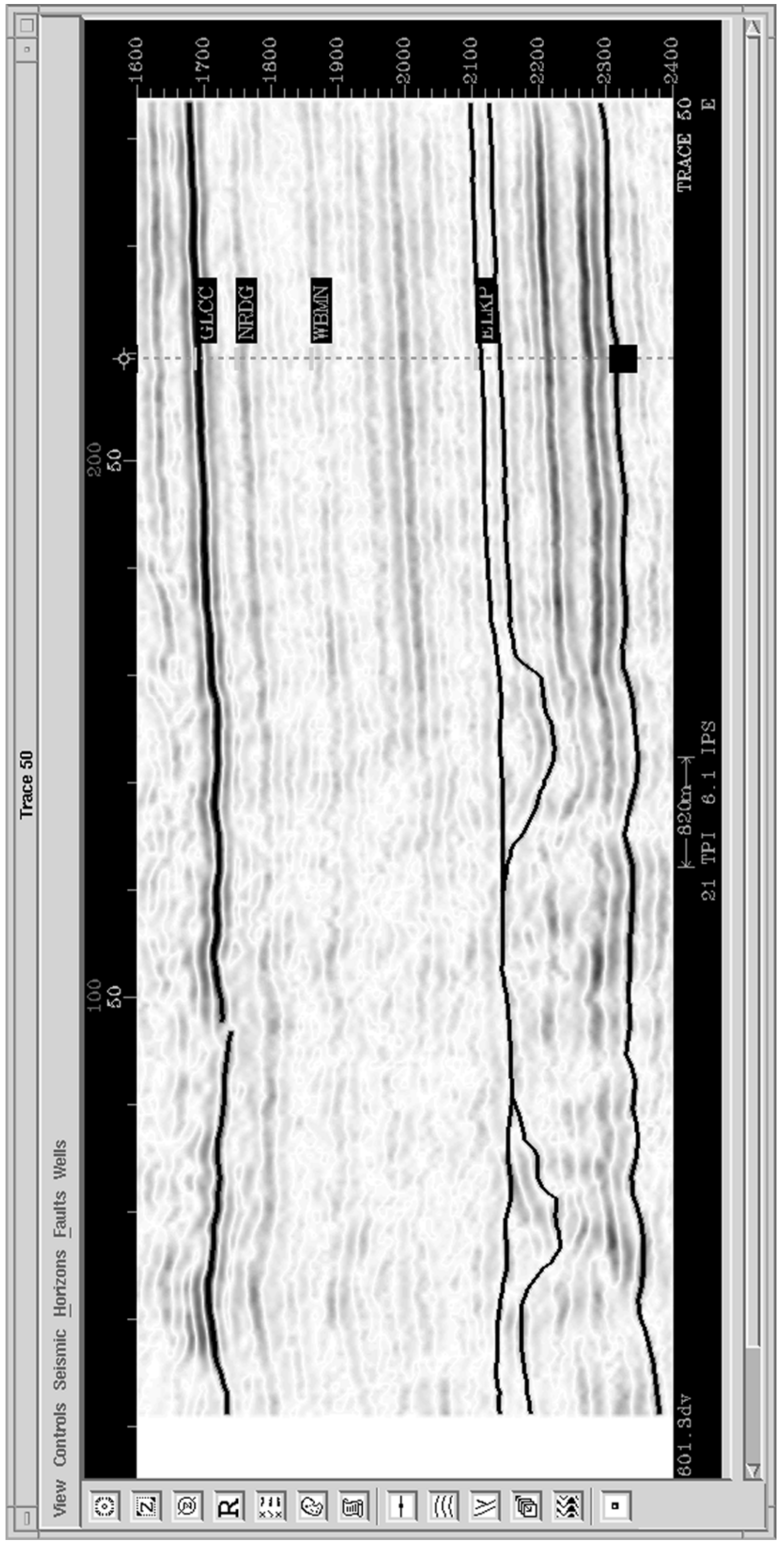

Figure 6. An example of the quality of seismic data in the James River 3-D volume. Several interpreted horizons are shown.

