Preliminary Examination of Cross-well Seismic Reflection Images
Detroit River International Crossing

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High Frequency Images of Classic Michigan Basin Geology –B-Salt to F-Salt

First let's look at some of the images that display normal, unperturbed Michigan Basin geology. These surveys are

X10N1 to X10N6	X11-6 to X1-1
X10N5 to X10N4	X11-6 to X11-2
X10N1 to X10N4	X11-5 to X11-1
X10N6 to X10N4	X11-5 to X11-2
X10N5 to X10N6	X11-5 to X11-6
X10N3 to X10N4	

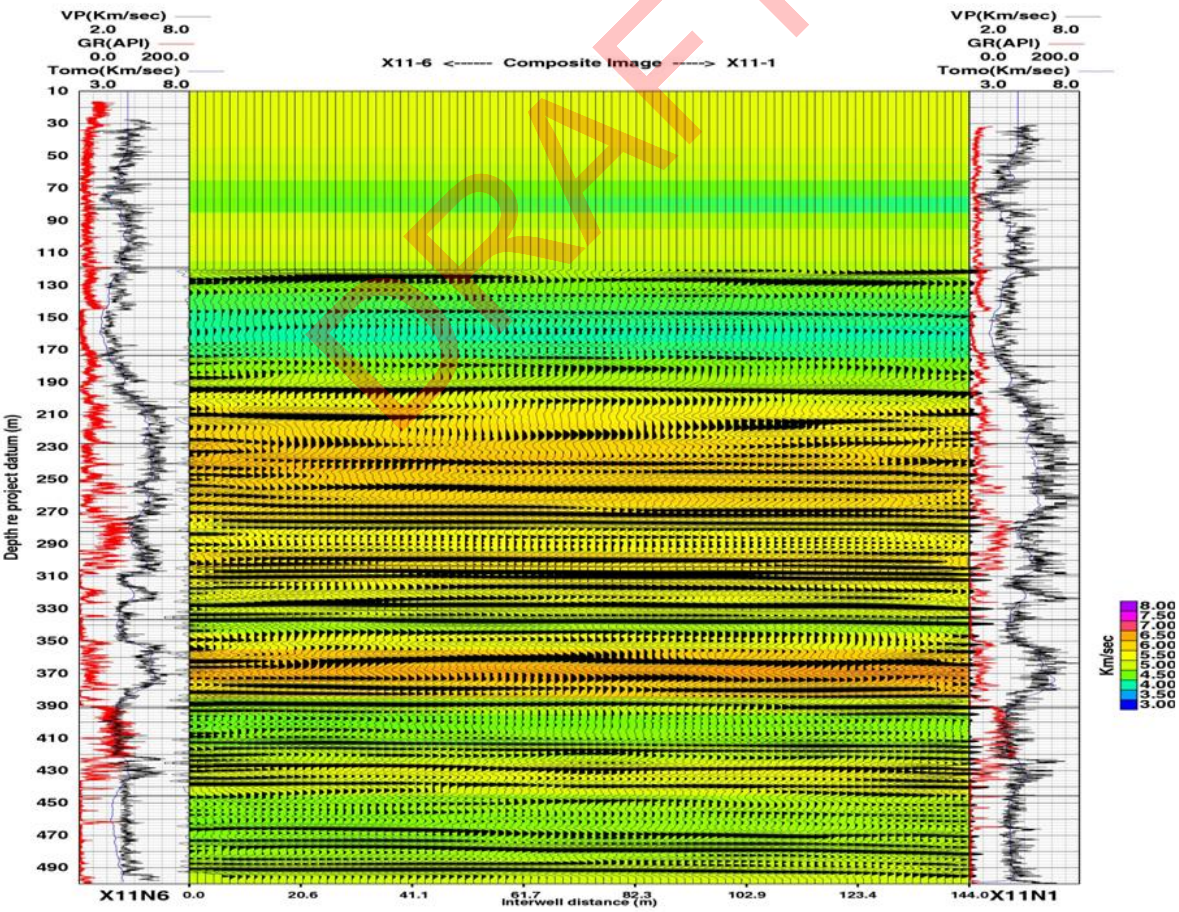

Figure 1 Cross-well reflection survey between boreholes X11-6 and X11-1 in the X-11 corridor.

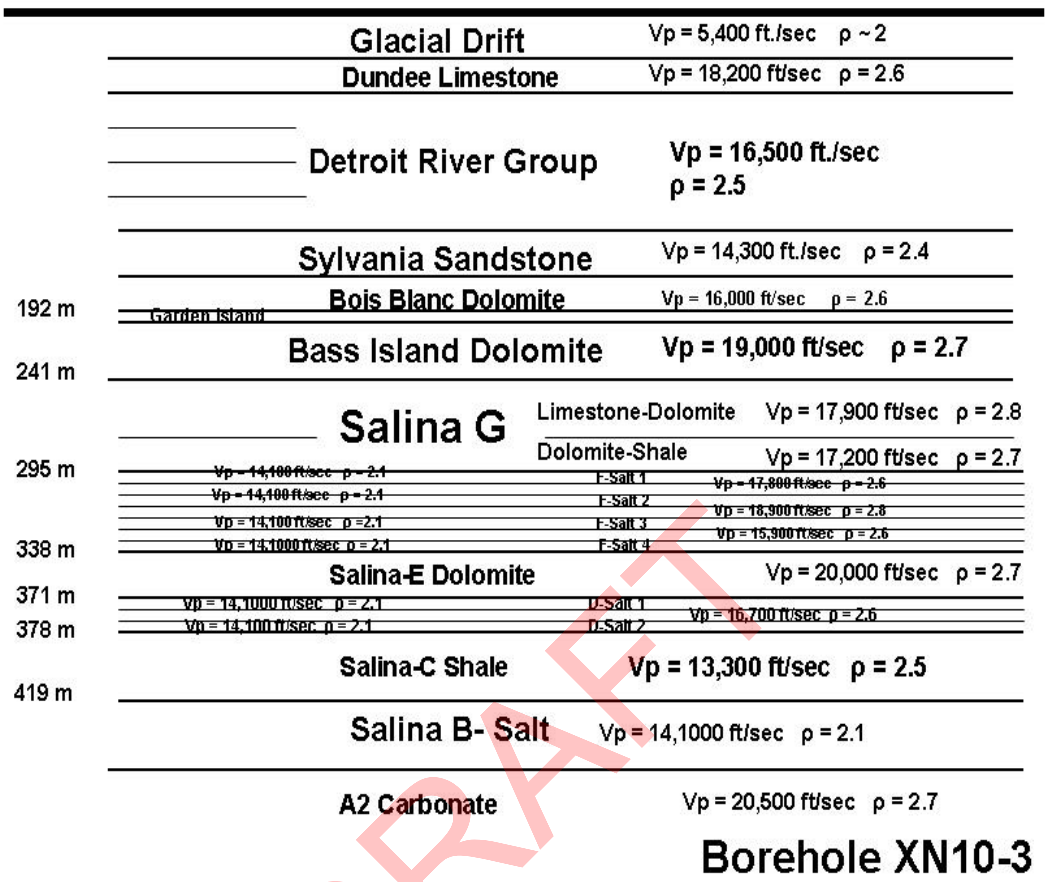

Figure 2 Approximate cross section for the Canadian side of the DRIC project area. The depths indicated here vary slightly as a function of location in the X-10 and X-11 areas.

Our study area is so small and Michigan Basin geology is so flat and unperturbed on that scale that the images listed above are nearly identical . Gentle unconformities do exist and small carbonate mounds are present on the A2 Carbonate, however, major faults, large anticlines and synclines do not occur here.

Looking, first, at the B-Salt interval, especially in X10N1 to X10N6 and X10N5 to X10N6 at the base of the B-Salt (490m), at the very bottom of the image, we see a strong, flat wavelet with two positive (blackened "kicks" of the wavelet to the right) legs, this is the A2 Carbonate. More specifically it is the tuned event from the A2 Carbonate and the underlying A2 Evaporite. In some surveys (e.g. X10N1 to X10N4 and X11-6 to X11-1) we see a perturbation on top of that layer indicating a carbonate growth (tiny reef?) on the A2 Carbonate. Even in the 10-1 to 10-6 image we see a thickening of the top of the A2 in the middle of the survey. We will use the A2 Carbonate layer, in general, as a marker bed in future discussions

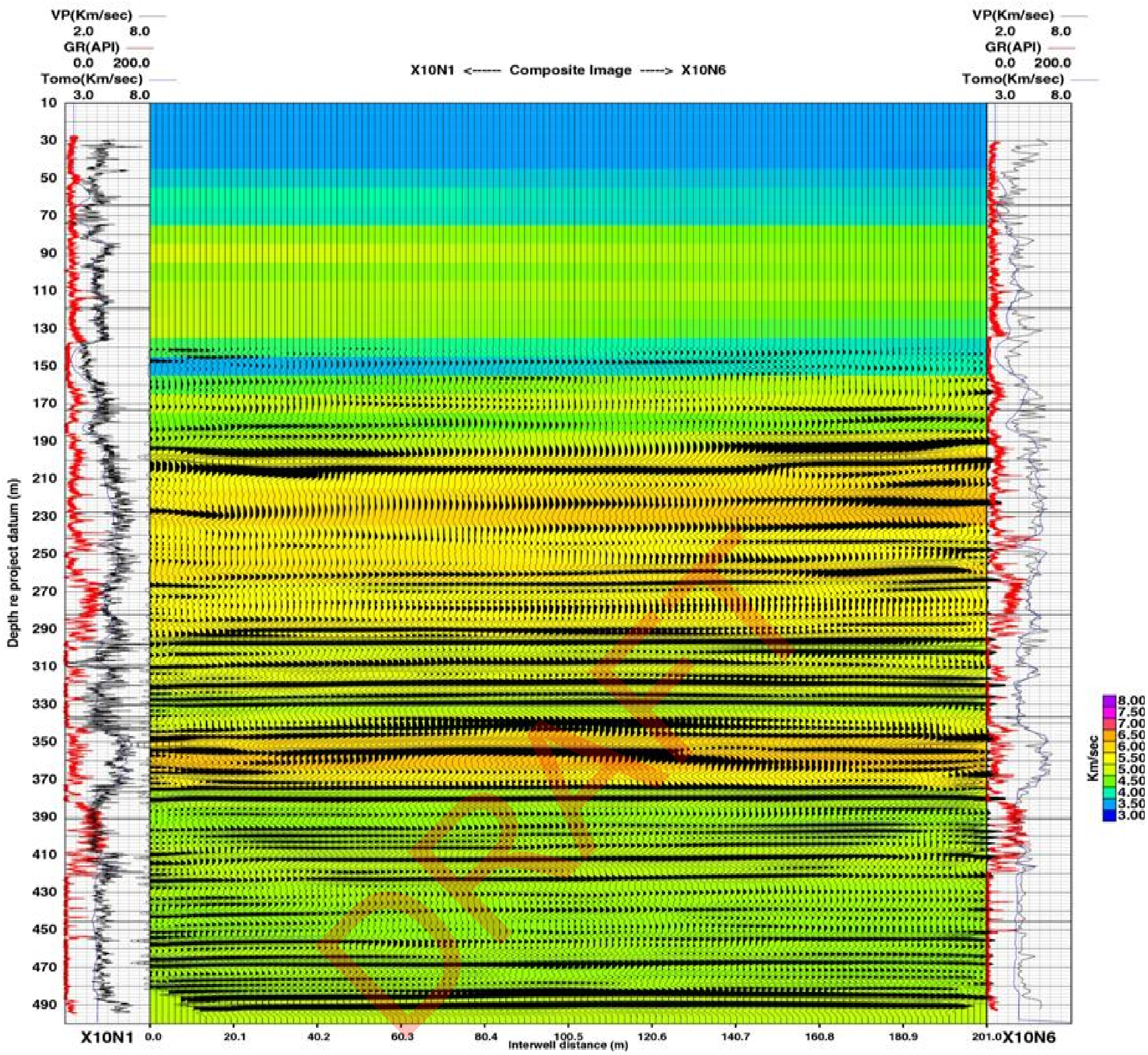

Figure 3 Cross-well reflection survey between boreholes X10N1 and X10N6 in the X-10 corridor.

