Seismic interpretation of the White Valley structure: A possible meteorite impact crater

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ABSTRACT

The White Valley structure in Southwestern Saskatchewan is a major anomaly evident on four 2-D seismic lines. Two of these lines, WV-021 and WV-017, are presented in this paper. The structure has many of the morphological characteristics of a complex impact crater. It has an outer raised rim, annular synform and a raised central uplift. The rim of the structure shows many normal faults indicative of extension during the uplift phase of crater formation. The maximum depth of the structure is estimated at 1300m. The structure disrupts mainly Late Cretaceous rocks giving an age of impact of less than 75Ma. The seismic shows the feature to be about 6km wide with a 4km diameter inner trough and a 3km circular uplift.

INTRODUCTION

Impact cratering has been a part of the Earth's history probably since its formation. While rates for large impacts are small for the Earth - on the order of 10^{-5}yr^{-1} (Wetherill and Shoemaker, 1982) - debris from space still falls to the Earth's surface. Some 150 craters have been discovered worldwide about one-quarter of which have economic importance in terms of mineral and hydrocarbon deposits (Masaytis, 1989; Grieve, 1991). Table 1 shows a list of some craters that have hydrocarbon fill. Many scientists also surmise that meteorite impacts may have led to mass extinctions documented in the fossil record. The large Chicxulub crater on the Yucatan Peninsula, Mexico, has been suggested as the site for an impact at the end of the Cretaceous that may have caused the dinosaur's demise (Hildebrand et al., 1991).

Table 1. Impact craters and associated hydrocarbons (Isaac and Stewart, 1993.)

Crater	Diameter (km)	Age	Hydrocarbon Production
Viewfield, Sask.	2.4	Triassic/ Jurassic	65m^3/d (400bbl/d) with 3.2x10^{6}m^3 (20MMbbl) reserves from raised rim
Red Wing Creek, N.Dakota	10	Triassic/ Jurassic	6.4x10^6 to 11x10^{6}m^3 (40-70MMbbl) in recoverable reserves from central uplift
Newporte, N.Dakota	3.2	Late Cambrian	Oil shows and some production from raised rim
Ames, Oklahoma	8	Early Ordovician	7x10^{6}m^3 (50MMbbl) in estimated reserves from crater rim and floor
Steen River, Alberta	22	pre-Late Cretaceous	Producing 95m^3/d (600bbl/d) from basement complex

Many meteorites are believed to be samples from the asteroid belt, which resides between the orbits of Mars and Jupiter some 2.2 to 3.2AU from the Sun (one AU or astronomical unit is equal to the average distance from the Earth to the Sun, or about $150x10^6$km). Asteroids, pulled out of the belt through collisions with each other or by gravitational perturbations, have the potential to intersect any of the terrestrial planets once they enter the inner solar system, including Earth. Meteorites, then, are any asteroids or smaller pieces of asteroids which reach the Earth's surface.

This differentiates asteroids from comets which originate in the Oort cloud, a spherical region in the outer solar system possibly some 20000 to 100000AU from the Sun (Allaby and Allaby, 1991). Other comets originate closer to Earth in the proposed Kuiper Belt just beyond the orbit of Neptune It remains unclear what potential there is for cometary collisions, however, some investigators believe that cometary impacts may account for a substantial portion of terrestrial craters (Weissman, 1982).

Terrestrial craters are characterized by two basic forms: simple and complex. Simple craters occur up to a diameter of about 2 to 4km depending on the target rocks while larger diameter craters have a complex form (Pilkington and Grieve, 1992). Simple craters are formed by lower-energy events with a subsequently lower explosion component to the impact often resulting in pieces of the meteorite remaining intact (Krinov, 1963). They are characterized by a simple bowl-shaped profile, the bottom of which is filled with an allochthonous brecciated lens from the slumping of the transient crater walls (Pilkington and Grieve, 1992). For larger impacts, though, the meteorite is not slowed appreciably by the atmosphere (Grieve, 1991). The resulting impact involves such high shock pressures (50-100GPa), that the meteorite is largely vaporized in the explosion. The transient cavity floor in this case rebounds from its initial downward displacement to form a central uplift region characterized by shock metamorphic effects. The rim of the crater often is terraced due to rim faults and the annular trough is characterized by allochthonous shocked materials and impact melts (Grieve, 1991; Melosh, 1989). This is the basic morphology of a complex crater.

STUDY AREA AND GEOLOGY

Figure 1 shows the location of the White Valley structure in Southwestern Saskatchewan and a base map of the area showing the four seismic lines and the 07-07-010-23W3 well near the center of the structure. Lines WV-021 and WV-017 are the two lines presented here since they pass completely over the structure. The stacked, unmigrated data were donated by Mark Resources Inc. and Enron Oil Canada Ltd. for the purposes of this study. Tables 2 and 3 briefly summarize the acquisition and processing of the data to final migrated stack. The data were acquired by Enertec Geophysical Services Ltd. with line WV-021 processed by GEO-X Systems Ltd. and line WV-017 processed by Pulsonic Geophysical Ltd. except for the migration which was performed by the author on Advance's ProMAX software.

The generalized stratigraphic chart of this region is shown in Figure 2. Disruption of the stratigraphic column occurs primarily within Late Cretaceous and possibly into Tertiary sediments. The target of the 07-07-010-23W3 well, drilled in the center of the structure, was the Birdbear Formation of the Late Devonian. It was dry and abandoned.

TABLE 2. Survey acquisition parameters.

ACQUISITION PARAMETERS	
Source	• Vibroseis: 4 vibs over 50m • Frequency: 8 sweeps, 10-90Hz • Interval: 125m
Receiver	• Interval: 25m • Geometry: 9 inline per group
Shot-Receiver Geometry	• 2D split spread • offset range of 100m to 1575m • 3 W-E lines, 1 N-S line
Sample Rate	• 2ms

TABLE 3. Basic processing flow.

PROCESSING FLOW	
Demultiplex	
Amplitude Recovery	
Deconvolution	• spiking • 80ms operator length
Statics	• elevation, weathering, drift
Velocity Analysis	
Normal Moveout Correction	
Mute	
Stack	
Migration	• memory Stolt FK • 100% stacking velocities
Filter	• bandpass: 10/15-70/80Hz

INTERPRETATION

Well Correlations

Sonic logs from wells 01-04-010-22W3, 07-07-010-22W3 and 04-01-011-24W3 were used to correlate horizons on the seismic data. 01-04-011-22W3 was correlated to line WV-016 as well as WV-021. The projection distance to WV-021 was approximately 8.7km. The well was located on line WV-016. 07-07-010-22W3 was projected along a circle arc around the center of the structure to lines WV-017 and WV-021. The distances of projection were approximately 700m for both lines. Well 04-01-011-24W3 was projected a distance of 4.7km to line WV-017 and correlated there. Despite some long projection distances, the horizontal nature of the regional stratigraphy, with only a very slight dip, allowed for confident correlations of seven horizons including the Belly River formation, the Milk River formation, an inter-White Speckled Shale horizon, bottom of the Second White Speckled Shale, the Mannville, the Mississippian and the Birdbear formation. The latter formation was actually correlated based on the 07-07 well only as the other two regional wells did not penetrate to this depth.