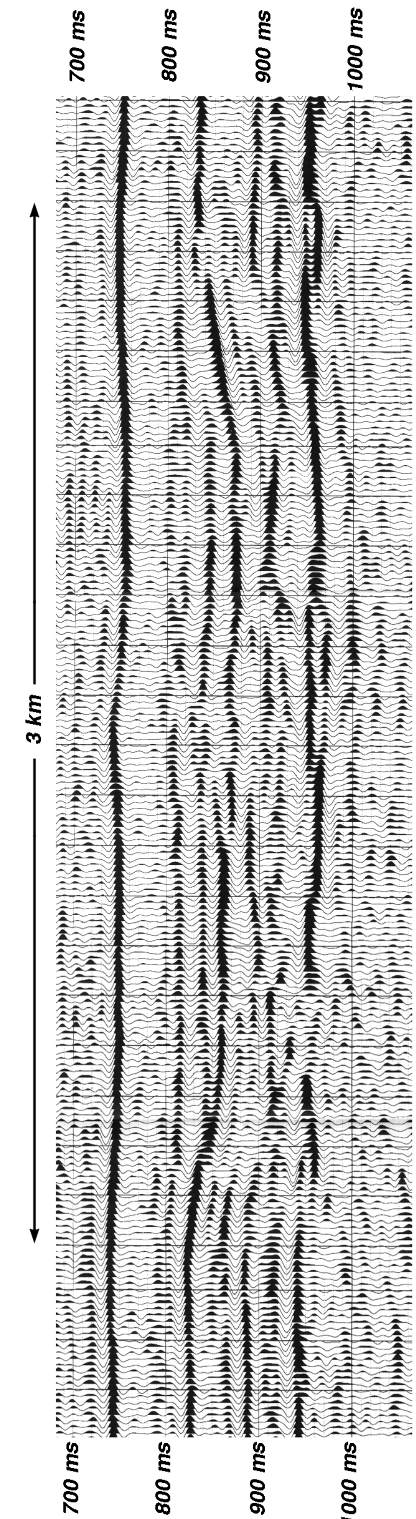

Figure 7. The Muskingum structure in Ohio exhibits the general characteristics of a simple impact crater. The width of the structure is about 3 km.