Directly above the A2, we see (480m interval) one, two, sometimes three, clear, flat stringers in the B-Salt. There are carbonate stringers in the B-Salt and above them are shale stringers (450m to 430m depth interval). Some of the stringers are very strong and clear all the way across the image while others become weak in places, but nonetheless go all the way across the survey. Nowhere in the B-Salt can one move vertically very far without encountering a strong, continuous stringer. We frequently see some stringers at broad, low, undulating surfaces.

The top of the B-Salt is seen as a nearly continuous reflection event, but at times not as strong a reflector as some of the stringers in the B-Salt. The lower portion of the C-Shale is high in velocity therefore it provides a second reflector above the top of the B-Salt. Then in the C-Shale at approximately 400m we see three or four nearly continuous reflectors, again, sharply seen with the kilohertz energy used here.

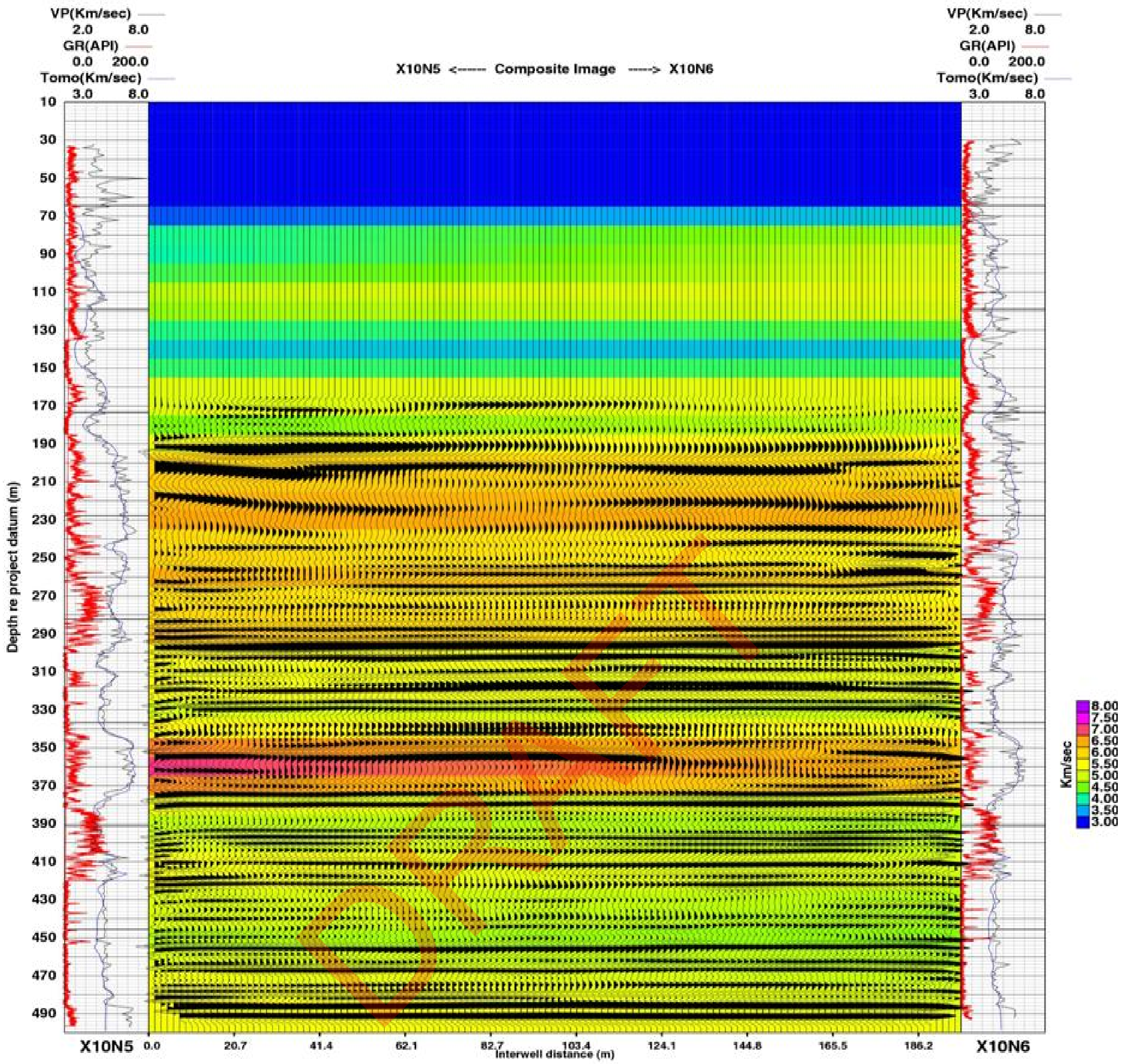

Figure 4 Cross-well reflection survey between boreholes X10N5 and X10N6 in the X-10 corridor.

The bottom of the D-Salt, at approximately 380m, is a very strong, clean reflector with the top of the D-Salt the same. In fact, these are probably not the specifically the top and bottom of the D-Salt, but rather a tuned wavelet caused by the D-Salt and the stringer in the middle.

Because of the low velocity D-Salt the interface with the overlying high velocity E-Dolomite is a very strong reflector, a much better reflector than the top of the E-Dolomite at approximately 340m. In fact, there are one or two reflectors internal to the E-Dolomite that are stronger reflectors than the top even though the F-Salt overlies the E-Dolomite.

In Figures 1, 3 and 4 the F-Salt is composed of three or four salt layers with clear, high velocity stringers between them. This one major stringer (at approx. 310m) that is so thick that it produces distinct reflections from its top and bottom (at kilohertz frequencies). The top of the F-Salt is at approximately 300m and it is expressed as a strong, flat reflector, with a thin, parallel stringer immediately below it.

We will stop here at the F-Salt with the comment that unusual features or anomalies will be seen in the formations above the F-Salt but they must begin in the F-Salt. In Figures 1, 3, 4, 5

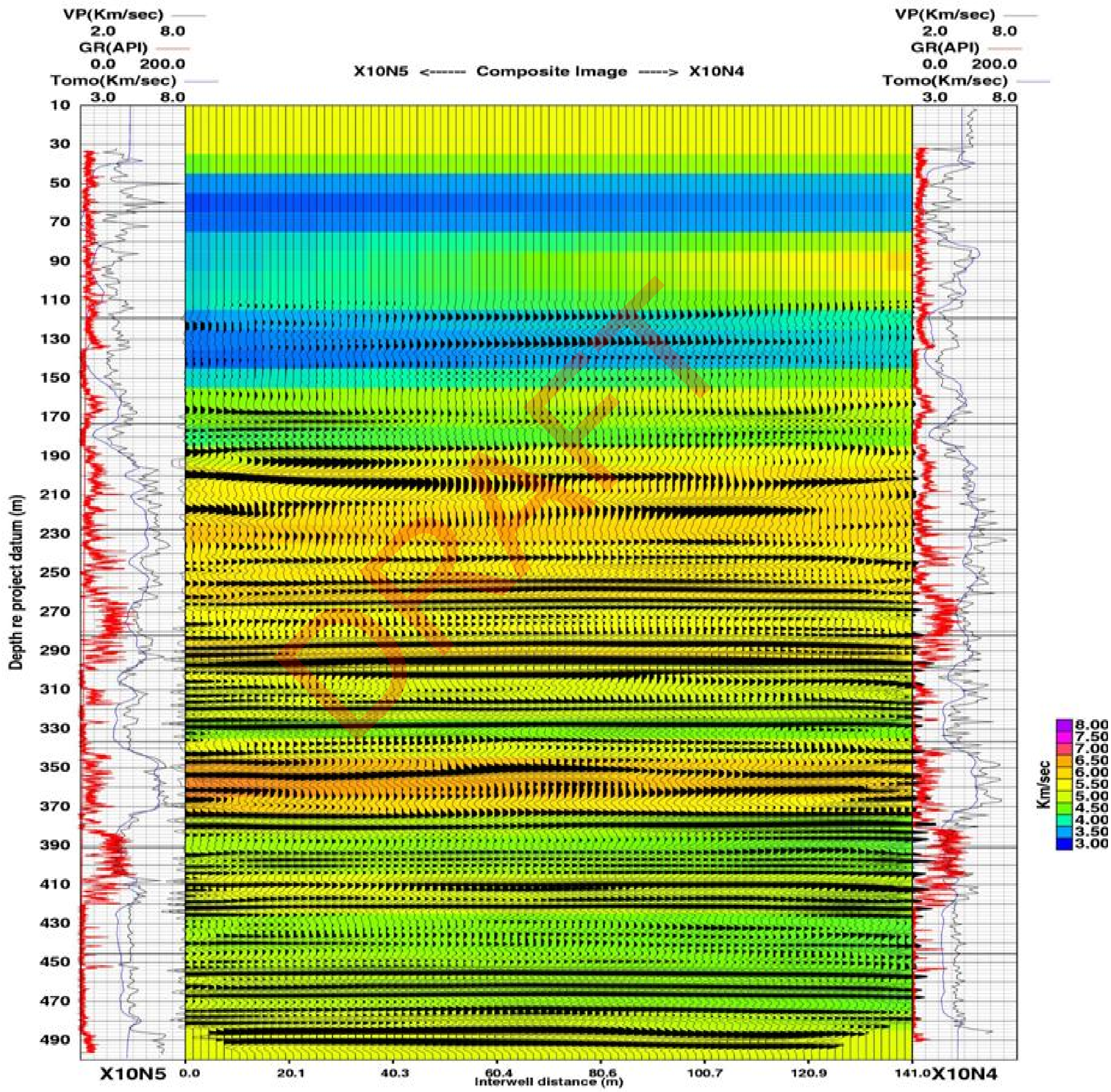

Figure 5 Cross-well reflection survey between boreholes X10N5 and X10N4 in the X-10 crossing.

