Interpreting the Hotchkiss structure: A possible meteorite impact feature in northwestern Alberta

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ABSTRACT

The Hotchkiss structure in NW Alberta is an enigmatic feature whose appearance on seismic data closely resembles that of a complex impact crater. Using a single 2-D seismic line, this study interprets the current extents of the feature, the pre-erosional dimensions, and possible drilling locations. The current size of the area of disturbance is 3.5 km in across and 400m thick. Using well established 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. The Gething-Debolt unconformity marks a period of erosion during which an estimated 500 m of the structure was eroded.

INTRODUCTION

Of the more than 140 impact craters that have been discovered worldwide, approximately 25% have economic importance in terms of mineral and hydrocarbon deposits (Masaytis, 1989; Grieve, 1991). Examples of confirmed impact structures that are of current hydrocarbon interest include Steen River, Alberta, Viewfield, Saskatchewan, and Ames Hole, Oklahoma. Like their counterparts on other planetary bodies, terrestrial impact craters are characterized by two basic forms: simple and complex. Simple craters (Figure 1a) generally have diameters up to about 2 km in sedimentary rocks and 4 km in crystalline rocks (Dence, 1972). They are characterized by a simple bowl-shaped cavity, the bottom of which is filled with an allochthonous breccia lens and are generally the result of relatively low energy events.

At larger impact energies, the crater begins to become more complex in nature. These complex craters (Figure 1b) are characterized by a central uplift region, rim terraces, and allochthonous shocked materials and melts within the annular trough. The central uplift arises when the transient cavity floor rebounds from its initial downward displacement.

Located in township 98 near the Chinchaga river is an anomalous feature that has been observed on seismic data. The structure is similar in appearance to the White Valley structure (Figure 2) and bears many of the diagnostic features of a complex impact crater. The structure is 3.5 km across and is buried approximately 1000-m below the surface. There are few wells in the area. Also in the area are a number of kimberlite pipes that are of considerable economic interest to local mining companies. The presence of these pipes, however, complicates the interpretation of this feature as an impact structure.

It is hoped that a thorough examination of the seismic characteristics of this structure will provide some insight into its origin. If we are correct in postulating an impact origin for this structure then not only should certain diagnostic features be present but also crater scaling relations should be relevant. This paper examines these features and attempts to reconstruct the initial dimensions of the Hotchkiss feature using well established scaling relations. We also estimate the age of the structure and suggest areas worthy of further investigation as drilling targets.

REGIONAL GEOLOGY

Located near the foothills of northwest Alberta, the Hotchkiss structure appears as an anomalous feature affecting the Mississippian carbonates and shales. The regional dip of the Precambrian basement is to the southwest. Overlying the structure are Cretaceous sediments with parallel stratigraphy that also show evidence of drape. The Debolt carbonate unit is terminated by a significant unconformity. Above this unconformity, the lower Cretaceous Gething sands show evidence of differential compaction in the form of an obvious drape feature. Figure 3 gives a generalized stratigraphic column of the area. Note the Gething-Debolt unconformity and the absence of more than 200 million years of sediments.

METHOD

Using logs from two wells (06-18-098-06W6 and 14-22-098-07W6) in the immediate study area, an interpretation of several important seismic horizons is made. Synthetic seismograms were created using GMAplus Modeling software with information from the sonic and density logs. A convincing correlation between the synthetic seismograms and the seismic data can be made (Figure 4). Horizons were picked in the area of post-impact sedimentation (Peace River and Spirit River), within the zone of maximum disturbance (Debolt, Pekisko, Banff, Wabamun, and Kakiska), and below the area of disturbance (Moberly, Slave Point, and Muskeg). The unconformity marking the transition from post-impact sedimentation to disturbed material is interpreted as a Gething (≈120 mybp) to Debolt (≈330 mybp) unconformity. Also interpreted on the seismic section are the locations of faults and slump blocks, possible breccia infill, and central uplift material.

INTERPRETATION

An examination of the post-Gething sediments reveals layer-cake stratigraphy with evidence of drape over the central region of the structure (Figure 5). Continuation of the drape feature to the surface suggests the presence of smooth topographic feature that is approximately 15-30 m above regional. This degree of relief should be apparent in local drainage patterns and satellite imagery such as that collected by RadarSat.

Uniquely identifying this structure as an impact structure is a difficult task since there are no wells penetrating the disturbed rocks of the structure. Regional evidence of an impact origin is not expected to be present. This assumption is made since the Gething-Debolt unconformity marks a period of erosion that is likely to have removed all tektites and signs of an ejecta blanket. The only direct evidence is found in the disturbed rocks themselves. Since these data are not available, identification of this feature must rely on its comparison to known examples of impact structures and other cryptoexplosion features.