Figures 3, 4 and 5 show each of the velocity logs, the corresponding synthetic seismograms based on a 30Hz zero-phase Ricker wavelet and the tie to the seismic data. The horizon lines (gray) mark the tops of the formations and are shown in dashes where the correlation is less obvious. Note that the 07-07 well, drilled near the center of the structure, was used to correlate the bottom of the Second White Speckled Shale to the Birdbear formation on line WV-021 and the inter-White Speckled Shale to the Birdbear on line WV-017. Shallower formations could not be seen clearly on the seismic data do to the proximity of the data to the central uplift.

Line Interpretations

Comparison of lines WV-017 and WV-021 shows that there is a time shift at the tie point. This shift does not appear to be static with depth. The time shift is about 53ms at the Mannville, 63ms at the Mississippian and 73ms at the Birdbear formation. In all cases, the horizons are at lower two-way travel times on line WV-017. This time shift is probably due to two different datums being used in the processing of the seismic data. A different decon was also used on the two lines resulting in a further time shift. Consistent processing of the two lines would have reduced this problem.

Figures 6 and 7 show the uninterpreted and interpreted sections migrated sections of lines WV-021 and WV-017 respectively. There is approximately no vertical exaggeration in these displays. Horizon and fault markers that are dashed indicate that the seismic data does not clearly show these horizons or faults in these areas. The projected well locations and line ties are also clearly marked. It should be noted that a balanced interpretation of line WV-017 is difficult to achieve. The line does not run through the center of the structure and so much of the movement within the subsurface, believed to be radial in nature, probably occurred across the plane of the section rather than within the plane of the line. Line WV-021, crossing much closer to the center of the structure probably has less of this problem. Both lines, being 2-D, suffer from side scatter interference off of structures outside the plane of the lines.

The Belly River formation (BLYRIV) is the shallowest correlateable reflector in the sequence and demonstrates that the structure is less than 75Ma old or post-Late Cretaceous. This formation is disrupted as the structure is approached from all directions primarily by normal faults. These faults form terraces from the outer rim to the annular synform located at about SP 230 and 390 on line WV-021 (Figure 6) and SP 410 and 570 on line WV-017 (Figure 7). The formation is then further disrupted near the central uplift region by a series of thrust faults acting in opposition to the normal fault direction. This is believed to be caused by subsidence after the central uplift is initially up-thrown. They may in fact be reactivated normal faults which were formed during the uplifting process. The formation then becomes uncorrelateable across the center of the uplift region where complete disruption of the subsurface has resulted in chaotic, scattered reflections.

The Milk River (MILKR), inter-White Speckled Shale (IWSPK), bottom of the Second White Speckled Shale (BSWSPK) and the Mannville formation (MANN) represent good regional markers which, by there deformation in the structured area, help to delineate the trajectory of the major faults seen in the Belly River formation mentioned above. As can be seen on both lines, the normal rim faults penetrate and delineate the outer-most extent of the structure. However, only on a portion of line WV-017 does the two northern-most rim faults penetrate to just below the Mannville

(Figure 7). It is unclear, though, where the shallow portion of these two faults terminate (see SPs 386-396 at 750ms). Following the above horizons through the structure shows that the beds, rather than being brecciated, have been normally faulted in an extensional stress regime and rotated upwards towards the central uplift. Like the Belly River formation, these horizons also become uncorrelateable through the most disrupted portion of the central uplift.

The Mississippian (MISS) and Birdbear (BRDBR) formations also represent good regional markers which delineate the deepest portion of the central uplift. Both of these horizons occur at shale-carbonate interfaces with a corresponding velocity contrast of about 3000m/s. On line WV-017 (Figure 7) the Mannville is also more continuous beneath the central uplift indicating that the heavily brecciated region, becomes shallower further from the center of the structure giving it a bowl shape in three dimensions.

From the seismic data, some general morphological dimensions can be approximated. The outer raised rim measures about 6km based on the topographic expression of the structure (not shown on the sections). The ring trough measures about 4km in diameter and the central uplift is about 3km wide. The maximum depth of the chaotic portion of the structure appears to be about 1.3km as this is the depth to the Mississippian in the 07-07 well. However, it is thought that the transient crater was much shallower than this, perhaps only 600m deep. The effect of the rebounding process, though, may have been to pull up underlying strata to the depth of disruption now seen in the seismic data.

A peculiar feature seen on line WV-021 is the portion of heavily rotated beds near the central uplift approximately located from SP 220-250 at about 800-1100ms (Figure 6). This region of the subsurface appears to have suffered greater rotational deformation than corresponding areas on the other side of the central uplift and on line WV-017 (Figure 7). This leads also to the observation that the structure is fairly asymmetric on both lines. This may be because the impact did not result in a pure explosion as is believed to occur in the case of complex cratering but instead there was a substantial amount of momentum transfer to the target rocks as well as explosive energy. The force of the impact was not equal in all directions resulting in asymmetric deformation of the target rocks. This structure may also represent a more transitional form of crater between the purely simple and complex forms. Heterogeneities within the target rocks might also have contributed to this asymmetry as they would have reacted differently to the compressional and extensional forces acting on them during crater formation.

Although not readily apparent from any one 2-D line, the circular nature of the structure becomes clear once the 2-D lines are combined to create a 3-D time-surface map. This was accomplished for the Belly River and Mississippian horizons by digitizing the sequence on each line, assigning a surface location from the base map and then gridding the data. The results are shown in Figure 8. This diagram would have obviously been aided by a denser dataset but the general morphology of the crater can still be clearly seen.

Time Structure

Both the Mississippian and Birdbear formations show about 40ms of two-way time structure on both lines. In both cases, and for both formations, the time structure takes the form of pull-up beneath the central uplift region. Comparison of the 01-04 well statistics and the 07-07 well statistics show that there is an increase in the elevation of the Mississippian of 43m (increasing elevation at 07-07). The average velocity to the Mississippian at the 07-07 well is given from the well data as 2646m/s. This results in an estimated two-way time structure of 32ms at 07-07 due to real structural uplift of the Mississippian. Hence the rest of the pull-up of about 8ms is likely due to an increase of velocity at the 07-07 well. The data for wells 07-07 and 01-04 show that there is an average velocity increase of 150m/s to the Mississippian. It is unclear though, whether this is sufficient for an 8ms additional pull-up.