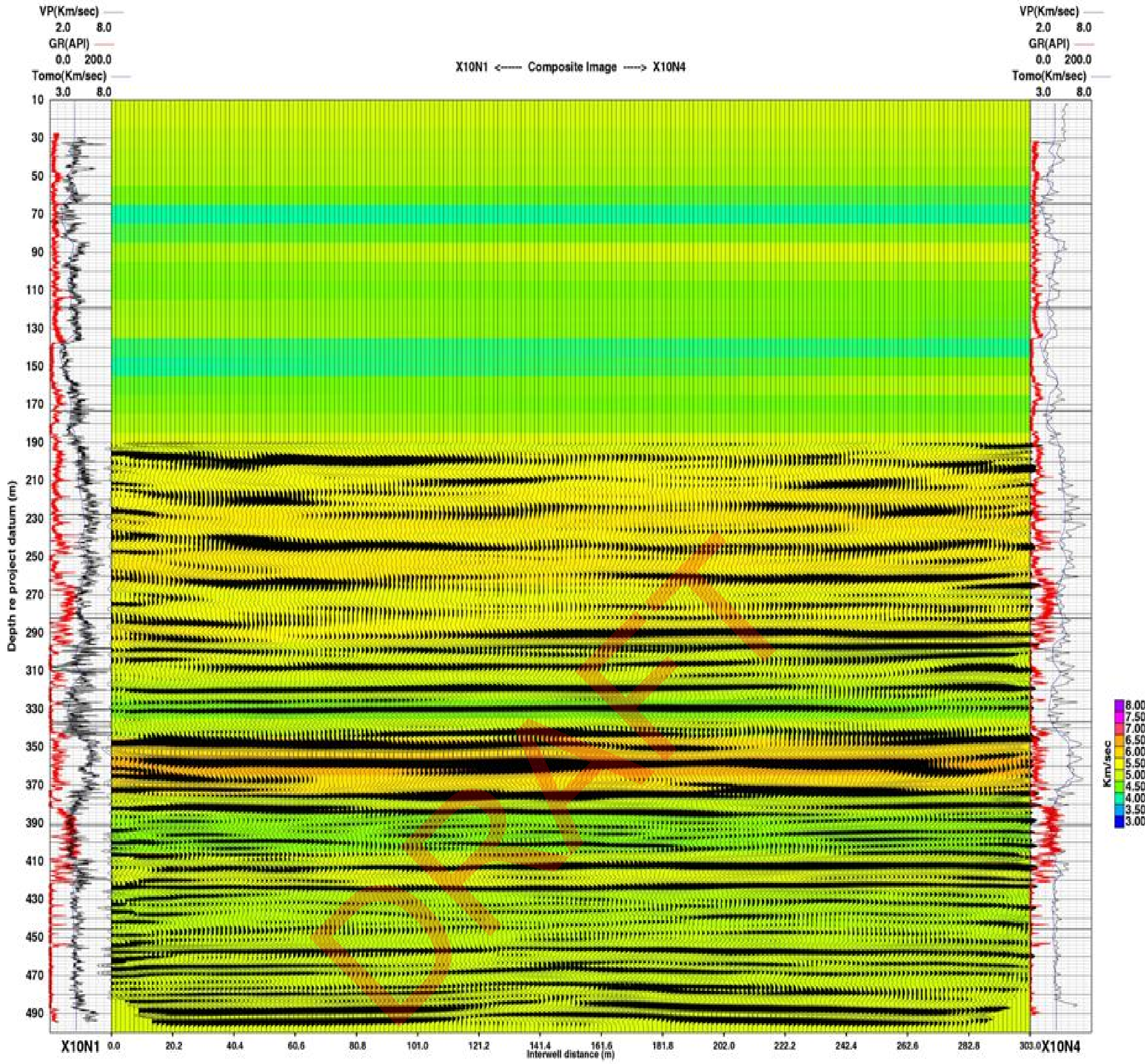

Figure 6 Cross-well reflection survey between boreholes X10N1 and X10N4 in the X-10 crossing. Note the tiny anticline (approximately 2-4m in height) in the tuned A2 Carbonate reflection event at the bottom of this image. Stringers in the B-Salt arch conformably over the A2 anticline. This is typical of Niagaran reef structures.

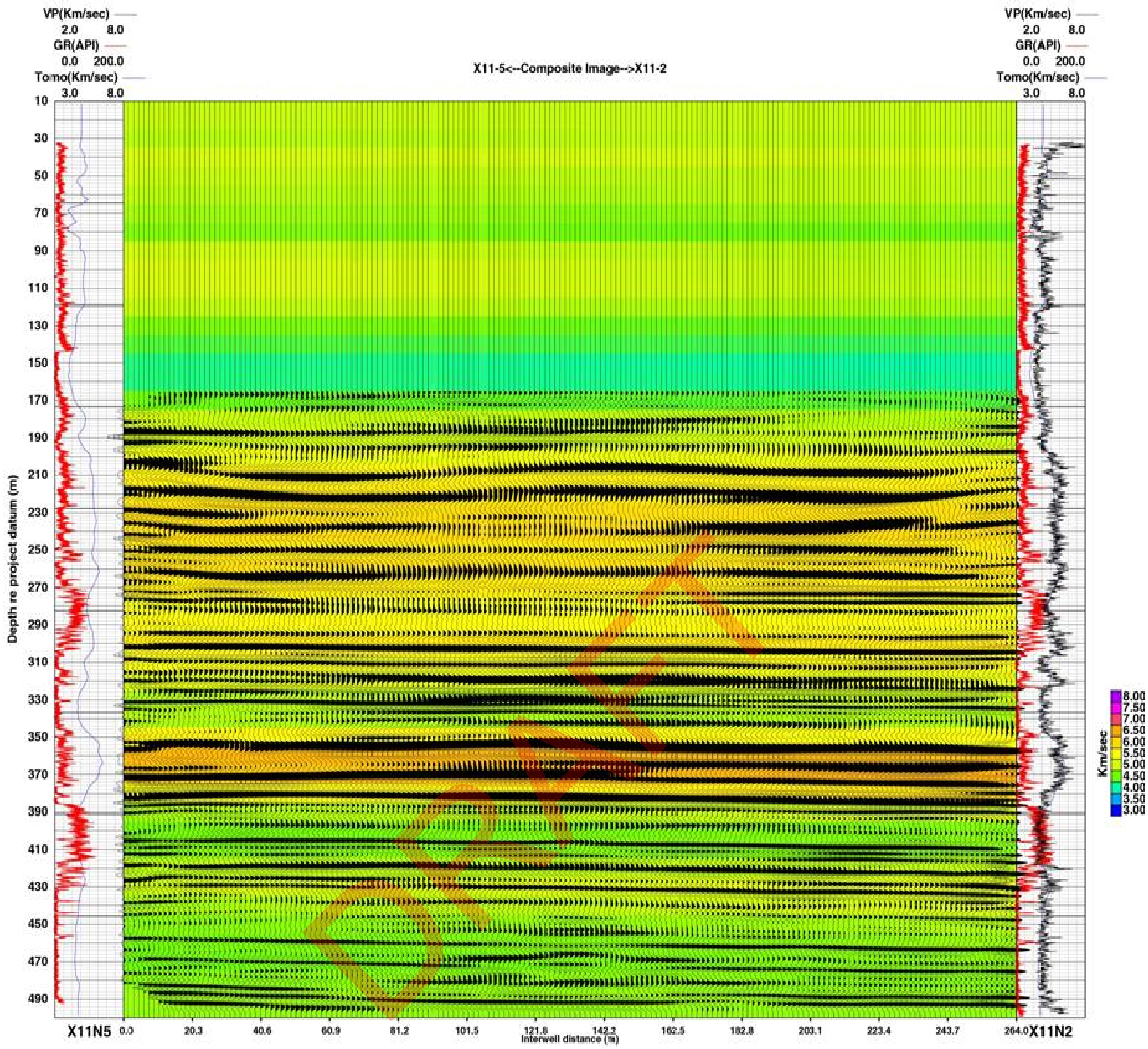

Figure 7 Cross-well reflection survey between boreholes X11-5 and X11-2 in the X-11 corridor. Compare the small feature in the center of the B-Salt with that seen in Figures 6 and 8.

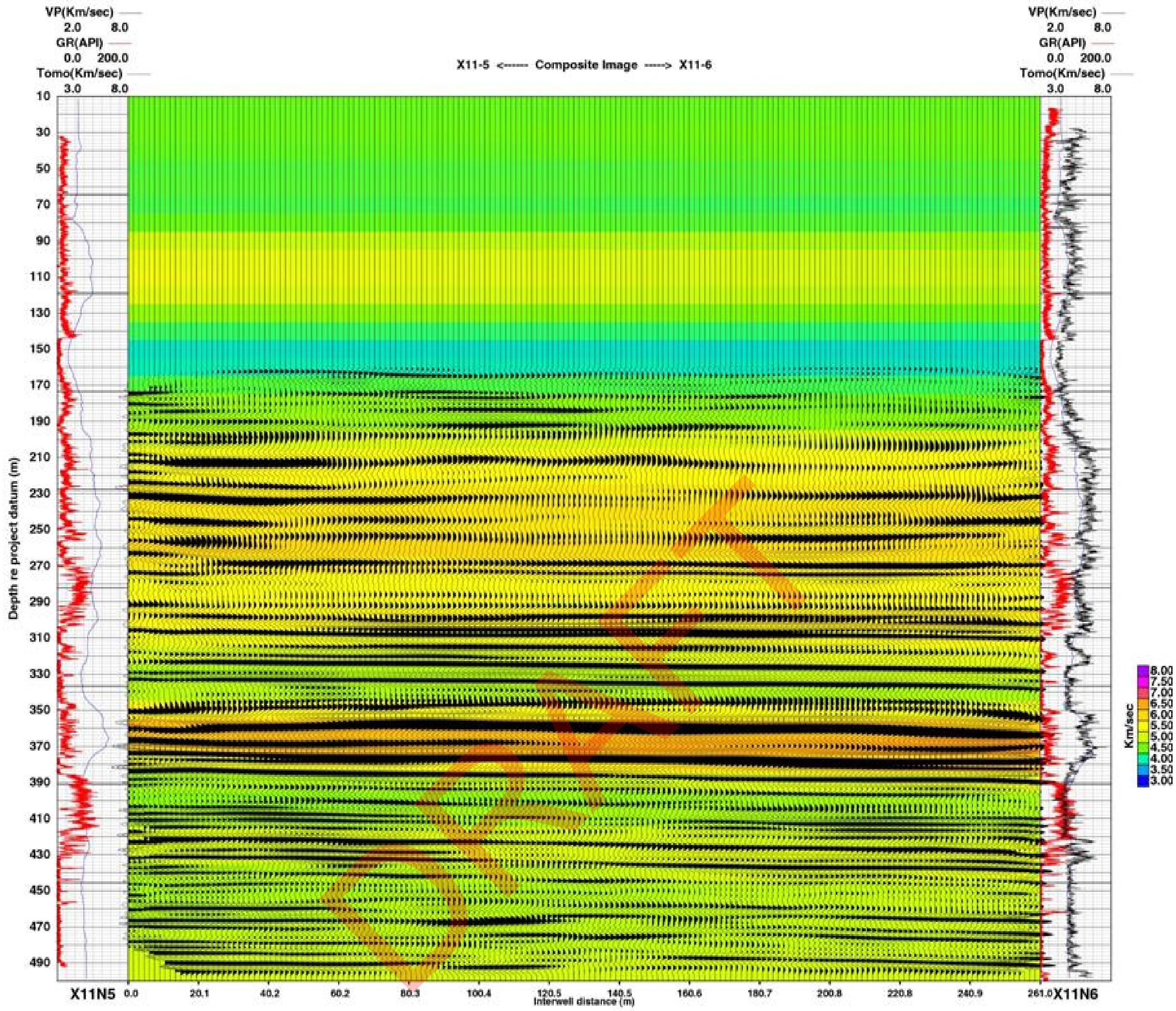

Figure 8 Cross well reflection survey between boreholes X11-5 and X11-6 in the X-11 corridor. Note the feature in the center of the B-Salt that is possibly a small carbonate mound or reef. A similar feature can be seen in Figures 6 and 7.

Anomalies

Let us now compare the above cross well reflection images with other surveys acquired in the X-10 and X-11 areas. These surveys are:

X11N4 to X11N3
X11N4 to X10N3
X11N3 to X10N2 (in the processing queue)
X11N3 to X10N3 (in the processing queue)

X10N3 to X10N2
X10N4 to X10N2
X10N6 to X10N2
X10N1 to X10N2

General Remarks

This report should be taken apart, with figures lying on a table, as it is being read. The surveys presented below should be compared frequently with the previous surveys and the structural model in Figure 2. It is important to observe and remember the appearance of normal interfaces such as the B-Salt/A2 Carbonate (referred to here as the "A2 interface" or simply the "A2"; the top of the B-Salt; the top of the D-Salt, i.e. the D-Salt/E-Dolomite interface, and the top of the F-Salt. The stringers in the B-Salt and in the F-Salt are very important.