Several unique observations can be made from the appearance of the structure. The first immediate observation that can be made is the lateral asymmetry of the Wabamun and asym1 horizons (Figures 6 and 7). Although it is expected that some of this structure can be explained as a velocity effect, the majority is undoubtedly real due to the lack of similar structure at greater seismic travel times. Asymmetries in the bedding could be explained as a non-spherical release of energy at the time of impact (a condition that might arise in a non-vertical impact).

Determining the timing of this event is a relatively tricky proposition since the Gething-Debolt unconformity marks a nearly 200 million-year gap in the geological record in this area. To more closely estimate the time at which this structure was formed, a thorough examination of impact crater scaling relations is undertaken. By calculating the original size and shape of the structure, an estimate of the amount of erosion since formation can be made. Using this figure, we can then proceed to better estimate the time of formation.

Although this feature closely resembles an impact feature, a careful consideration of other possible causes must be made. Circular features can also result from diatreme intrusions, salt or limestone dissolution, salt or shale plugs, and volcanoes. Of the available alternatives, only the diatreme intrusion is capable of creating a central uplifted region surrounded by an annular synform. The current theory on the formation of explosive diatereme intrusions, however, states that the intrusion rises as a narrow pipe that widens as it approaches the surface. At the surface, a large amount of energy can be released forming a crater (Figure 8). The by-product of such an event should be a carrot shaped stalk extending to great depths. On a seismic section, this type of feature will appear as a washed out, poor data area. Generally, diatreme expressions are much smaller than the 3.5-km anomaly observed here.

Interpreting this structure as an impact event allows us to reconstruct the events leading up to the formation of the Hotchkiss structure as it is observed today (Figure 9). If the impactor is assumed to have been an iron object traveling at 20 km/s, we find that the diameter required to create a 4.5 km crater is about 240m. As the iron meteoroid crashed into what was likely a shallow sea, the excavation of the transient cavity and start of the central uplift began. Within about 20 seconds, the central uplift was nearly formed and the rim was beginning to collapse. After several minutes the crater had assumed its final shape. A period of erosion followed the formation of this structure whereby nearly 200 million years of the sedimentary record in this area was erased.

MORPHOMETRY

Using well established scaling relations, we can begin to estimate the original dimensions of the structure. However, we must keep in mind that the current scaling relations have been developed from studies of lunar craters. For the most part, these structures show very little signs of erosion unlike the highly eroded Hotchkiss structure. Studies of terrestrial complex craters have shown that the maximum stratigraphic uplift (Figure 10-a) of the crater's center, H_{su}, is related to the final crater diameter (Grieve et al., 1981), D, by

$$H_{su}=0.06D^{1.1},$$

where all distances are in kilometres. Although this relation has been shown to apply to several terrestrial impact features (Grieve, 1981), the severe level of erosion in this case means that we can only place an upper limit on the pre-erosion diameter using this method. The maximum stratigraphic uplift can be estimated by continuing the slope of the central uplift to a peak and then measuring its height above regional (Figure 10-b). In doing so we find a value of 350 m. This gives a maximum original diameter of 5 km.

Other relations exist such as a comparison between the central peak diameter, D_{cp}, and the total diameter of the crater (Melosh, 1989).

$$D_{cp}=0.22D$$

Using D=5 km, we find a maximum central peak diameter of 1.1 km. This value is quite reasonable when we consider that the current diameter of the interpreted central peak is equal to 1.1 km when measured at the Gething-Debolt unconformity.

Using these two scaling relations, we have shown that the maximum possible diameter of the original structure is 5 km. Another estimate of the pre-erosion diameter of this feature can be made by assuming that the original crater had a roughly parabolic shape. A parabola can then be designed that is tangent to the current dip at the rim. Extrapolation outwards along this parabola to the angle of repose (approximately 30 degrees) will yield an estimate of the pre-erosion diameter. Measurements of the bedding at the rim of the structure yield present dip angles of about 25 degrees, giving a pre-erosion diameter of 4.3 km.

The original depth of the structure can be calculated by using scaling relations deduced from lunar studies (Melosh, 1989). The depth, H, of a complex terrestrial impact feature can be given as,

$$H=0.32D^{0.3}$$

Using a midrange estimate of 4.5 km for the original diameter of the structure we find that the initial depth was on the order of 500 m. The height of the rim above the regional levels can also be computed by using the relation (Melosh, 1989),

$$H_r=0.036D^{1.014}$$

Using this relation we find a value for the rim height of 165 m above regional. Utilizing these two values, we see that at the time of formation the surface was about 335 m above the present-day Gething-Debolt unconformity.

CONCLUDING REMARKS

The Hotchkiss structure exhibits many of the diagnostic features of a meteorite impact structure. These features include evidence for a central uplift, large-scale faulting at the rim and in the central uplift, a breccia infill, and a continuation of the disturbance to depths in excess of 1500-m below the top of the feature. The Hotchkiss structure also obeys many of the scaling relationships relating to impact features. At the time of formation between 120 and 330 million years ago, the original size of this structure is estimated to have been 4.5 km in diameter by 500 m in depth.