Apparently, after the transient crater formed, the bottom began to rebound which in effect drew in material from below and the sides of the transient crater. This not only resulted in the normal faults along the rim but also caused structural pull-up along the lower horizons of about 42.8m. Additional pull-up, perhaps achieved by an increase in velocity, is more difficult to explain as one would expect brecciation of the target rocks to decrease the average velocity. The well data is currently inconclusive on this point. However, shock metamorphic effects and the rotation of higher velocity rock units into the region of uplift may contribute to the overall average velocity increase in the central uplift region.

OTHER EXPLANATIONS

There are other geological processes which can produce similar features. Volcanoes produce similar conical shaped structures but these generally go to a great depth (Issac and Stewart, 1993). The White Valley structure, in contrast, clearly shows coherent reflectors beneath the disrupted units of the central uplift. There is no evidence in previous geological work done in the area that suggests any volcanic activity (Kent, 1968).

Dissolution phenomena are quite prevalent in the region (Kent, 1968). While there is strong evidence for dissolution of the Prairie Evaporite formation of the Middle Devonian, most of the larger structures occur as channels with overlying strata collapsing into them. This would produce elongate collapse structures rather than such a circular structure as is seen at White Valley. The dissolution of the Prairie Evaporite would have to cause disruption of the Mississippian strata before it would be seen in younger rocks. The strong coherency of the Mississippian and Birdbear formations suggests that other phenomena are at work here. Dissolution phenomena would also not likely produce structures which demonstrate such prevalent uplift as the White Valley structure does.

The structure is not likely to be a reef as reef growth was generally confined to central Alberta (Kent, 1968). Southwestern Saskatchewan was predominantly covered by a shallow sea shelf allowing for predominant sedimentation of carbonates in a series of transgressive and regressive events. Evaporites were probably deposited during periods of still stand (Kent, 1968). In any case, reefs are unlikely to have the same morphological characteristics. The Redwater field, located 40km northeast of Edmonton, Alberta, is a large triangular shaped reef structure measuring about 600km^2 in area. However, the maximum thickness is only about 270m (Anderson et al., 1989). The White Valley structure has a maximum thickness of at least 1300m and is only about 110km^2 in area.

The explosive release of highly compressed gasses and fluids during the formation of diatremes can also lead to crater formation (Isaac and Stewart, 1993). Usually, though, such structures are evidenced by a succession of them along a lineament. It is currently unclear whether this is the case in the region around the White Valley structure. There is currently no evidence to suggest reactivation of deeper zones of weakness in the Precambrian or indeed if such zones exist. However, Kent (1968) alludes to epeirogenic rejuvenation of structural elements in the Precambrian which bears further investigation. Epeirogenic movements, though, are not as dynamic as those associated with the mountain building episodes of an orogeny and tend to occur on a much larger scale (Allaby and Allaby, 1991). There is also currently a lack petrological evidence from the 07-07 well although a preliminary study suggests there was no crystalline rock encountered. It is also difficult to explain the normal faults when an intrusive would likely cause a primarily compressional stress regime and thrust faulting.

APPLICATION OF SCALING CRITERIA

It appears from the literature that there are many methods for determining the size of the meteorite and its energy at impact. Some of these involve compressional characteristics of the target rocks, hydrodynamic theory, the effect of gravity and other considerations (Shoemaker, 1960; Roddy et al., 1977; Melosh, 1989). In this case a very simple scaling relationship is used as a first approximation for calculating various parameters of the meteorite and its impact. This section follows the approach taken by Roddy (1977a).

The initial premise is that the diameters of two craters are related to the cube root of the explosive or yield energies that formed them as follows:

$$\frac{D_1}{D_2}=\left(\frac{W_1}{W_2}\right)^{\frac{1}{3}} \tag{1}$$

where D_1 and D_2 are the diameters of craters 1 and 2 and
W_1 and W_2 are the respective yield energies

This was later adjusted to incorporate data from large-scale nuclear experiments such that:

$$\frac{D_1}{D_2}=\left(\frac{W_1}{W_2}\right)^{\frac{1}{3.4}} \tag{2}$$

From a known explosion with diameter, D_2, and a yield energy, W_2, it is then possible to measure the diameter of a meteorite crater (D_1) and calculate its yield energy (W_1). A range for the meteorites mass can be found if we assume a range of probable velocities and that the impact energy is entirely explosive and is completely due to the kinetic energy of the meteorite. This gives:

$$W_1=\frac{1}{2}mv^2 \tag{3}$$

Finally, using a given density, it is possible to estimate the meteorite's volume and diameter.

For a comparison with the White Valley crater, the Snowball crater at the Defence Research Establishment in Suffield, Alberta was chosen. This crater was formed by a 500-ton detonation at the ground surface producing a complex crater approximately 100m in diameter and 9m deep. Further details of this experiment can be found in Roddy (1977a). Two comparisons between the craters were made. One involved the diameters of the rim crest while the other used the outside diameters of the annular trough. For the White Valley structure, these values were measured off the seismic data at 6125m and 3875m respectively. For the Snowball crater, Roddy (1977a) terms these dimensions D_{ave}^{rc} and D_{ave}^{bbr}, which are the rim crest diameter and the average diameter of the crater along the bottom of the brecciated lens, right along the trough. These had values of 108.5m and 53m respectively. The energy of the Snowball event was 500 tons of TNT which is equivalent to 2.1×10^{12}J. From the literature, a velocity range for meteorites appears to be about 15km/s to 40km/s with an average velocity of about 25km/s (Shoemaker, 1977). For each comparison, these two bounding velocities were used to calculate a range for the meteorite's mass. Further assumptions include the density of the meteorite which was taken to be 3.3g/cm^3 (Roddy, 1977a) and that the shape of the meteorite is spherical. Calculations for the comparison and the results are shown in Table 4.

The results of the calculations indicate that the meteorite was on the order of 214-286m in diameter if it was traveling at 15km/s and 111-149m if it was traveling at 40km/s. Since the average velocity for meteorites is at the low end of the range, the upper diameter range is thought to be more reasonable. The energy of impact was on the order of 10^9 tons of TNT or approximately equal to 50000 Hiroshima-magntitude bombs. Obviously, there are many approximations and assumptions in this approach but it does give a gross estimate of the nature of the impact that caused the White Valley crater. Comparison of these results with the table in Roddy (1977a) shows that this event was of the same order of magnitude as the impact that caused the Flynn Creek crater in Tennessee although it is morphologically a smaller crater. More work needs to be done to understand the processes of impacting to properly confine the size of the impact and to establish the various parameters of the impacting bolide with greater confidence.

Table 4. Calculation of relevant parameters for the White Valley event. Parameters are described as follows: D_{rc}=diameter of rim crest; D_{tr}=diameter of trough; W=yield energy; m=mass of meteorite; V=volume of meteorite with ρ its density; d=diameter of meteorite. Subscripts 15 and 40 indicate parameter calculations for meteorite velocities of 15km/s and 40km/s respectively.