The stringers in the bottom of the B-Salt are carbonate stringers and therefore are not seen very well in the gamma ray logs on either side of the surveys, but they are indicated nicely in the sonic log. The stringers in the top of the B-Salt are shale stringers and they show up very well in the gamma ray logs. Individual stringers can be intermittent in the B-Salt, but if all the stringers are missing then solution mining operations probably took place in that location.

The F-Salt is composed of three or four separate beds of salt with a major stringer, even a formation itself, in the middle.

The tops of all the salt layers are important markers and indicators, The D-Salt/E-Dolomite is an especially strong reflector because of the strong velocity and density contrast there.

Two figures for each survey are given below. The first one is presented in a plain, unmarked manner with no lines to alter, guide, or bias the reader's interpretation. The second image contains ellipses that are labeled. These ellipses highlight those portions of the image that I deem important and I use the labels to aid my discussion of those areas. The ellipses are not to be used to compute the size of an area or the volume of a body, they are meant only to focus the reader's attention and make discussion easier.

All of the images in this report are from the bottom portion of all of the surveys, this means that they were illuminated from above with seismic energy. These surveys contain all of the salt formations, if solution mining activities occurred it took place somewhere in these images. Certainly, slumping can propagate up-ward from these salt layers through the overlying Bass Island Dolomite, Bois Blanc Dolomite, Sylvania Sandstone, Detroit River Group, and Dundee

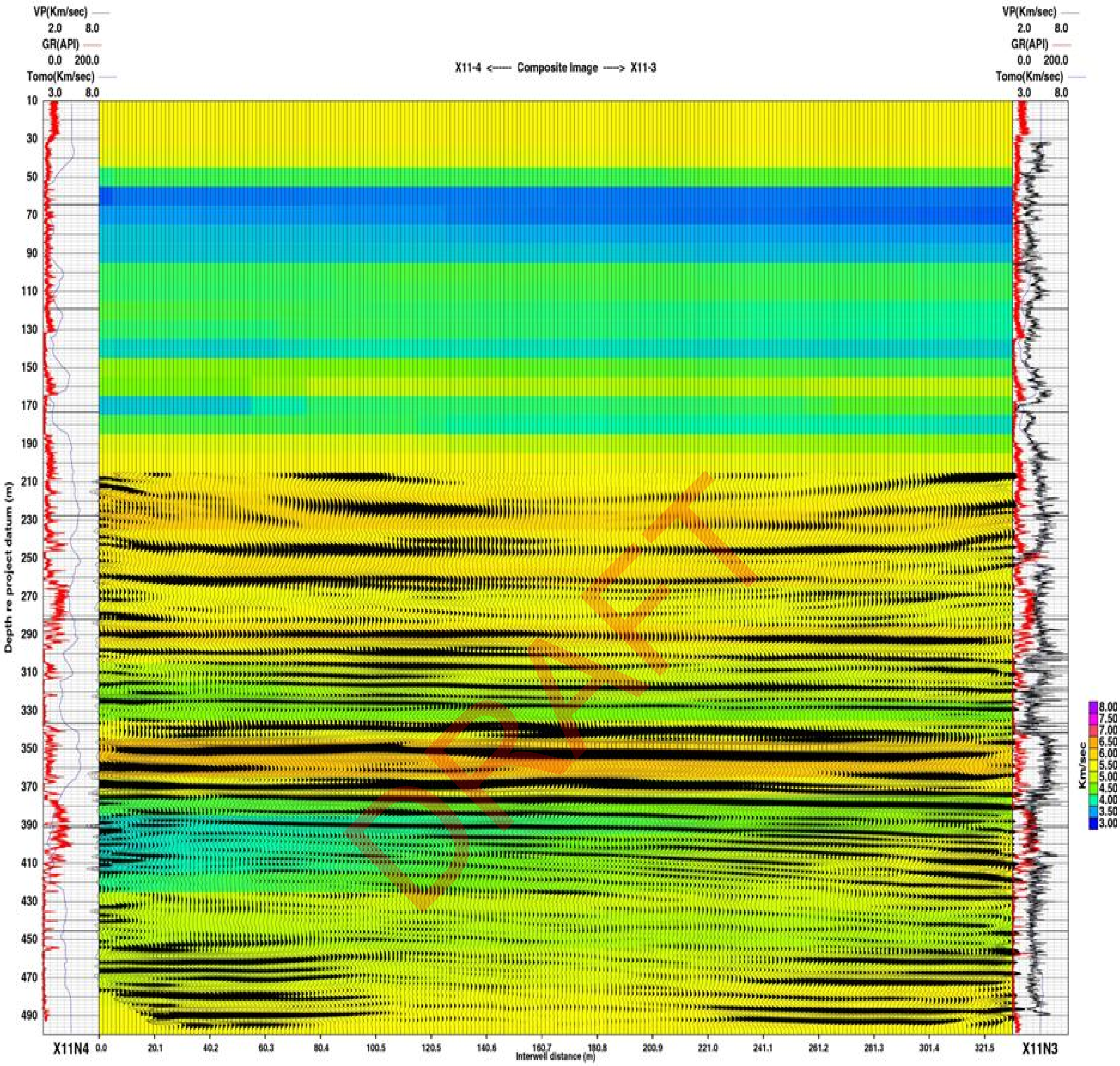

Figure 9a Cross-well reflection survey between boreholes X11-4 and X11-3 in the X-11 corridor. Note the distinct gap in the stringers in the base of the B-Salt along with the gap in the A2 Carbonate at the very bottom of the image.

Limestone, but originated in one of the salt layers.

Because the earth structure was illuminated from above the seismic energy that impinges on the base of large anomalies has passed through the anomalous zone itself. Thus we can be accused of "enlarging" the anomalous zone or "feature". However, as will be seen immediately in Figures 9a, b above this is a minor or no factor at all. However, the top of an anomalous zone or "feature" is imaged here without (this) distortion.

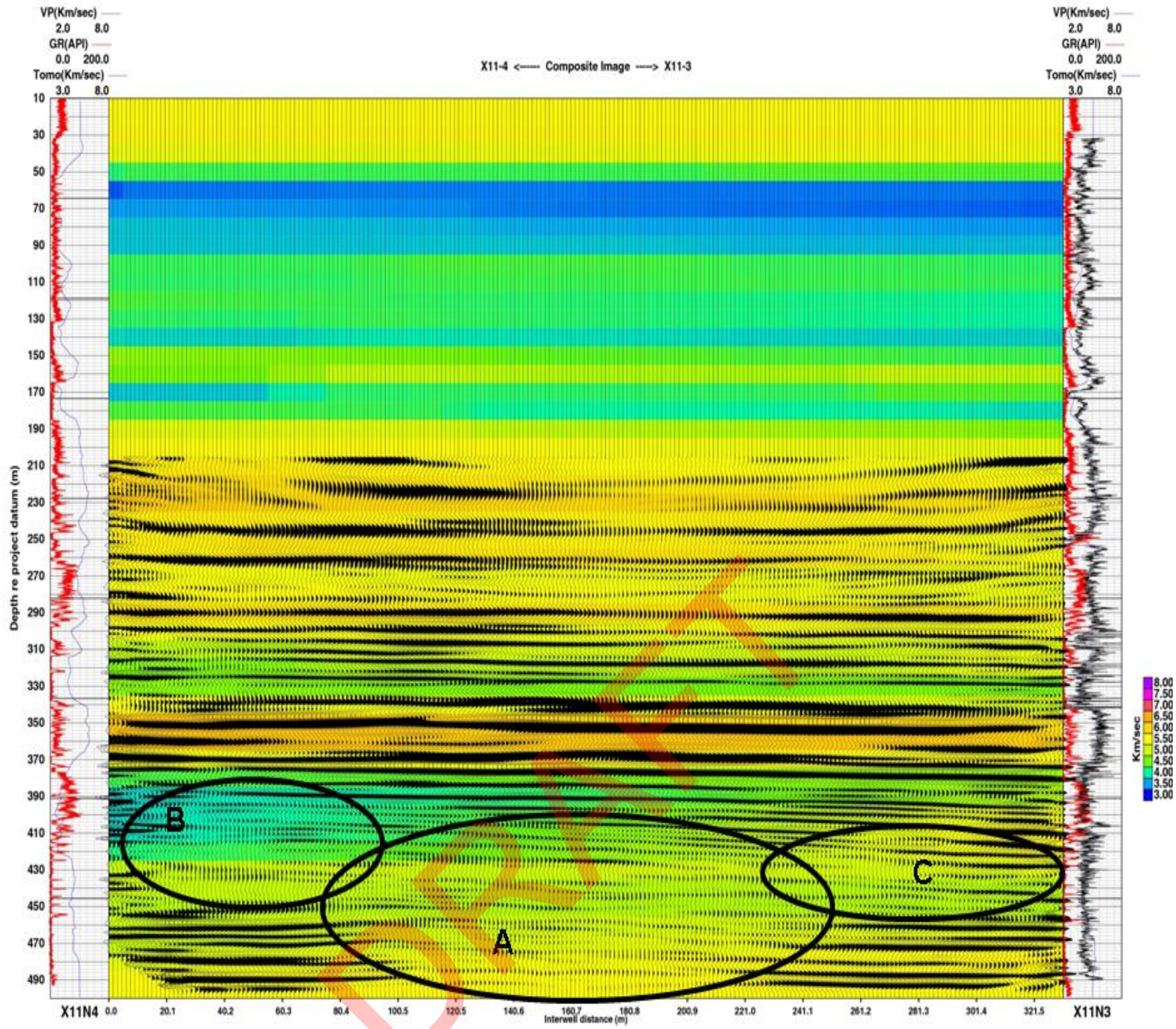

Figure 9b Compare this figure with Figure 9a. Major portions of the stringers in the B-Salt and portions of the overlying C-Shale are anomalously low in reflection amplitude. Moreover a large segment of the A2 Carbonate reflector can not be seen. Note that area "B" also contains a zone of low velocity and three, small, flat reflectors, probably a small section of C-Shale, disjoint from the adjacent reflectors just above the "B".

Survey X11-4 to X11-3

In this survey the B-Salt has been strongly altered as seen above in "A", "B" and "C". Zones "A", "B", and "C" taken together, show that the top of the B-Salt has been altered across the entire image and the entire thickness of the B-Salt has been changed in the center of this image.

Moreover the A2 Carbonate reflection at the base of the B-Salt can not be seen or seen faintly over the central portion of the image. The A2 Carbonate has been dissolved but rather the broken blocks of the formations above it have scattered the kilohertz seismic energy such that no reflection or a very weak reflection occurs at the A2 Carbonate.

Three features make zone "B" significant. First, note that the top of the B-Salt has been breached and the feature extends into the C-Shale and secondly, the underlying velocity tomogram shows a low velocity anomaly there. Lastly, distinct, flat, small, high frequency reflections are seen at the top of the anomaly. This appears to be a block of C-Shale displaced upward and separate from the other high frequency reflections in the C-Shale, seen to the right. Furthermore, the reflections in “B” are flat whereas the other C-Shale reflections form a long, low, arching structure across the image. Above these reflections and to the right we see the reflection from the base of the D-Salt has been reduced.

The E-Dolomite and the F-Salt have not been affected.