The presence of large displacement faults and structural disturbance within this feature makes the Hotchkiss structure a possible target for hydrocarbon exploration. Areas of interest might be the observed drape over the structure, the breccia infill (if it exists) within the annular synform, and the slump blocks around the rim. The central uplift, however, is not likely to be a good reservoir due to expected shock metamorphic materials.

An impact such as the one responsible for the Hotchkiss structure occurs approximately once every 25,000 years. Assuming a random impact distribution around the world, we expect ten additional impact structures with similar dimensions to have been formed in Alberta since the formation of the Hotchkiss structure. Intuitively, the frequency of impacts increases with a decreasing projectile diameter. As a result, there are possibly hundreds of impact structures greater than 1 km in diameter buried within the sedimentary record of Alberta alone.

ACKNOWLEDGEMENTS

Special thanks are extended to Ken MacDonald of Pulse for allowing us to interpret this interesting dataset.

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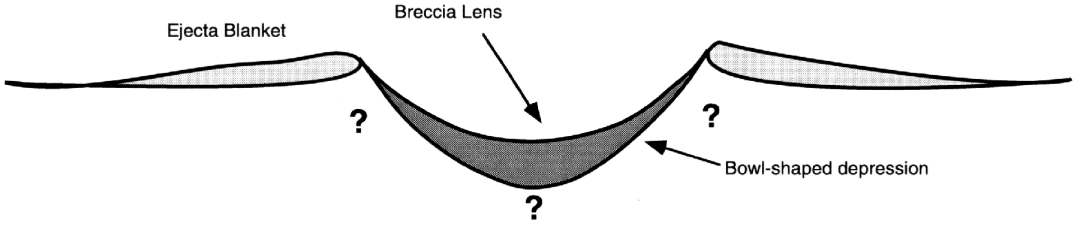

Figure 1a. Schematic depiction of a simple crater (Westbroek, 1995).

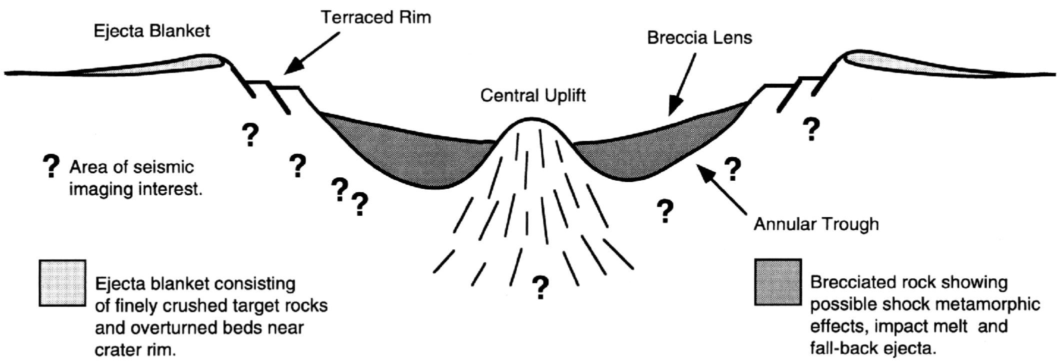

Figure 1b. Schematic depiction of a complex crater (Westbroek, 1995).