PARAMETER		WHITE VALLEY CRATER	SNOWBALL CRATER
D_{rc}		6125m	108.5m
D_{tr}		3875m	53m
W		for D_{rc}: 1.9×10^{18}J for D_{tr}: 4.57×10^{18}J	500 ton TNT (2.1×10^{12}J)
m	m_{15}	for D_{rc}: 1.70×10^{10}kg for D_{tr}: 4.06×10^{10}kg	N/A
	m_{40}	for D_{rc}: 2.37×10^{9}kg for D_{tr}: 5.71×10^{9}kg	N/A
V (ρ=3.3g/cm^3)	V_{15}	for D_{rc}: 5.15×10^{6}m^3 for D_{tr}: 1.23×10^{7}m^3	N/A
	V_{40}	for D_{rc}: 7.18×10^{5}m^3 for D_{tr}: 1.73×10^{6}m^3	N/A
d	d_{15}	for D_{rc}: 214m for D_{tr}: 286m	N/A
	d_{40}	for D_{rc}: 111m for D_{tr}: 149m	N/A

CONCLUSIONS

The structural anomaly seen on the 2-D White Valley seismic data shows many of the characteristics of a complex impact crater. It has a circular form with raised rim, an annular ring synform and a raised central uplift which in turn, shows evidence of possible post-impact subsidence. The structure's profile is mirrored in the topography of the area which indicates a rim crest diameter of about 6km. The ring synform has an outer diameter of about 4km while the central uplift is about 3km wide and is raised between 550-950m above regional levels. The amount of uplift below the Belly River horizon decreases with increasing depth. The maximum structural disruption occurs to a depth of about 1300m although the depth of the transient crater is perhaps half this distance. Pull-up of the predominantly coherent horizons beneath the central uplift appears to be due to a combination of actual structural uplift during rebound of the transient crater as well as velocity pull-up. Most of the disturbed zone occurs in Late Cretaceous rocks. The best age determination from the current data indicates the impact occurred at most 75Ma ago.

Application of simple scaling criteria estimate that the impact at White Valley had a yield energy approximately equivalent to 50000 Hiroshima events. The mass of the meteorite was about 2.0×10^{10} to 4.0×10^{10}kg with a diameter on the order of 210 to 390m. Difficulty in making accurate measurements of the crater dimensions from the seismic data and inherent approximations and assumptions in the scaling method used results in these rather broad estimates. Further refinement of the interpretation of the White Valley structure will be aided by better scaling techniques and the possibility of petrological information.

The deformed structural uplift, brecciated annular synform, and in particular, the large rotated blocks beneath the ring depression, may be targets for hydrocarbon exploration as these areas may contain good structural traps. Although the 07-07 well was dry, refinement of this interpretation with other geophysical data such as gravity and magnetic data, will lead to a better understanding of the structural elements of the crater and thus refine exploration efforts for hydrocarbons within these unique and intriguing features.

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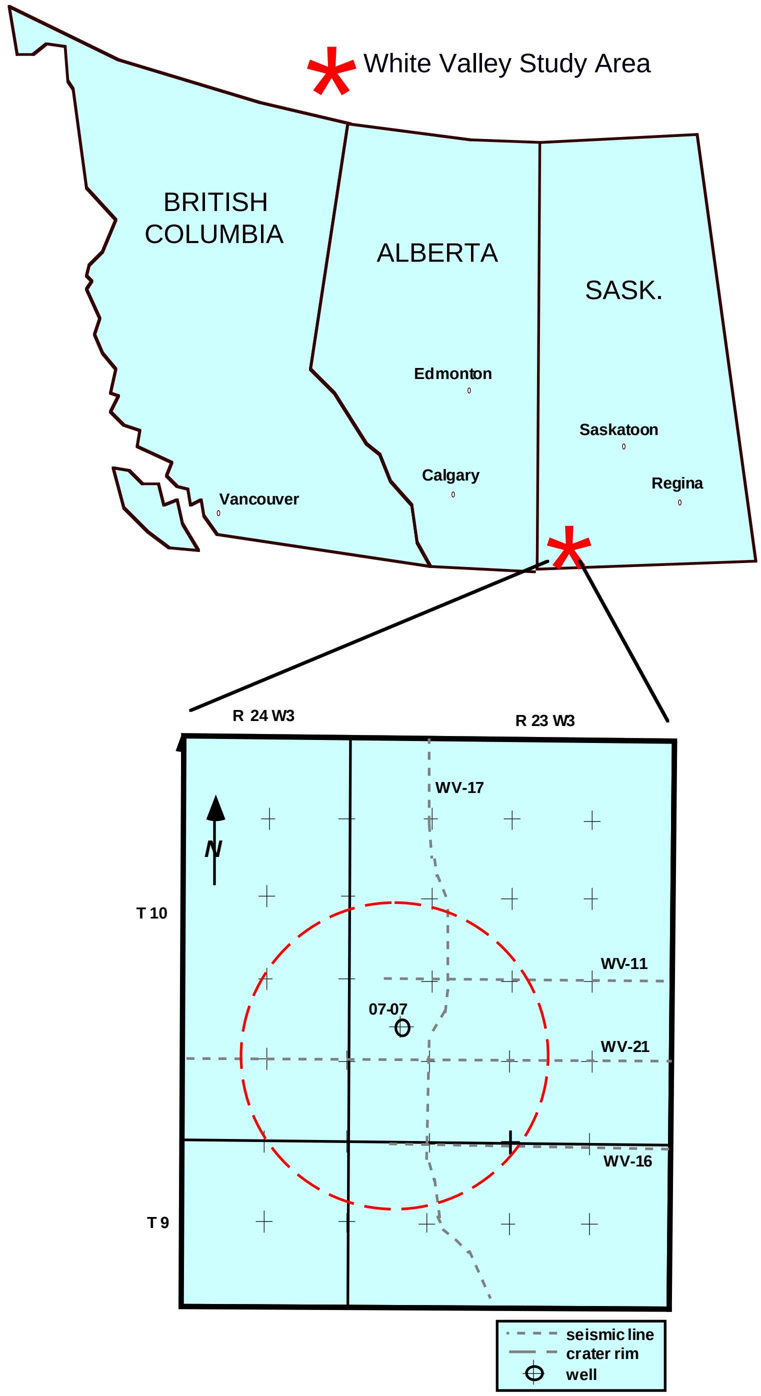

Fig. 1 Location of the White Valley structure in Western Canada (top) and the base map (bottom) showing the seismic lines and well 07-07-010-23W3.