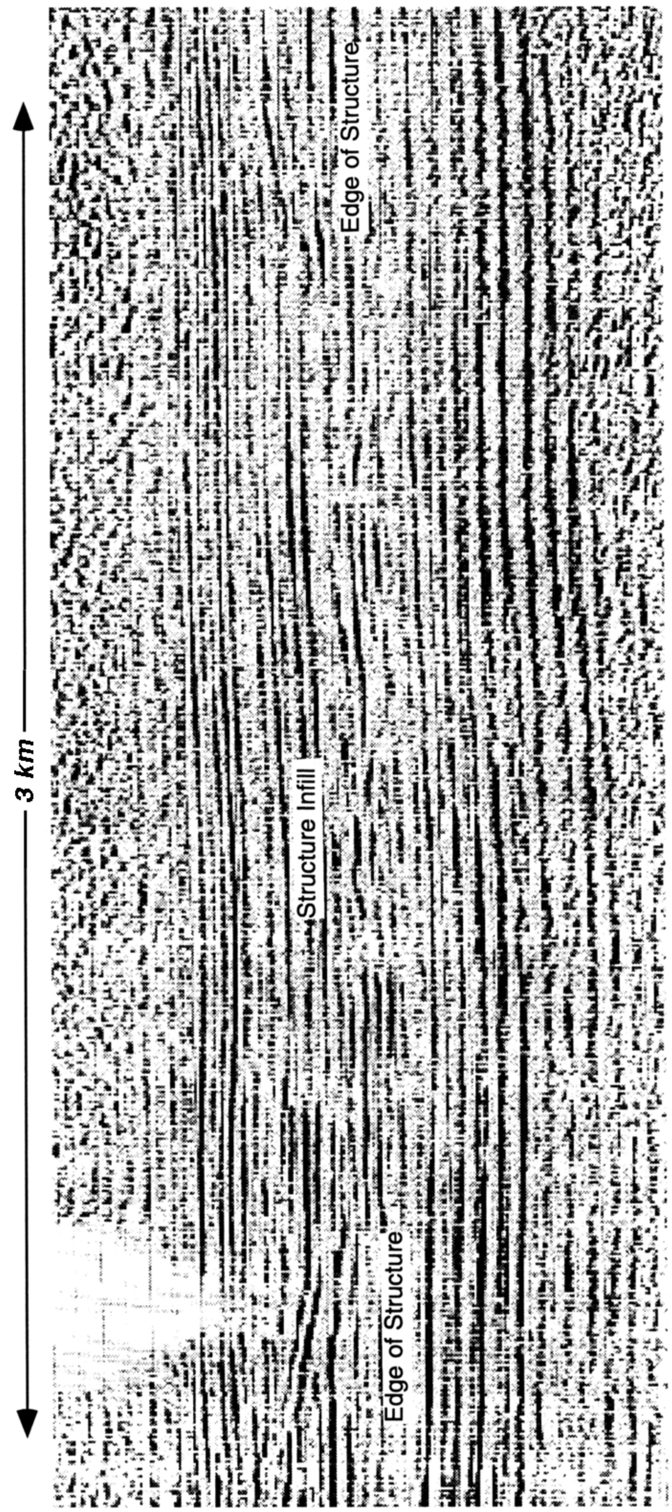

Figure 8. A migrated seismic section over the Purple Springs structure shows some of the characteristics of a simple impact crater. Rim-to-rim diameter is about 3 km.

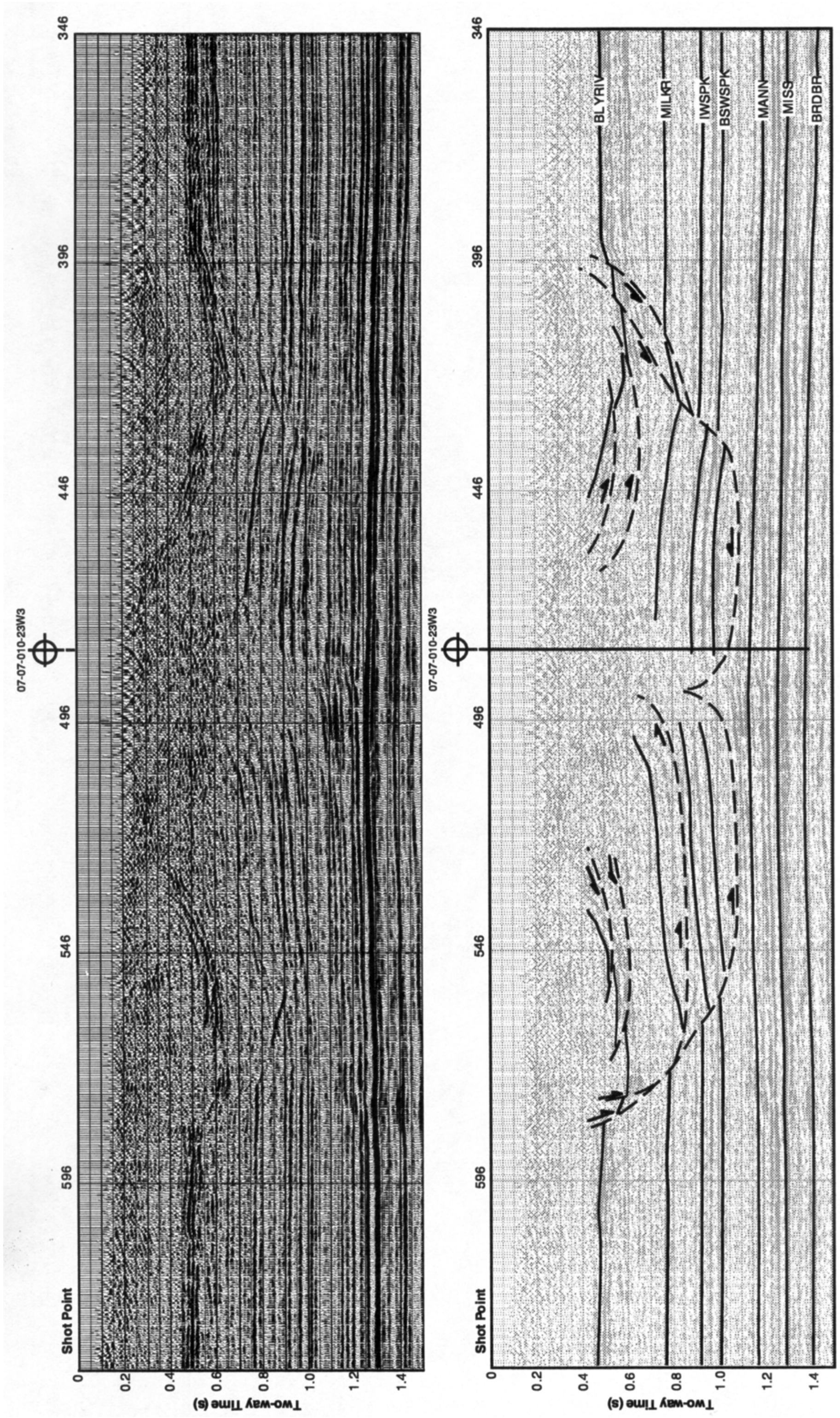

Figure 9. The White Valley structure is interpreted as a 6 km diameter complex impact structure (Westbroek, 1995). The asymmetries observed in the central region of the structure are also apparent in the Hotchkiss dataset (Figure 3) and possibly indicate impact direction.