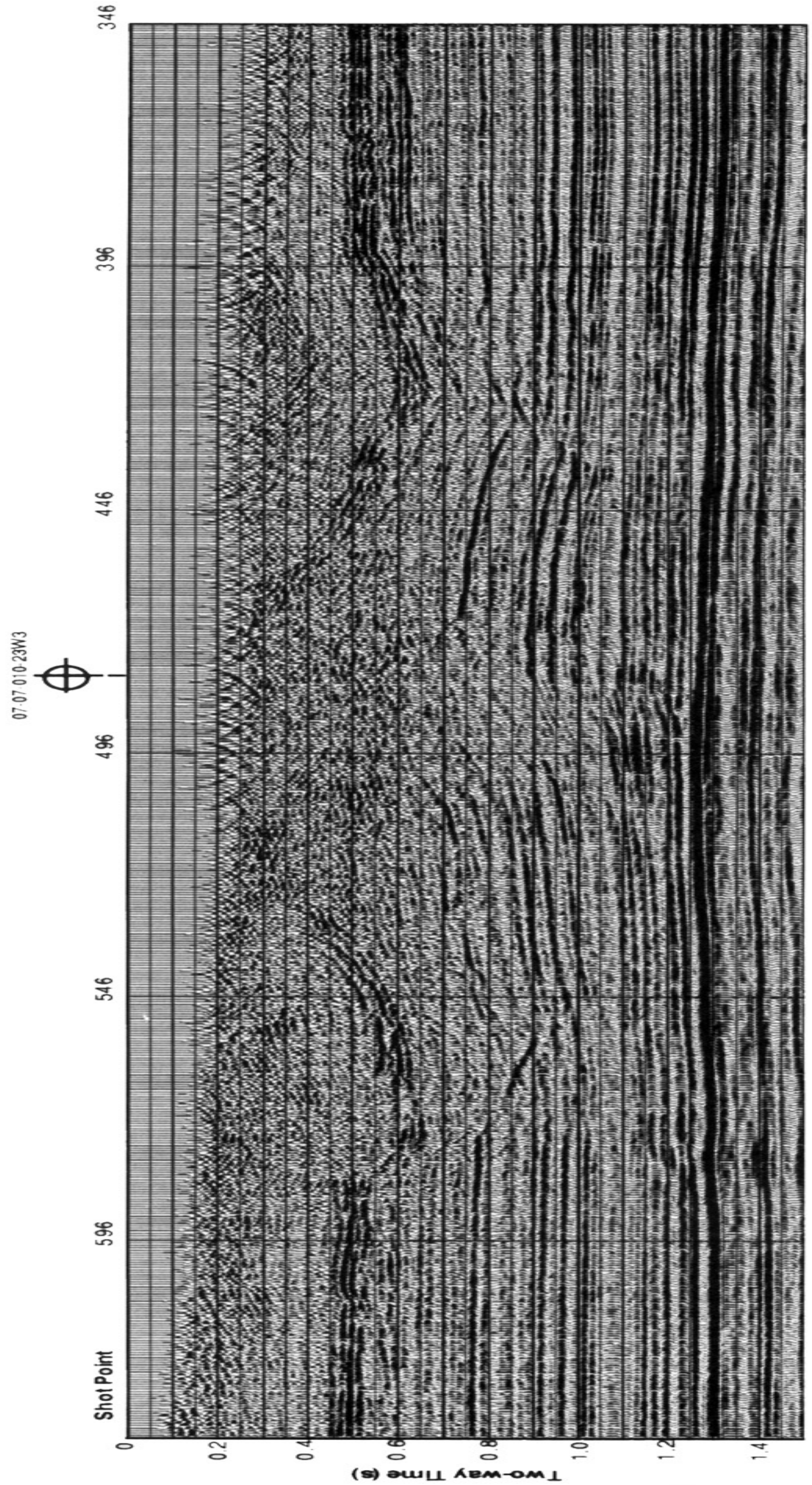

Figure 2. White Valley seismic line WV-017 showing the uninterpreted section. Notice the asymmetry in the bedding across the structure and the lack of coherent reflections in the central area.

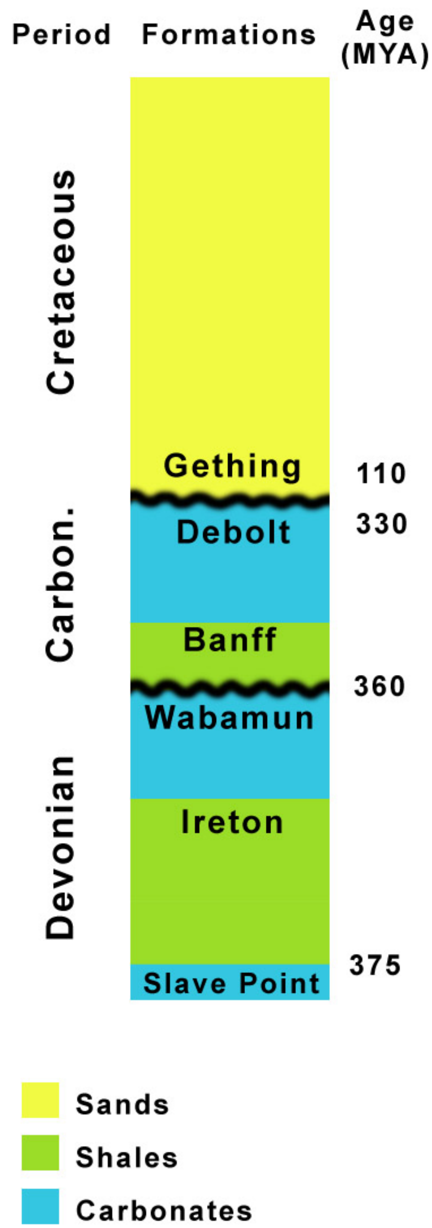

Figure 3. Simplified stratigraphic column for the Hotchkiss area.