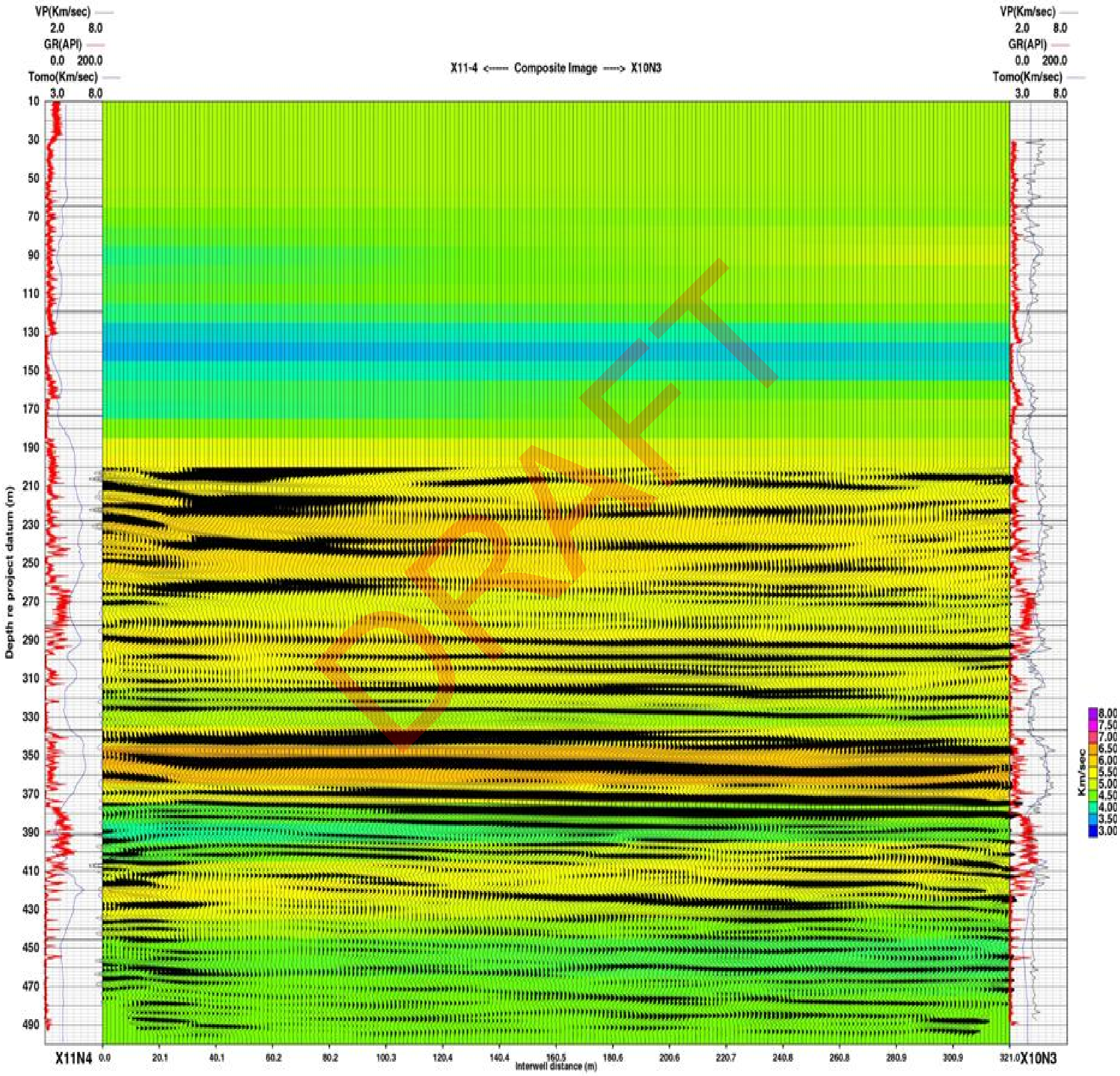

Figure 10a Cross-well reflection survey from borehole X11-4 to X10N3.

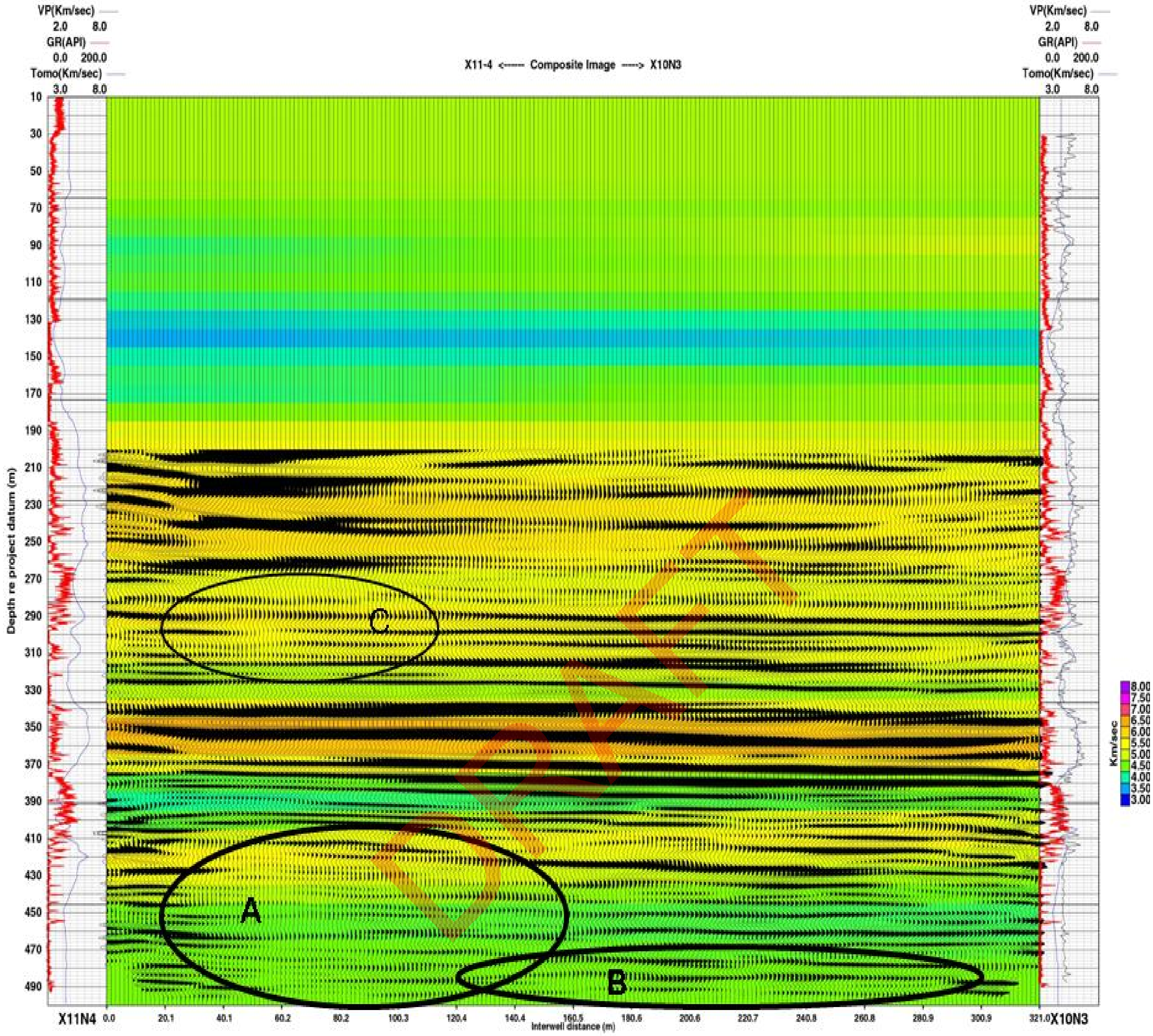

Figure 10b Compare this figure with Figure 10a. Zone "A" of very weak or zero reflection amplitudes extends up through the top of the B-Salt into the C-Shale. Furthermore the A2 Carbonate reflector is very weak or zero over the entire width of this image (areas "A" and "B"). Area "C" is important because it extends through the top of the F-Salt but leaves the base of the F-Salt in tact.

Survey X11-4 to X10N3

In this image we see that the entire A2 Carbonate reflection (areas "A" and "B") has been eliminated or greatly reduced in amplitude. Again, we do not think that the A2 Carbonate has been removed, instead the impinging seismic energy has been scattered before it reached the A2 Carbonate. In Zone "A" the phenomena that has altered the B-Salt has extended slightly into the C-Shale, but not at high up in the C-Shale as seen in the X11-4 to X11-3 image. Again, we see the long, low arching structure in the C-Shale and the reduction in velocity near the X11-4 borehole, but not as great a reduction as seen in the X11-4 to X11-3 survey.

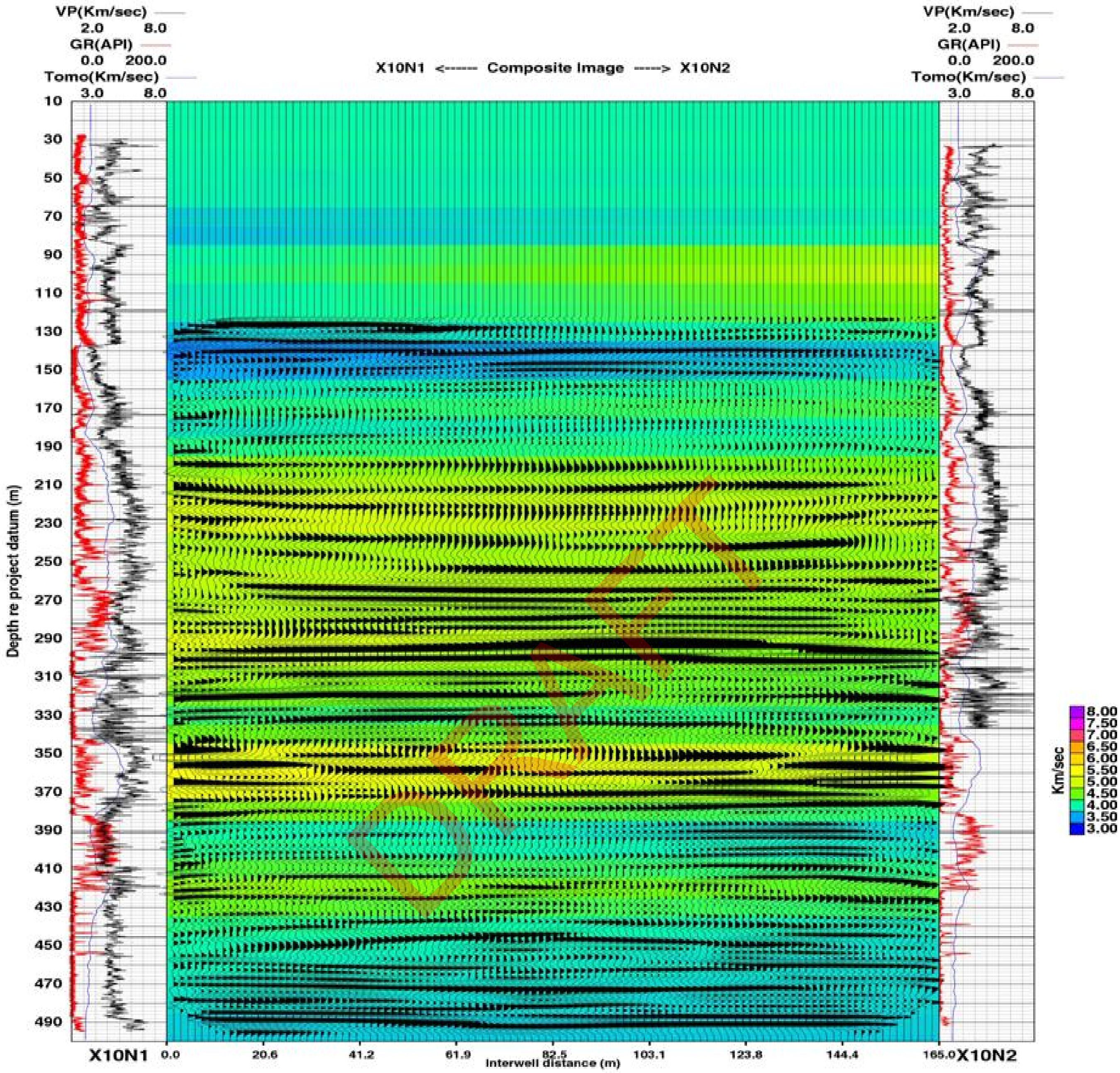

Figure 11a Cross-well reflection survey between boreholes X10N1 and X10N2 in the X-10 corridor.