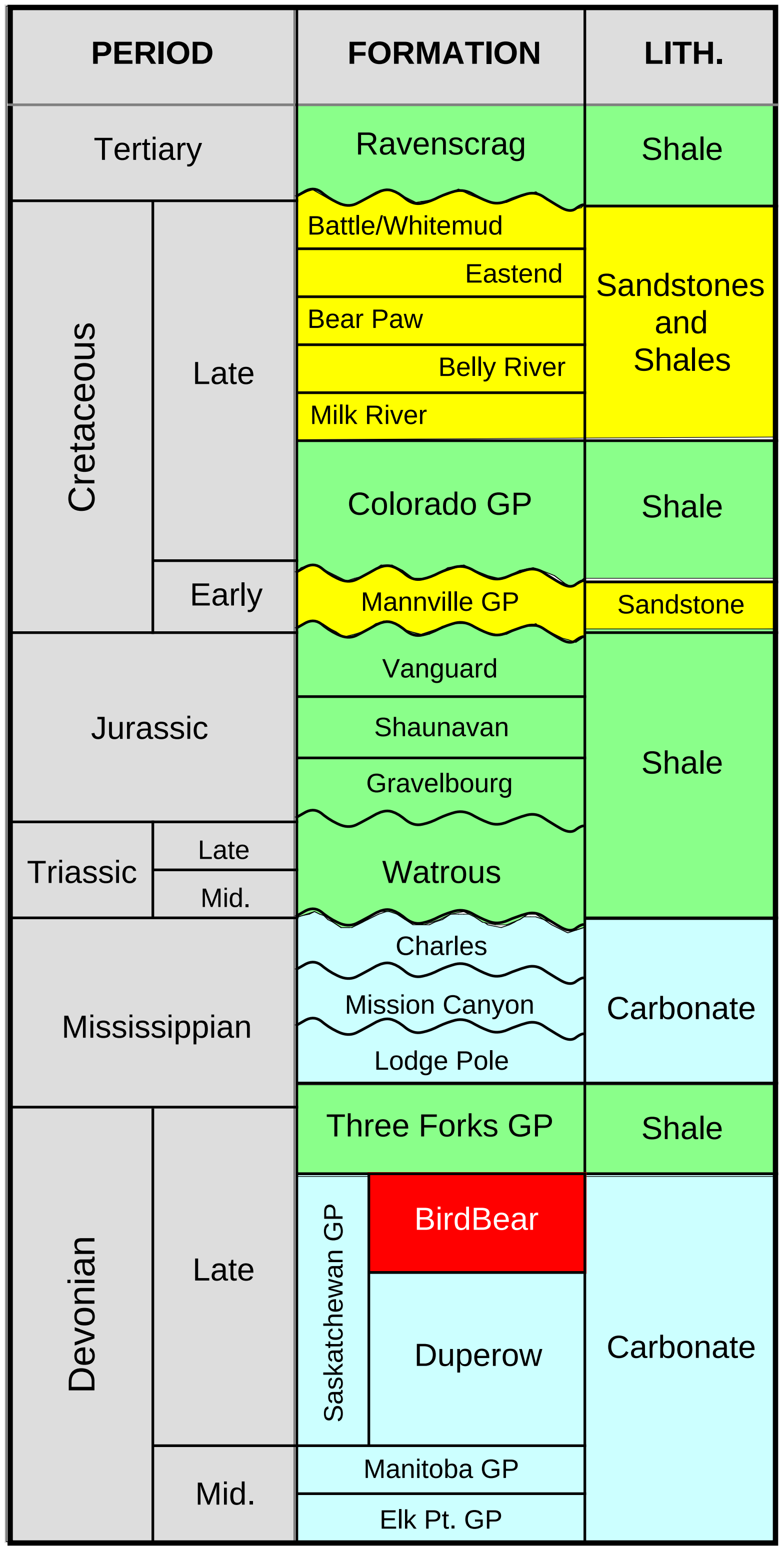

Fig. 2. General stratigraphy of the White Valley region. The target of the 07-07-010-23W3 well was the Birdbear formation, depicted in red.

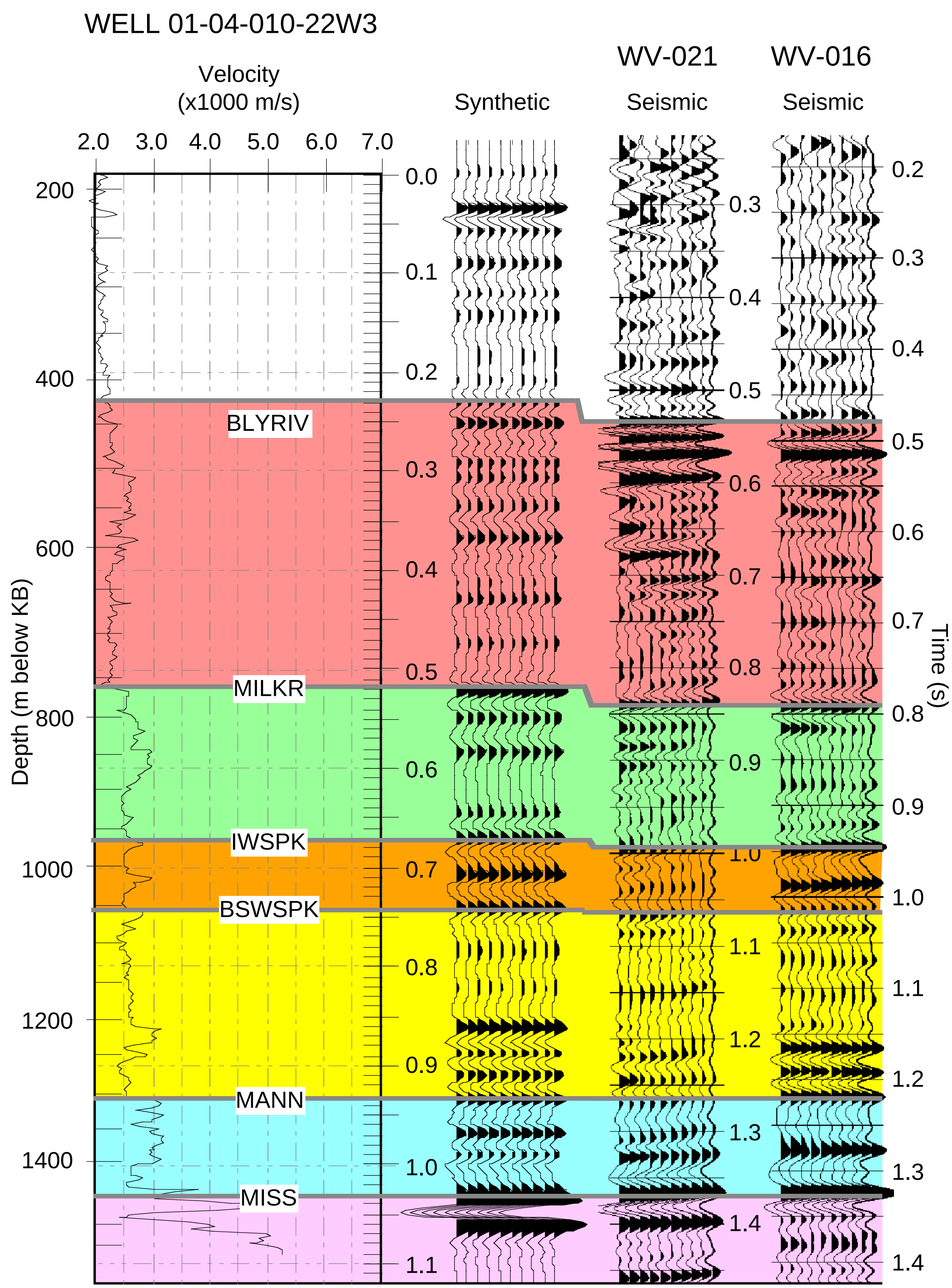

Fig. 3. Correlation of 01-04-010-22W3 with lines WV-021 and WV-016.