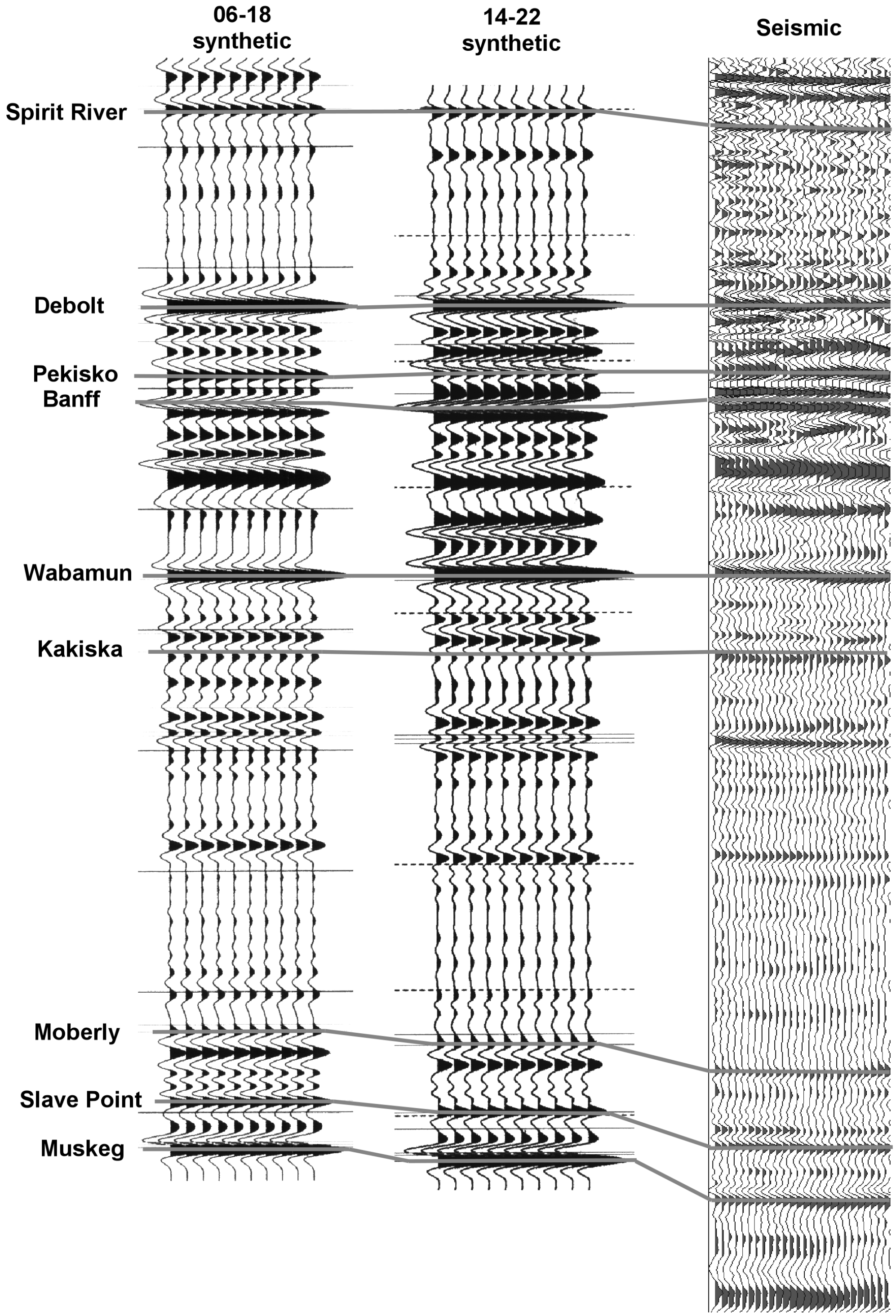

Figure 4. Correlation of the seismic data with synthetics created using well log data.