X10-1 to X10-2 Survey

In this survey it is very difficult to see the top of the B-Salt (Zone "A"), but the base of the B-Salt is intact and a strong reflection is seen from the A2 Carbonate. Area "E" displays a broad arch that appears to involve more than one stringer in its construction. One might say that it "steps" from one stringer to another to create the big anticline.

Zones "C" and "D" are significant because they are along the borehole where a gain has been applied to the data. Despite this gain the reflections in "C" and "D" are weak, indicating that indeed the reflectors there are broken or altered in some manner. Note the strong, clean reflections inside the E-Dolomite and the top of the F-Salt.

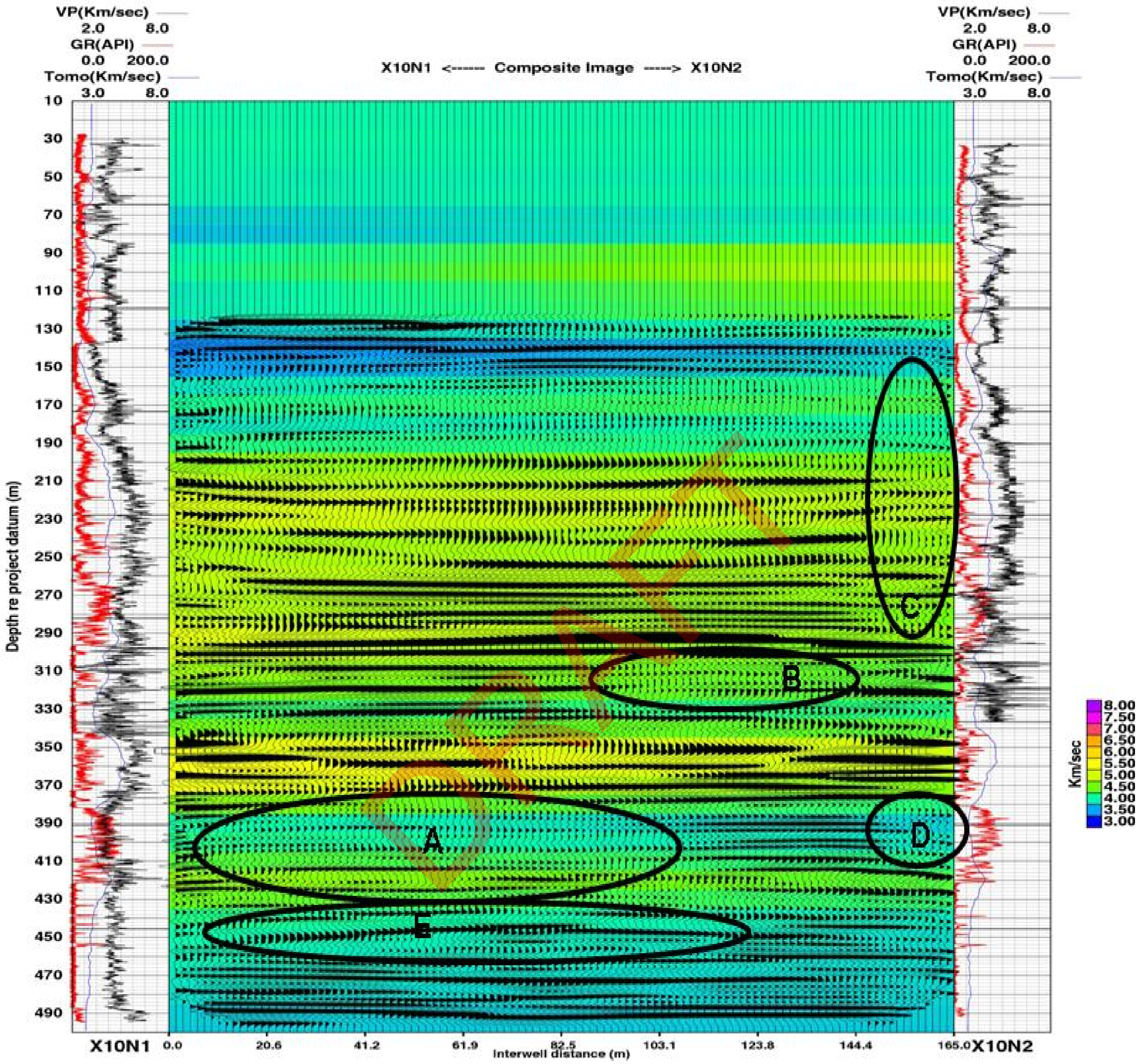

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Figure 11b Compare this figure with Figure 11a. Zone "A" is important because it extends through the top of the B-Salt and into a major portion of the C-Shale. At the same time the bedding plane reflections in the C-Shale are clear and strong between areas "A" and "D".   Zone "B" is significant because it is in the top of the F-Salt but does not go through the top of the F-Salt.   Zones "C" and "D" are important and valid because they are tangent to borehole 10-2 while the reflectors in the E-Dolomite, the base of the C-Shale, and the top of the F-Salt are strong and continuous right up to borehole 10-2.

Zone "B" is important here because the stringers in the F-Salt are broken, especially the thick stringer in the middle of the F-Salt.   However, the top of the F-Salt, although bowed upward it is strong across the image.

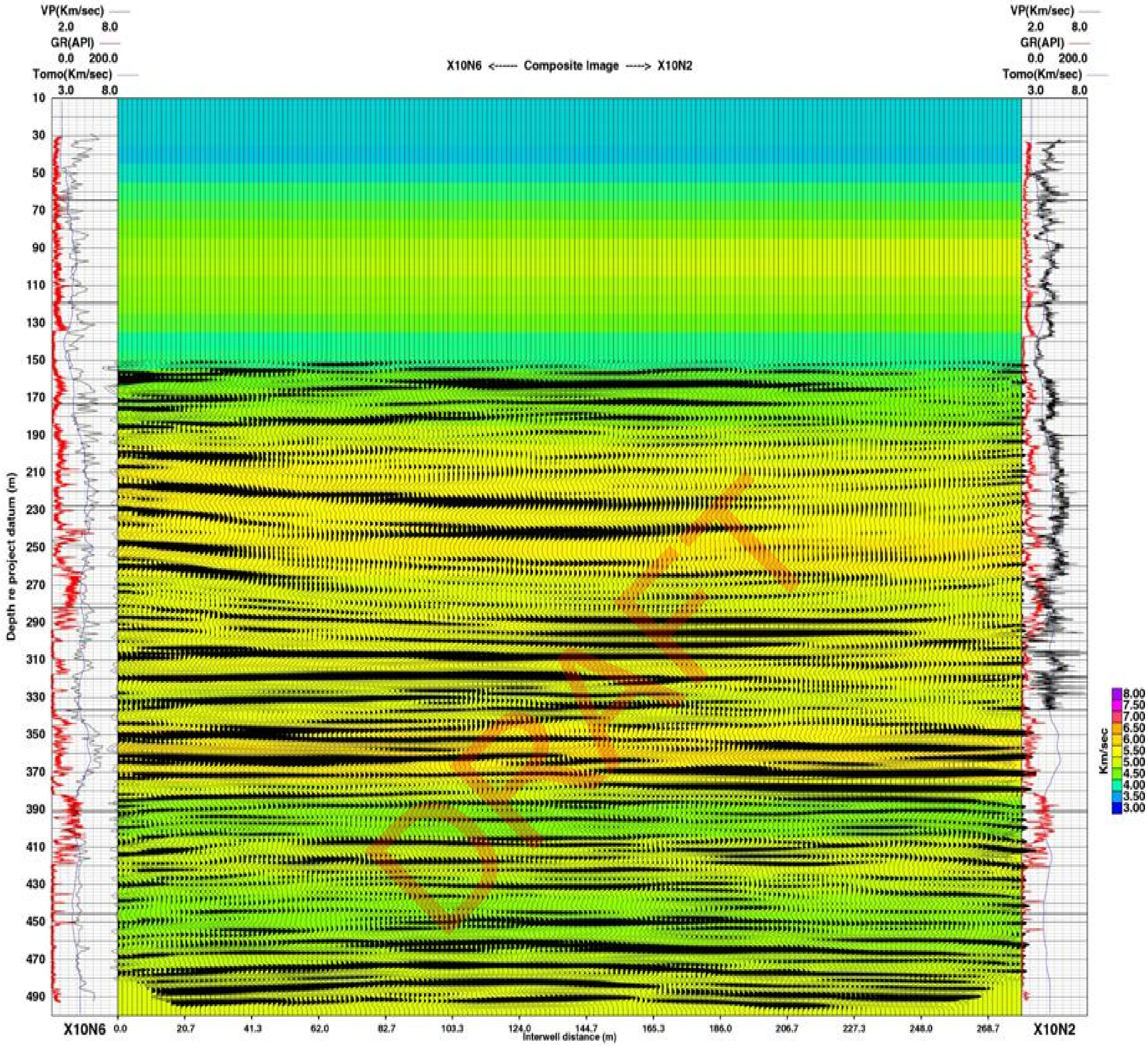

Figure 12a Cross-well reflection survey between boreholes X10N6 and X10N2 in the X-10 corridor.

X10-6 to X10-2 Survey

In this survey we see a major portion of the F-Salt near borehole X10-6 is intact, especially the thick stringer in the middle of the F-Salt formation. However, the very top of the F-Salt there and all of the F-Salt near X10-2 (bottom of zone "A") is altered as seen by the weak reflections. A major slump in the G-Shale and Bass Island Dolomite exists in the middle of the image and towards borehole X10-2

The top of the B-Salt appears to be altered/breached in zones "B" and "C" while the stringers in the base of the B-Salt are strong, clear, and in place. Furthermore, the A2 Carbonate reflection is good except for one fault with very small offset.