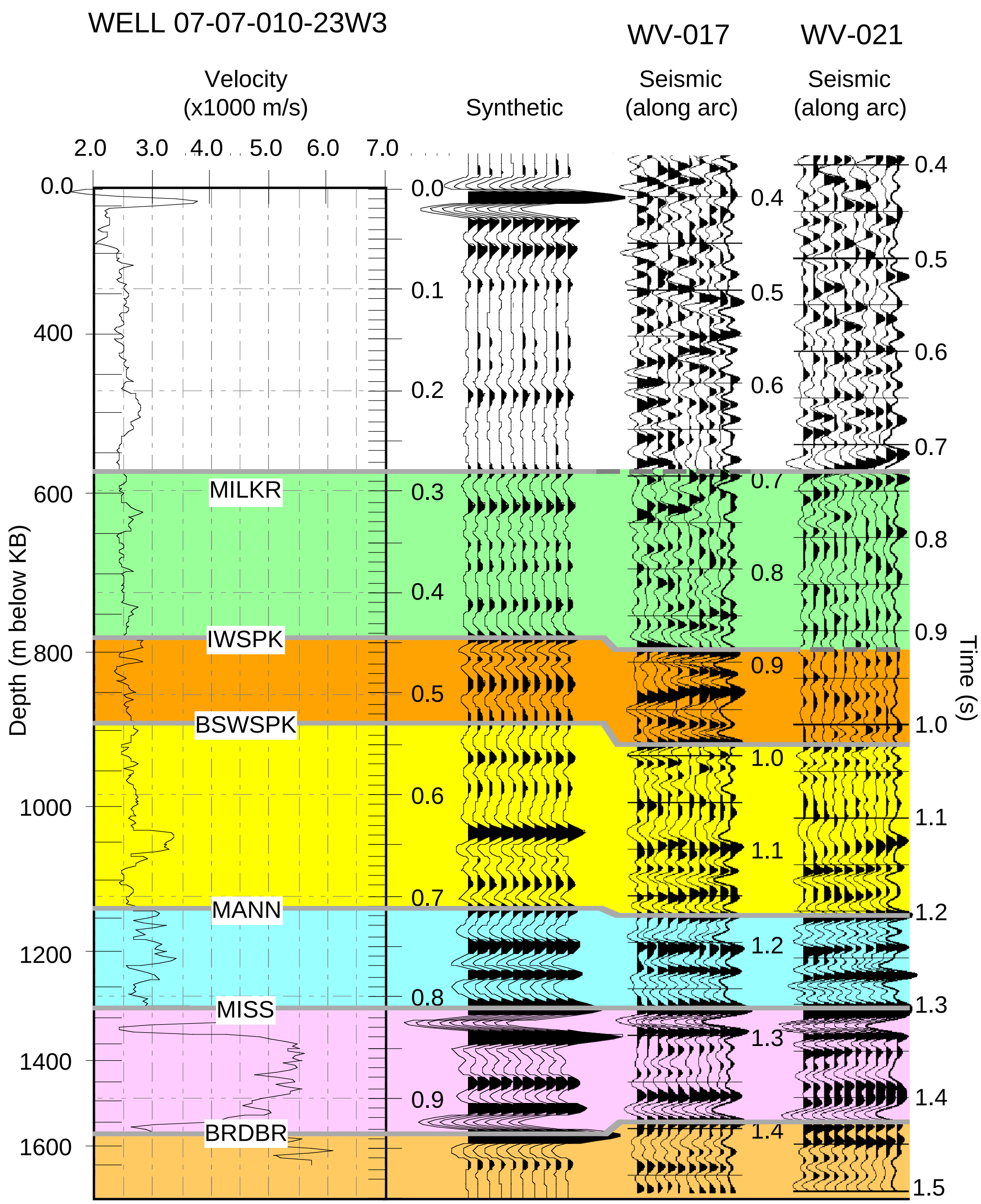

Fig. 4. Correlation of 07-07-010-23W3 with lines WV-017 and WV-021.