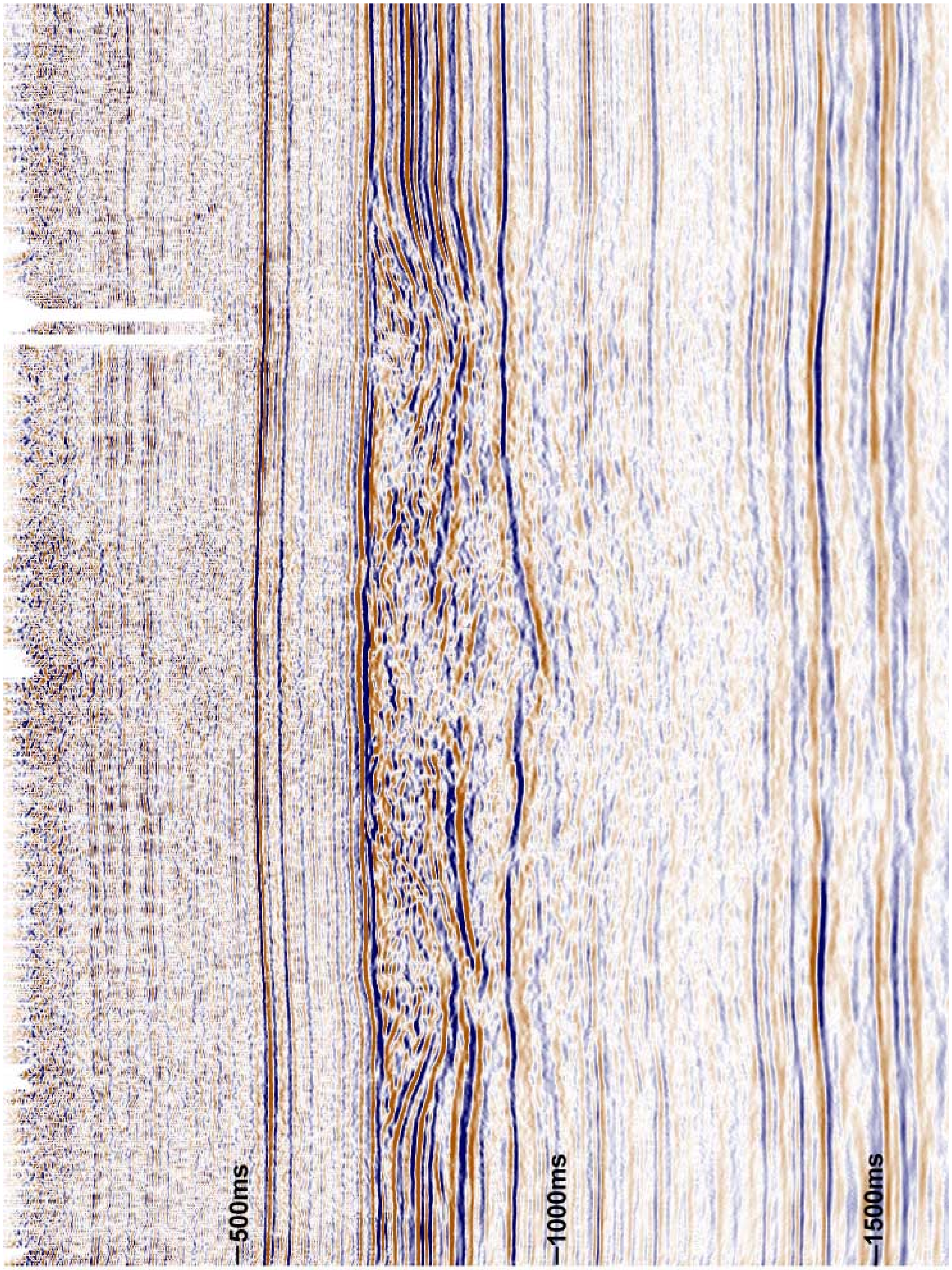

Figure 5. The Hotchkiss structure as it appears on seismic data.