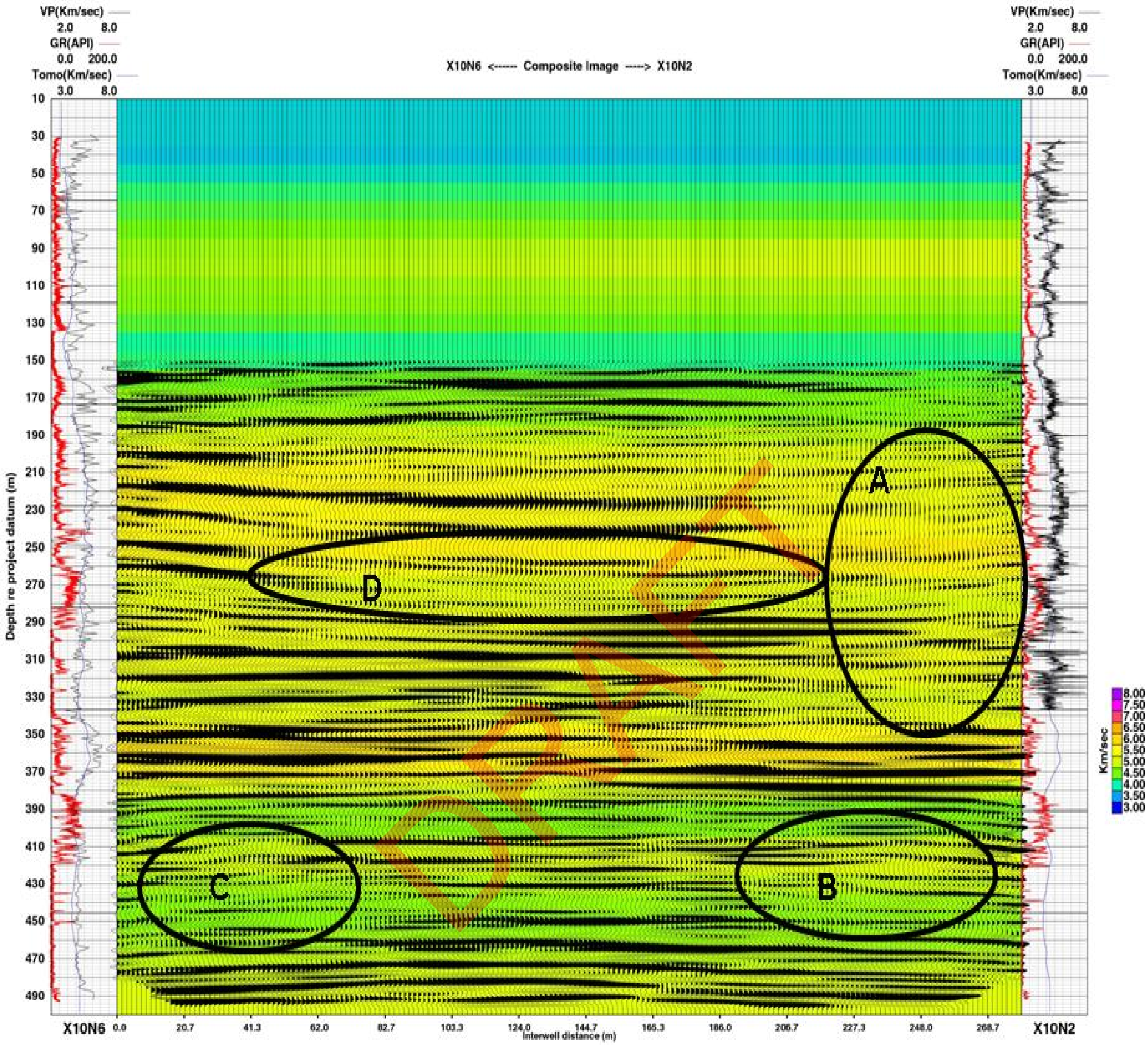

Figure 12b Compare this figure with Figure 10a Zone "A" is a large vertical zone of weak reflections that starts in the F-Salt and propagates upward into the slumped region in the G-Shale and Bass Island Dolomite. These weak amplitudes are real—note the very strong reflections in the E-Dolomite just below area "A". The weak amplitudes in zones "B" and "C" are important because of the small anticline like features also present in each case. Zone "D" is significant because it is connected to area "A" and it is in a slump feature.

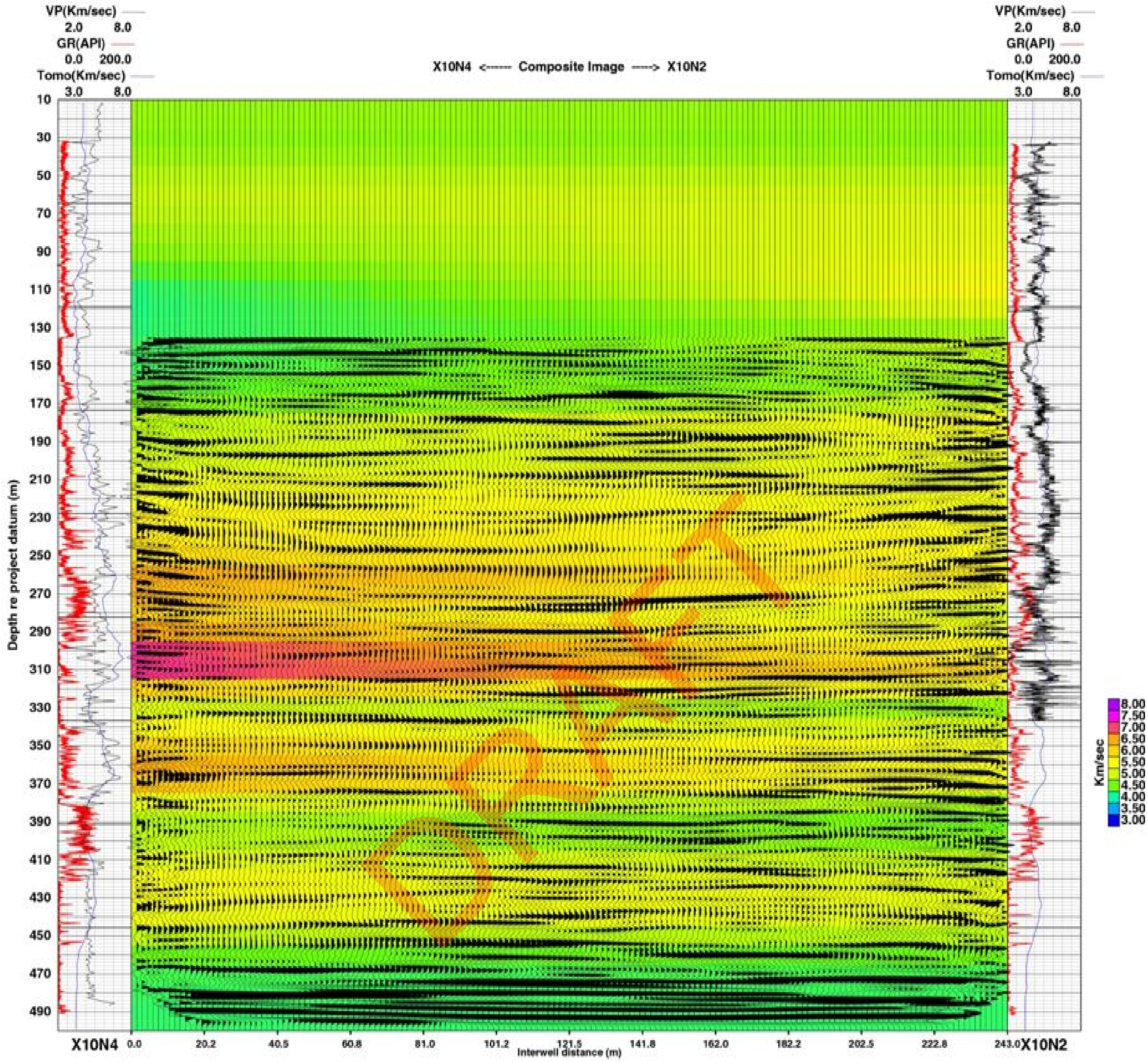

Figure 13a Cross-well reflection survey between boreholes X10N4 and X10N2 in the X-10 corridor.

X10-4 to X10-2 Survey

In this image, near borehole #4 we have lost nearly all of the major reflectors above the base of the B-Salt and the A2 Carbonate. This includes the top of the B-Salt, the C-Shale reflectors the big E-Dolomite reflectors, the F-Salt interfaces, the G-Shale reflectors. But, again the base of the B-Salt and the A2 Carbonate reflector is very clear and strong.

The red, high velocity zone (area "C") is important because it was created by pumping cement into the #4 borehole at the top of the F-Salt when borehole engineering problems occurred. One can see that the sonic log, run before the cement was pumped, did not see the high velocity, but the blue log, a trace through the cross-well tomogram clearly does see the cement.

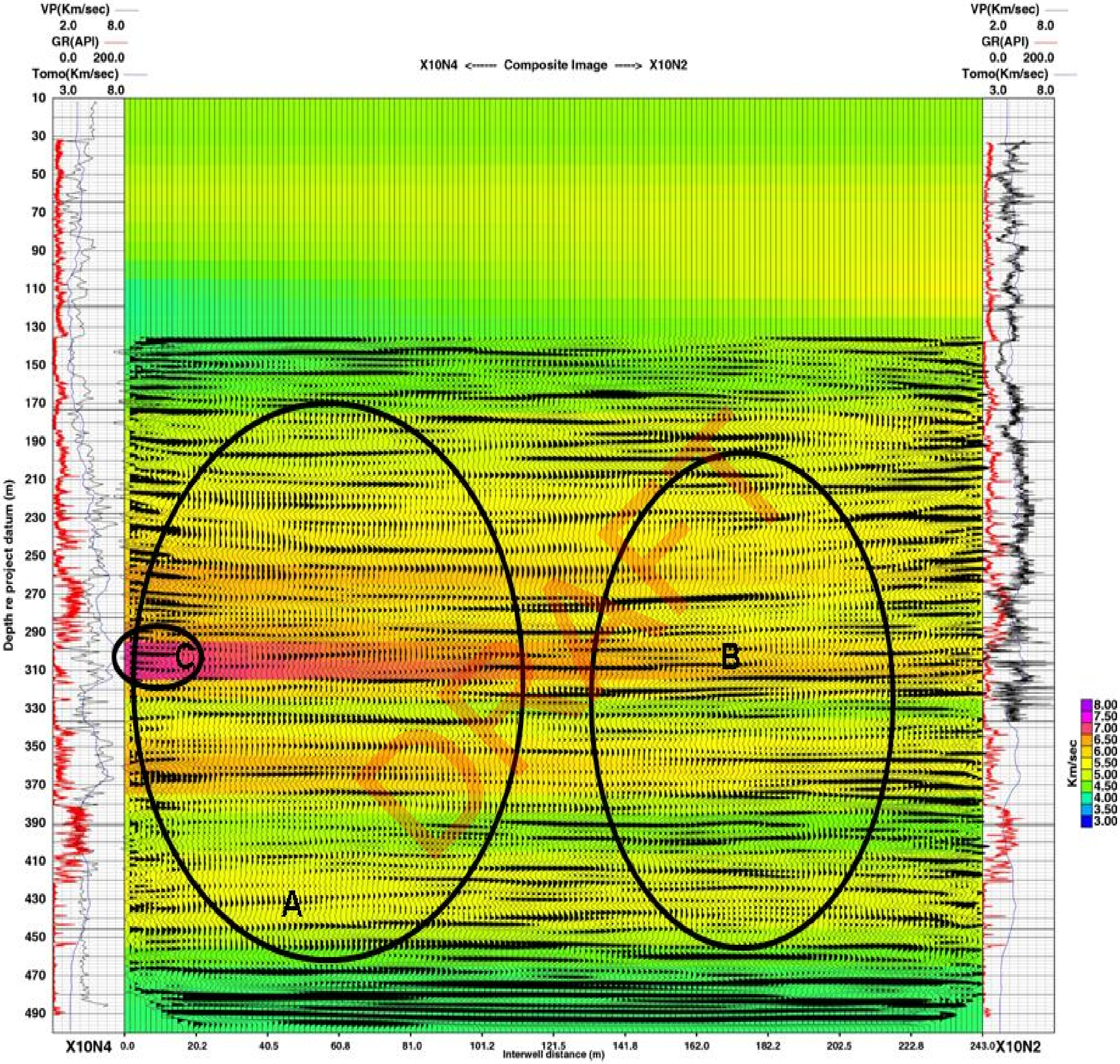

Figure 13b Compare this figure with Figure 13a. All of the major interfaces above the A2 Carbonate and the stringers in the bottom of the B-Salt are missing inside zones "A" and "B". Note in particular that the distinctive reflections from the top and bottom of the E-Dolomite are very weak or non-existent. Area "C" at the top of the F-Salt, the red band fading away from it and the blue and black logs next to it are important because the feature they highlight was created in the course of this project.