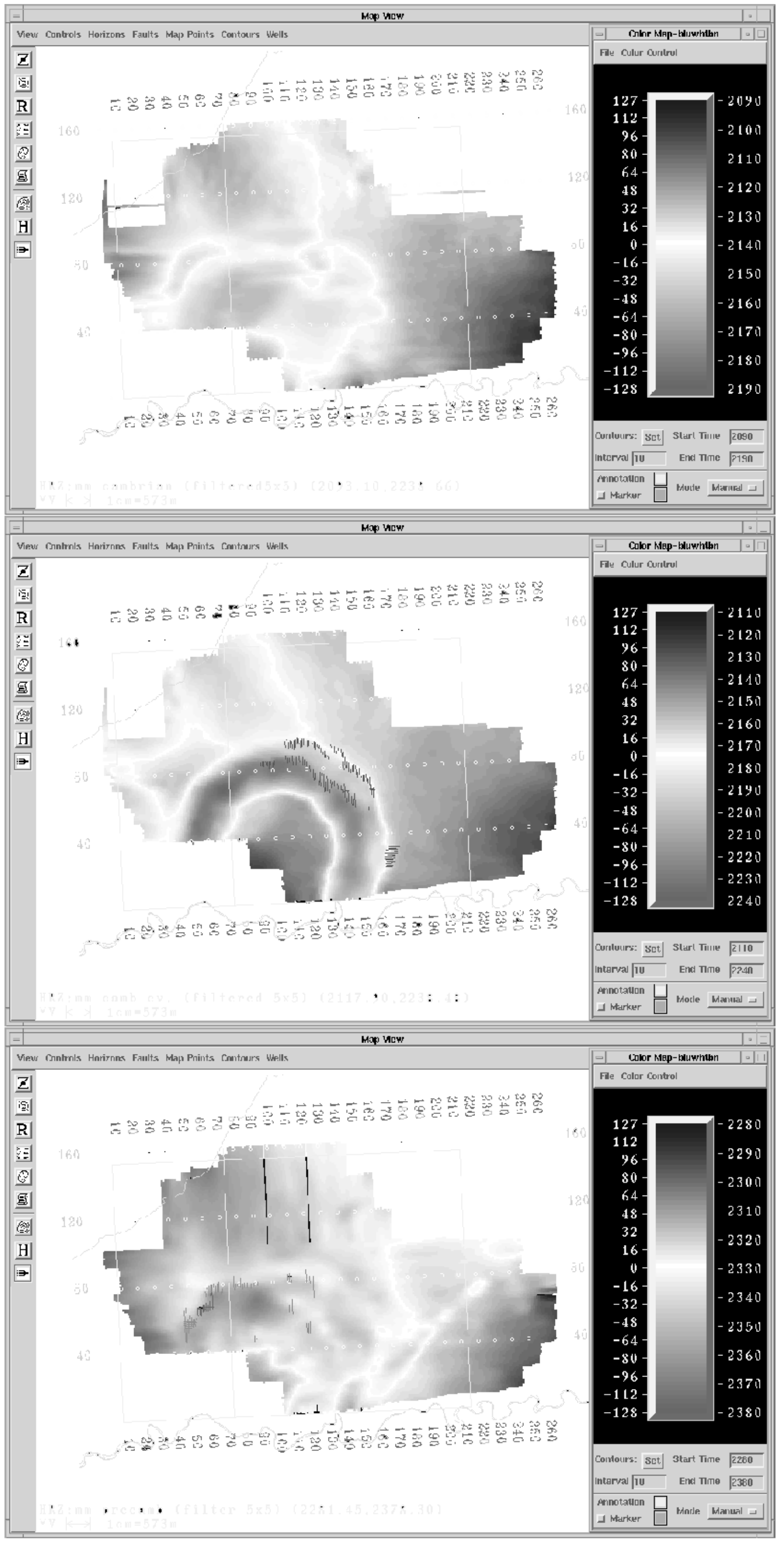

Figure 10. The above series of screen-grabs shows the 3 interpreted horizons in the James River data volume. The upper horizon corresponds to the top of the Cambrian, the middle horizon corresponds to the Cambrian 'event', and the lower horizon corresponds to the Precambrian. Faulting in the James River dataset is divided between shallow rim faults and deep central and rim faults.