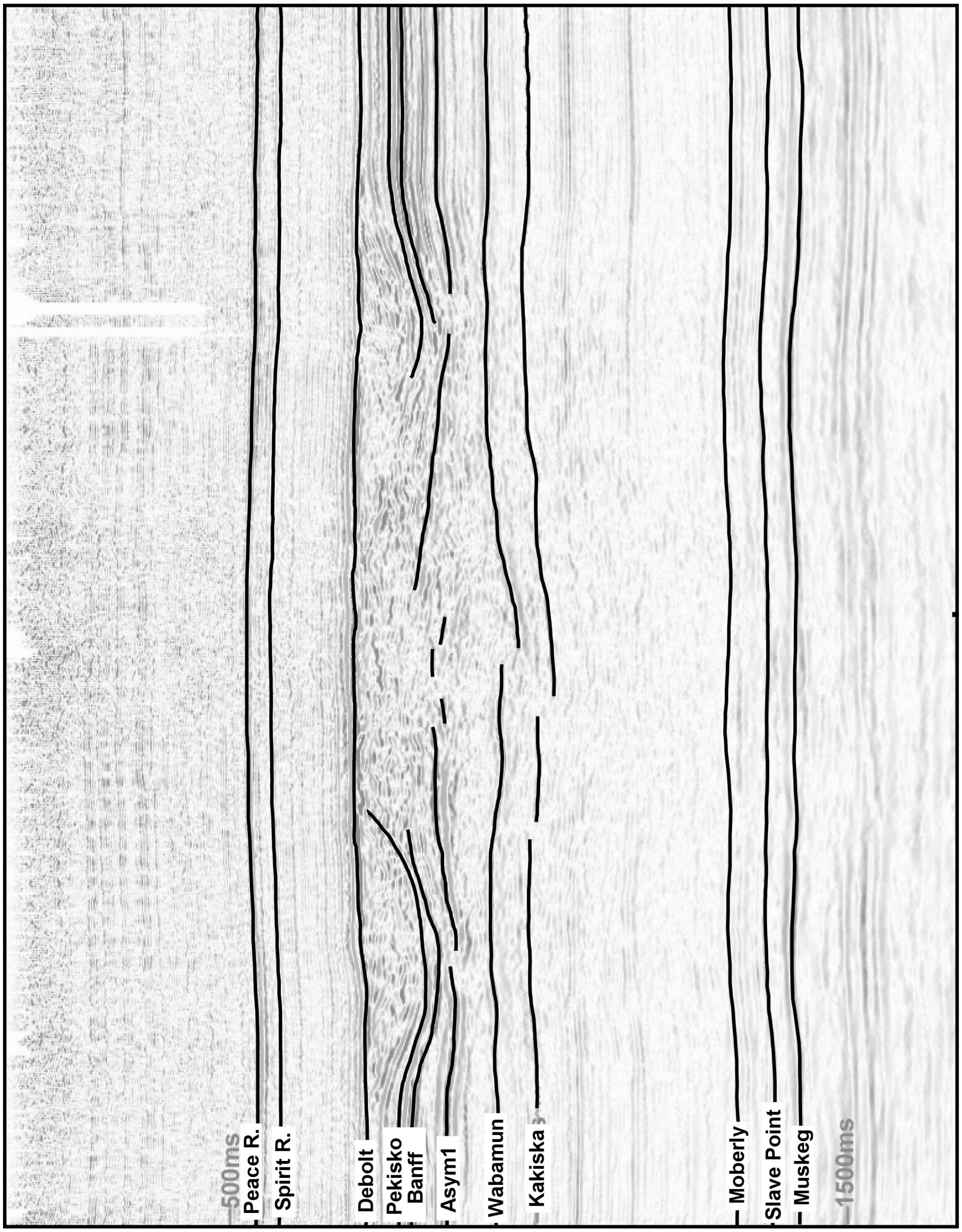

Figure 6. Interpreted horizons on the Hotckiss seismic data. Notice the horizontal asymmetries in the stratigraphy and the velocity pull-up effects.

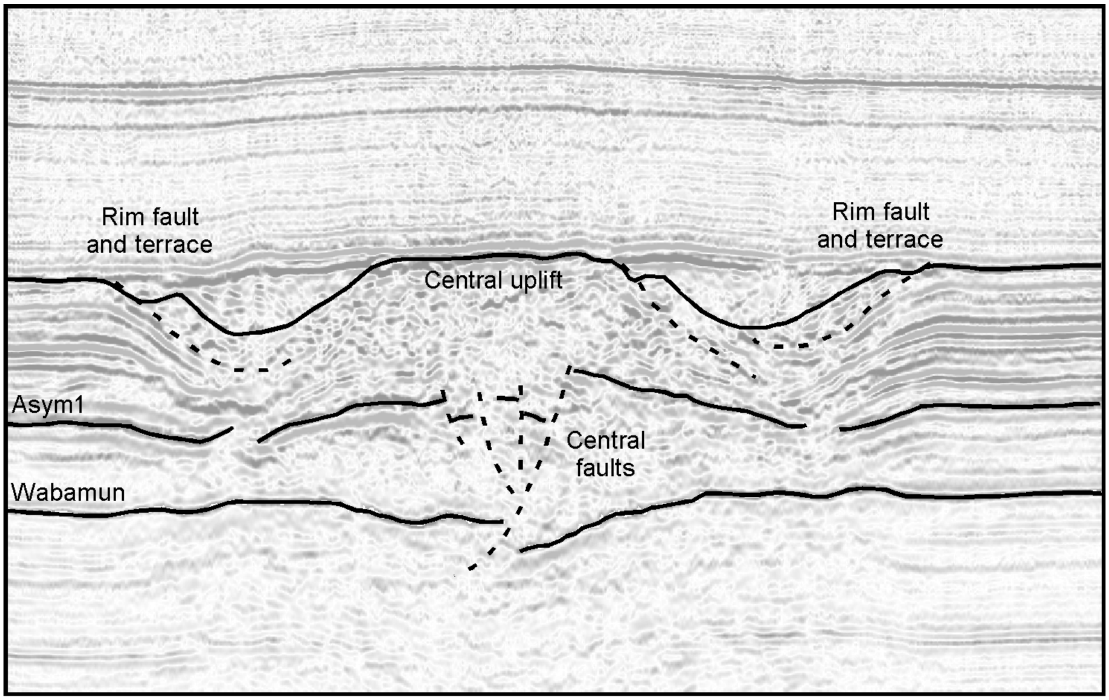

Figure 7. Faults as interpreted on the Hotchkiss structure. Also shown are a continuous surface representing the general shape of the structure, the Wabamun, and an intermediate asymmetrical horizon.