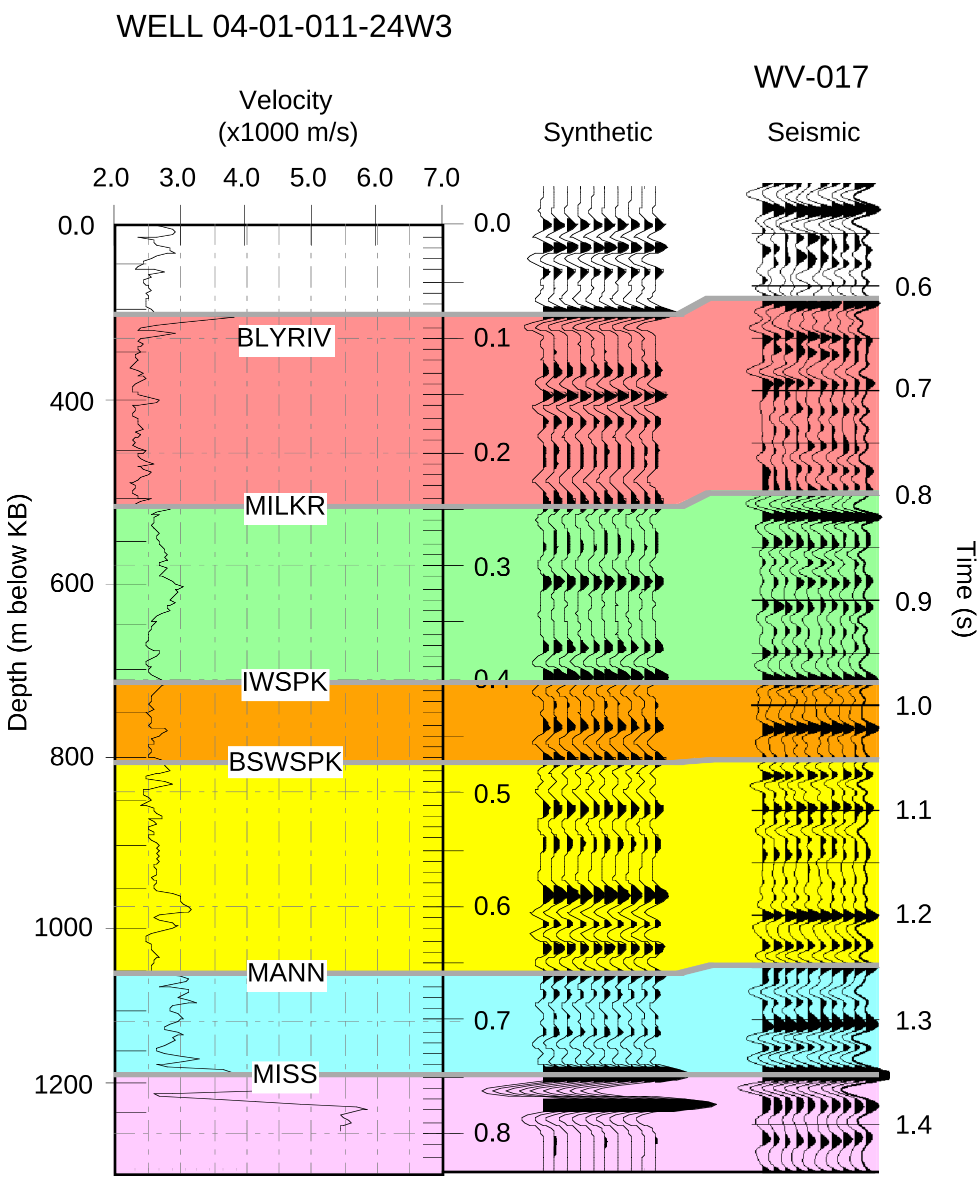

Fig. 5. Correlation of 04-01-011-24W3 with line WV-017.

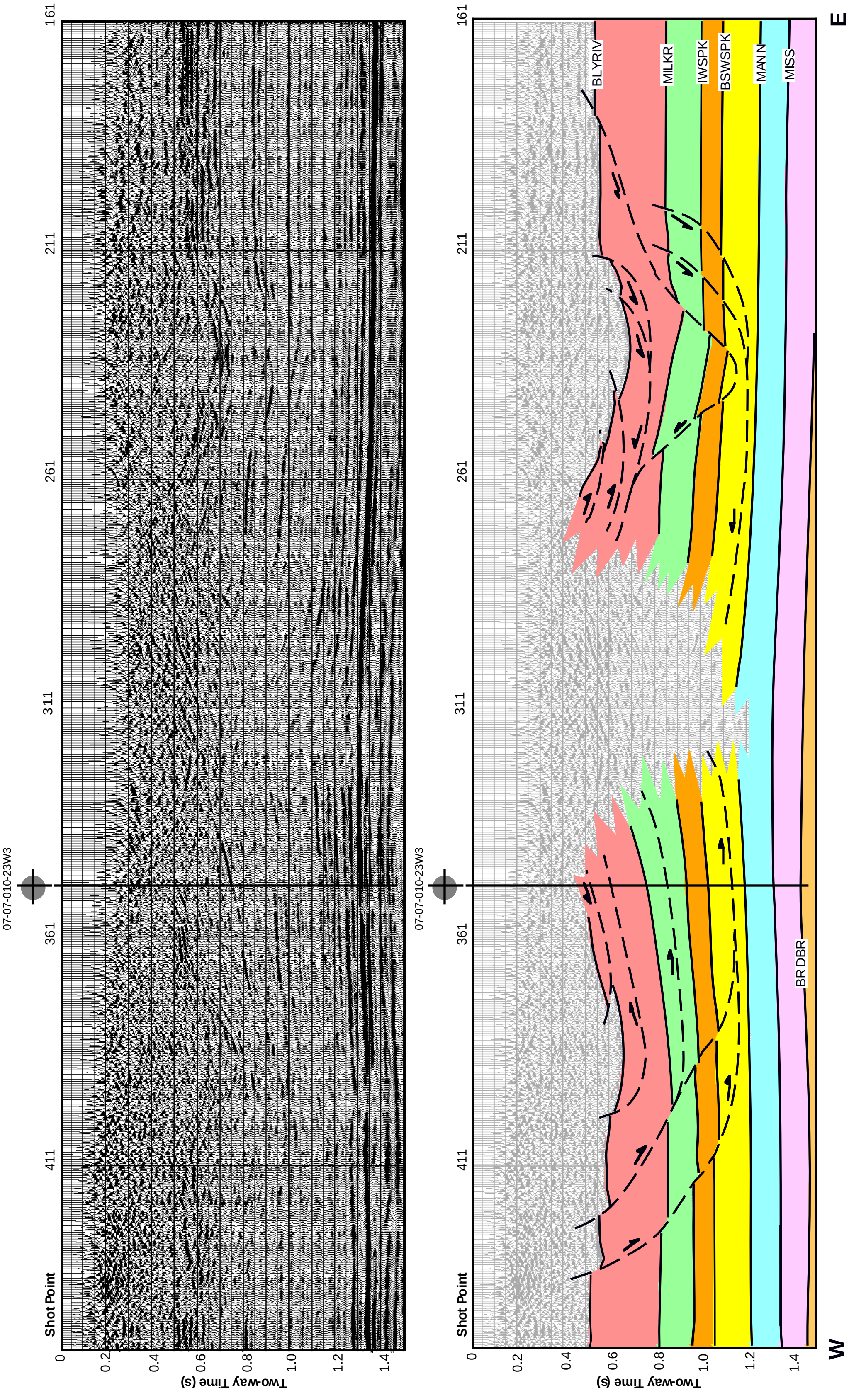

Fig. 6. Seismic line WV-021 showing the uninterpreted section (top) and interpretation (bottom). Faults are shown in dashed lines with arrows depicting relative movement.