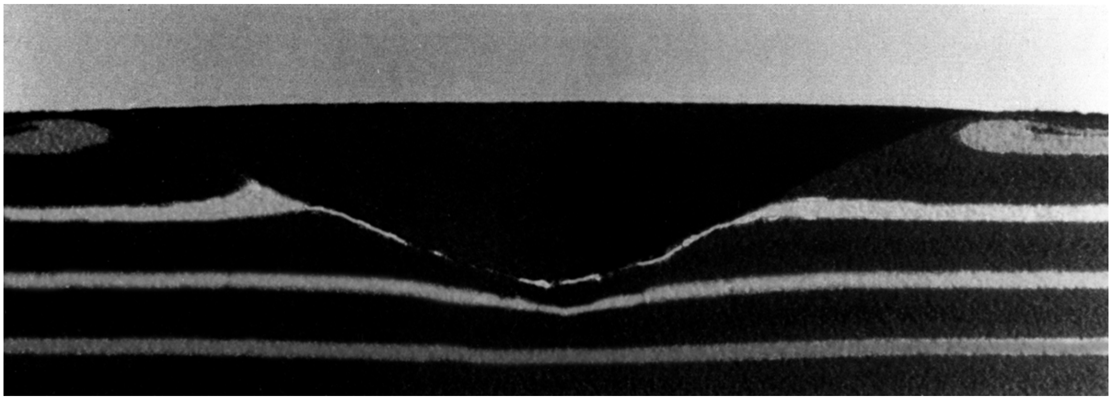

Figure 11. When examined in cross-section, a crater simulated by hypervelocity impact shows many of the morphological characteristics observed in seismic examples of impact structures. (Melosh, 1989)

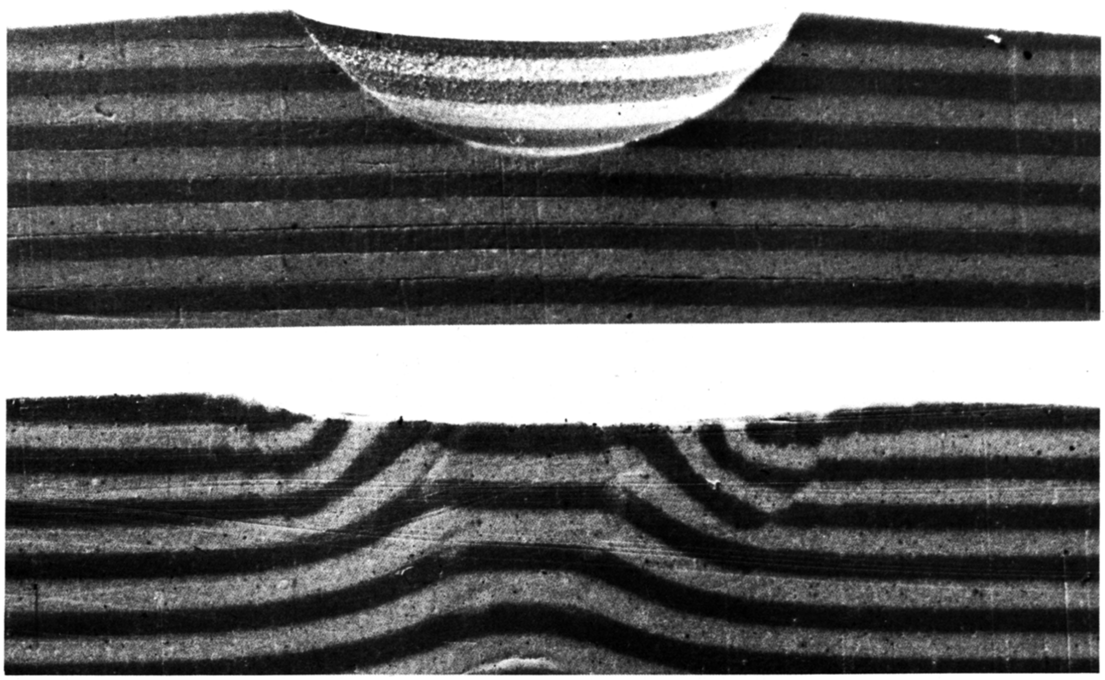

Figure 12. A complex crater can be created by centrifuging a model at gravities of up to 300g. (Melosh, 1989)