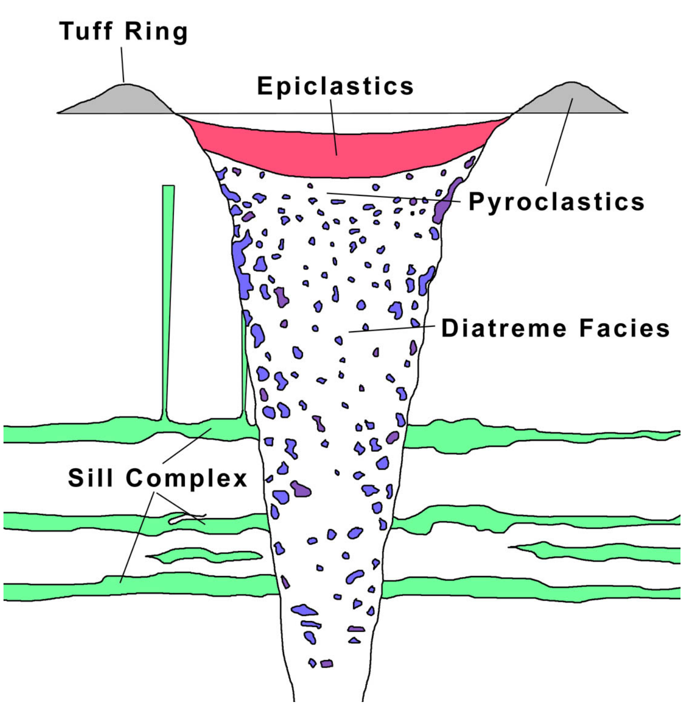

Figure 8. Generalized schematic of a kimberlite pipe.

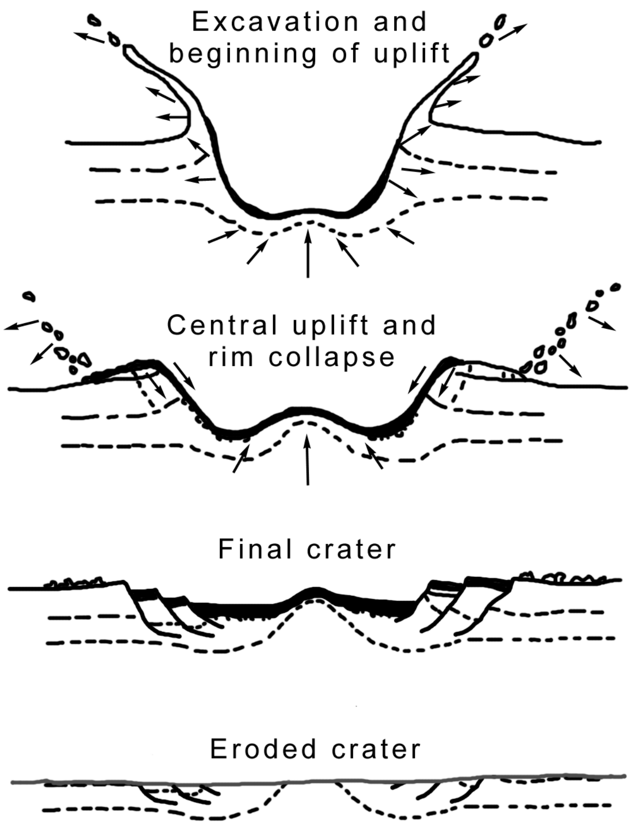

Figure 9. The formation of the Hotchkiss structure (after Melosh, 1989).

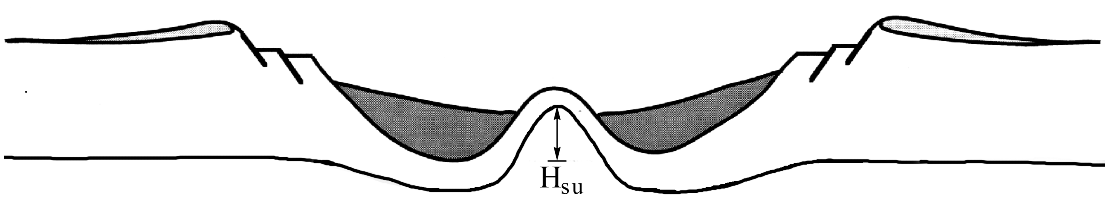

Figure 10-a. Pre-erosional schematic of a complex crater shows how the maximum stratigraphic uplift would be measured.

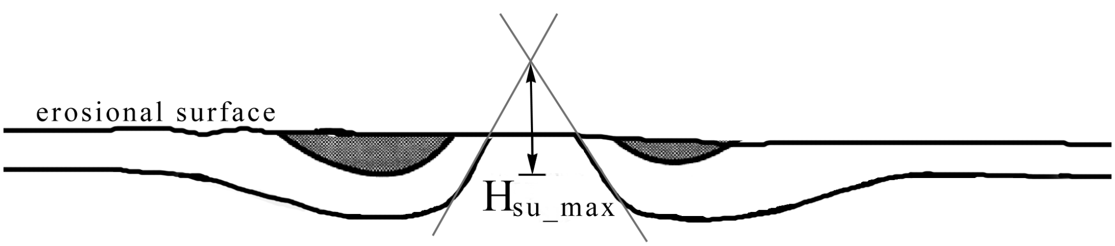

Figure 10-b. After erosion, the maximum stratigraphic uplift can be measured by continuing the slope of the first continuous reflector towards the surface.