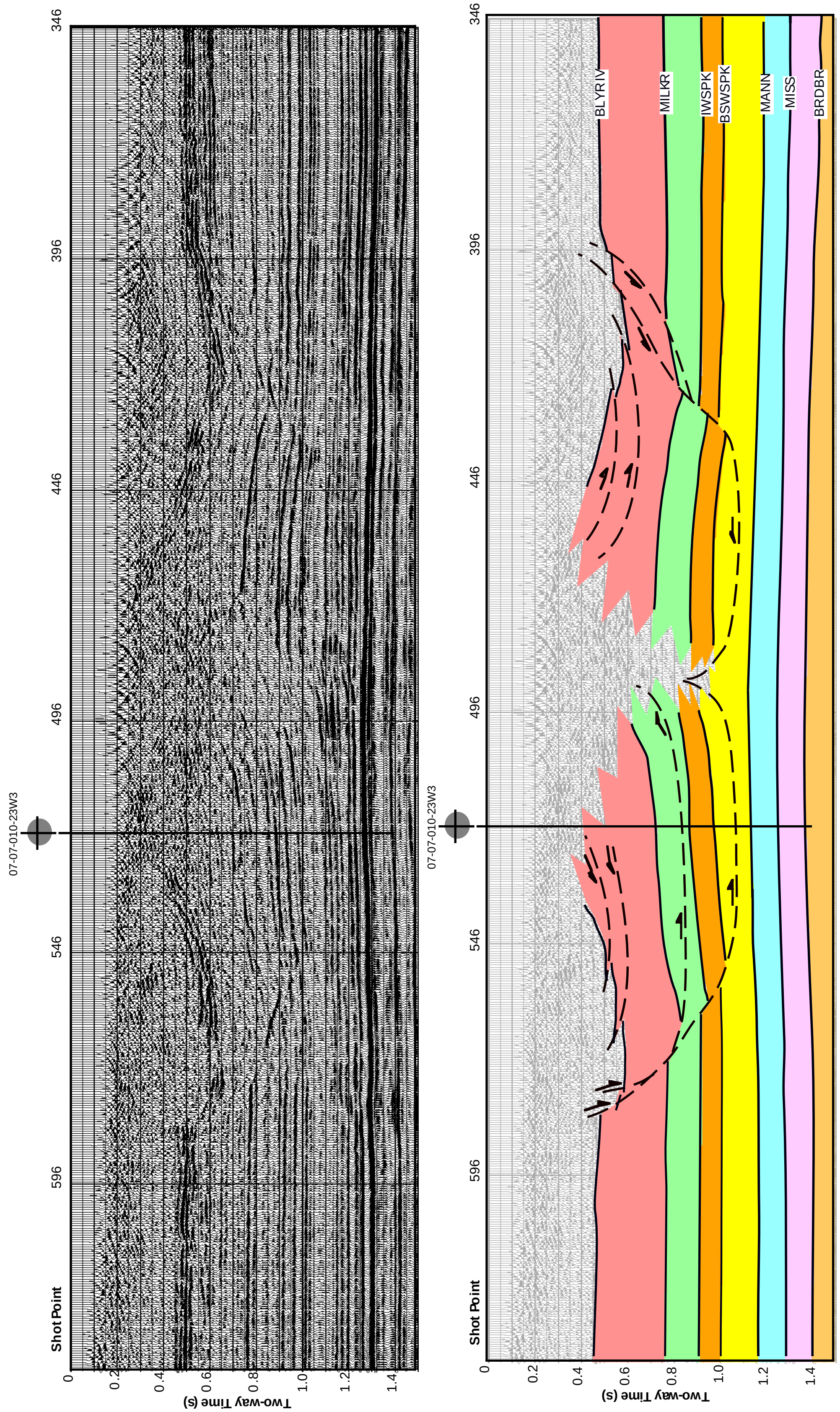

Fig. 7. Seismic line WV-017 showing the uninterpreted section (top) and interpretation (bottom). Faults are marked by dashed lines with relative movement depicted by arrows.

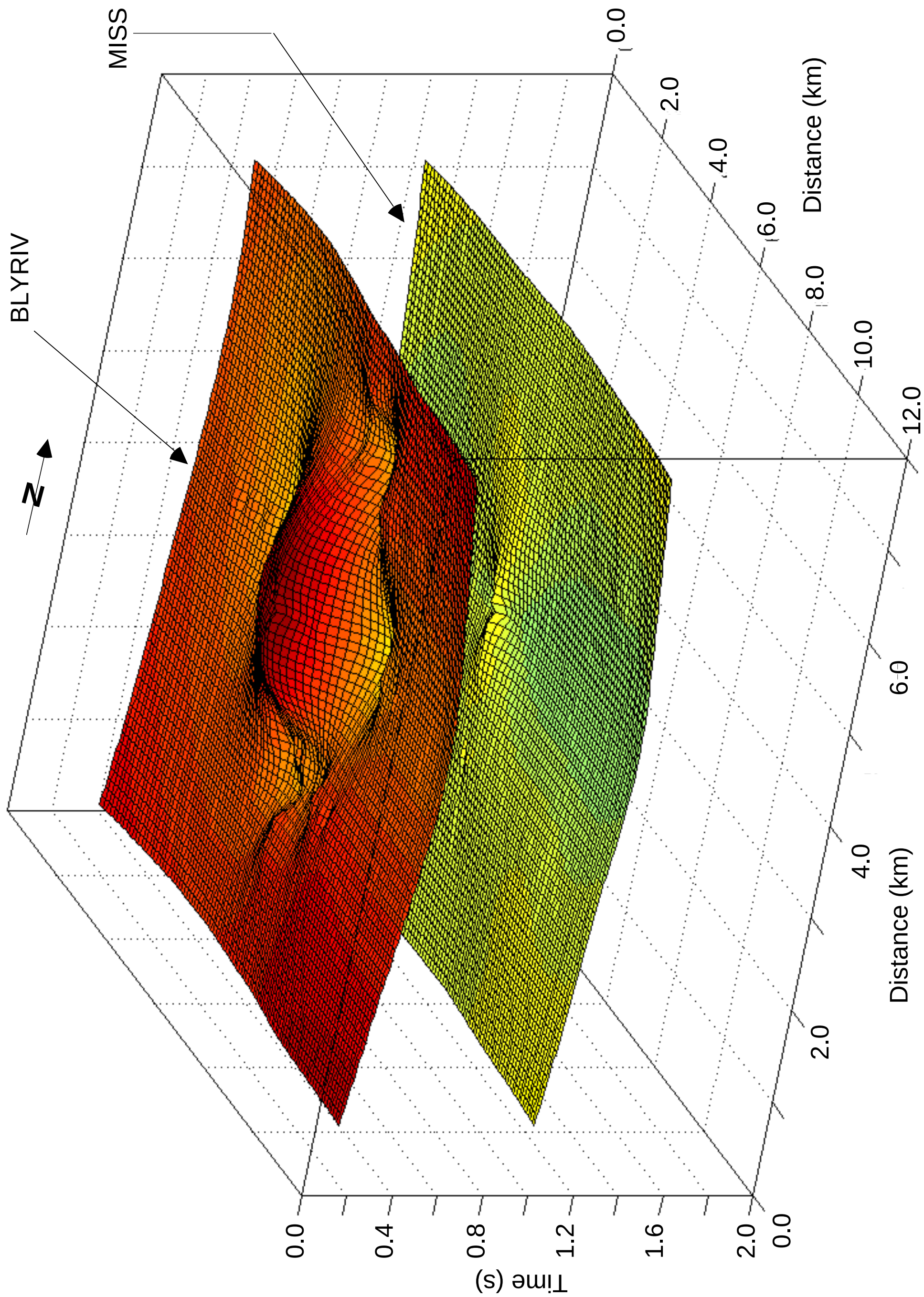

Fig. 8. 3-D perspective of the White Valley structure. Both the Belly River (BLYRIV) and Mississippian (MISS) horizons are depicted. The general morphology of the complex crater can be seen in the Belly River horizon.