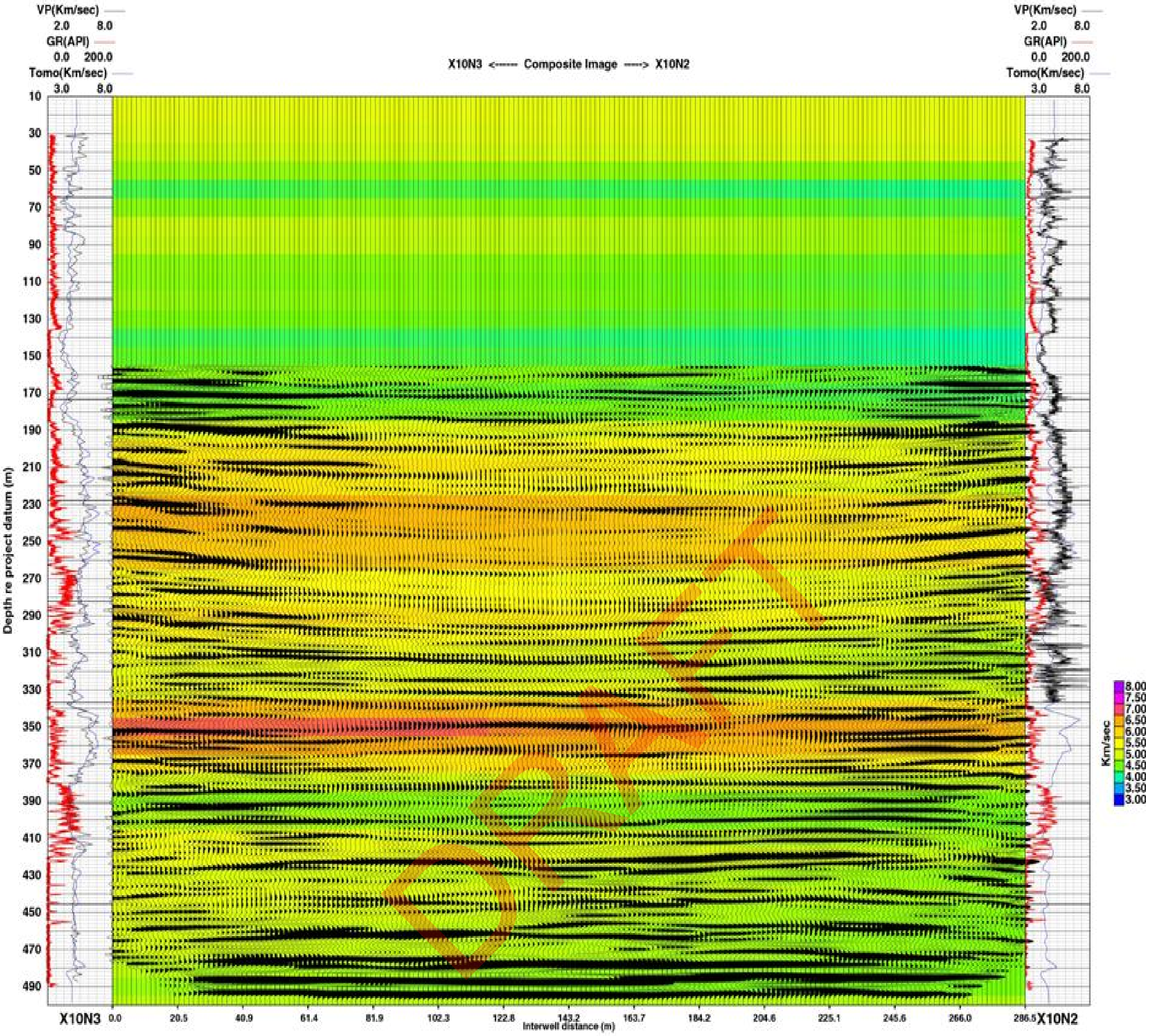

Figure 14a Cross-well reflection survey between boreholes X10N3 and X10N2 in the X-10 corridor.

X10-3 to X10-2 Survey

In this image we, again, see a large slumping zone in the middle of the survey. The stringers in the F-Salt (zone “A”) are present but rather weak and disjoint. The strong reflectors that delineate the E-Dolomite, especially the base of the dolomite are not present. The top of the B-Salt is present and the stringers in the B-Salt are present, but, again, not clear and strong. However, the large-amplitude, flat A2 Carbonate reflection, tuned with the underlying A2 Evaporite is present Zone “B” although less significant than “A” does highlight an area of generally low amplitudes in the B-Salt, next to the X10-3 borehole. These low amplitudes are valid because we see much larger amplitudes up hole which have experienced the same processing gain.

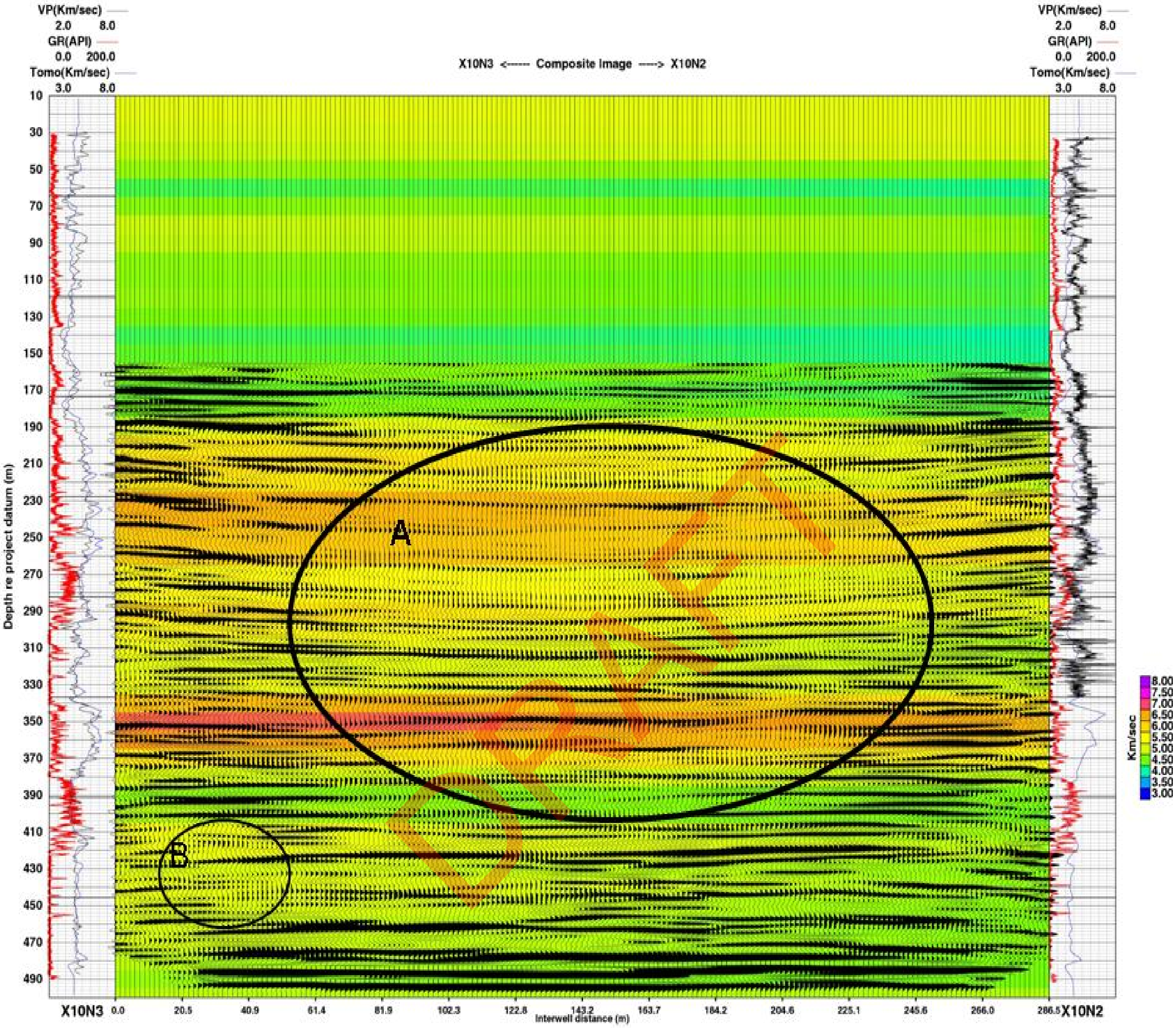

Figure 14b Compare this figure with Figure 12 a. Zone "A" is significant because it is encompasses weak reflections from the C-Shale, through the E-Dolomite and F-Salt into the overlying G-Shale and Bass Island Dolomite. Moreover there is a slumping nature to the F-Salt stringers, G-Shale and the Bass Island Dolomite. Area "B" is indicated by a light, thin circle because it is less significant than "A" but it does point out a feature that breaches the top of the B-Salt.

Conclusions

Many of the surveys in both the X-10 and X-11 corridors produced high-resolution images of very unremarkable, Michigan Basin geology. Clear, strong, high signal to noise ratio reflections were obtained from the internal features of all formations as well as their tops. Large and small stringers inside the salt formations, bedding plane reflections from inside shale layers, and details inside the dolomites were seen so consistently that they can be used as markers and standards of measurement in other images.

Other images in both the X-10 and X-11 corridors displayed dramatic differences from those mentioned above. When placed in juxtaposition the differences are especially clear. In several surveys the stringers in the B-Salt were very difficult to see and the underlying A2 Carbonate reflector was missing or very weak. In other surveys the zones of weak reflections extended upwards into the C-Shale and in one case (X11-4 to X11-3) the zone reached the base of the D-Salt. In this image we also saw an obvious drop in velocity at this spot in the C-Shale.

Other images showed large zones of weak reflections from the F-Salt and E-Dolomite while in the same image the B-Salt produced its usual set of stringers as well as the clear and strong A2 reflection.

We also saw low, arch-like features that could be reflections from cavity roofs, they were never accompanied with major drops in velocity. The small, low velocity feature, mentioned above, in the X11-4 to X11-3 survey was . This anomaly is close to a borehole therefore borehole gravity measurements would constrain the feature more tightly than seismic measurements alone.

What could these big zones of weak reflections be? It is suggested here that they are zones of broken interfaces—broken in such a manner that a reflector becomes a scatterer of energy. This is not proven here, although studies of the frequency content of the weak reflections could provide additional constraint on this answer. For relatively thin anomalies it is clear that seismic energy can propagate through such features and yet image, very clearly, layers beneath the anomalies. For large zones of weak reflectors it is possible that the base of the zone is in fact artificially produced (i.e. incorrect) by the scattering of the seismic energy on the way down from the source and again on the way up to the receivers. This is not proven here.

Some surveys, especially X11-3 to X10-3 and X11-3 to X10-3, and X10-6 to X10-2 encountered large zones of scattering, so large that the entire image, above the B-Salt and beneath the Bass Island and Bois Blanc are weak and faint. When large amounts of gain are applied to these images the result is an image of scatterers. Additional processing is required here to allow one to properly tie these images to intersecting images. That is being done now.

Topics Needing Further Study

The uniformly low velocity in the X10N1 to X10N2 survey must be examined.
The low velocity and low reflection amplitude feature, near the X11-4 borehole in the X11-4 to X11-3 survey, and (to some extent) in the X11-4 to X10N3 survey must be studied.
Media which partially reflect/scatter high-frequency seismic energy