3-D seismic attributes

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ABSTRACT

Attribute analysis of 3-D seismic data in time slices presents a great opportunity for reservoir characterization. The interpretable information of the 3-D seismic data can be enhanceded with complex seismic trace attributes. The correlation between various P-wave seismic attributes and lithology has been used for some time, however, the multicomponent seismic techniques promise augmented development. Two examples are presented: the Sierra Devonian carbonate gas play in northeast British Columbia and the Blackfoot Cretaceous sandstone oil play in Alberta. Landmark and Photon interpretive systems were used as well as Matlab and ERmapper applications.

INTRODUCTION

A typical seismic interpretation workstation displays the seismic data in vertical, horizontal and arbitrary crossing planes as images. The horizontal section is called a "time slice". In the process of seismic interpretation the geophysicist uses the seismic workstation to map seismic anomalies correlating them with geological settings in the subsurface. The seismic interpretation carried out on workstation is materialized in attribute anomaly maps of predicted oil and gas reservoirs in the subsurface.

In this paper, we present an approach to derive from the seismic trace attributes lithological information pertinent to hydrocarbon reservoir. After a short review of the seismic reflection aspects related to the complex seismic trace, for 3-D seismic data, we discuss the potential of the seismic attribute time slice to characterize the hydrocarbon reservoir.

Examples from a 3-D seismic set shot over the Sierra Devonian carbonate gas field in NE British Columbia and a 3C-3D seismic data set acquired over the Blackfoot Cretaceous sandstone oil field in Alberta illustrate our results.

After considerable analysis, the interpreted seismic attribute (two-way time, isochron, interval velocity, amplitude strength, instantaneous phase, instantaneous frequency, etc.) may contain the geological information necessary to uncover the subsurface anatomy, to detect the "reservoir anomaly". The reservoir is usually mapped and characterized by comparison and/or calibration to previous similar cases. Seismic calibration is based on well data (if exists) and previous experience, either one's own or from the literature.

The processed seismic data set encodes the geological information from subsurface boundaries between media with different acoustic impedance. The bandwidth of the seismic signal and processing approximations limit the subsurface resolution thus challenging the seismic interpreter. Numerous techniques as seismic inversion, AVO, coherency processing have developed to extract geological information from the seismic data, to decipher the subsurface geology, to uncover and evaluate commercial deposits of hydrocarbons.

From the original seismic data, new seismic attribute volumes are processed and time slice sets constructed. In time slice display, lithological lateral variations may be easier identified as the sedimentation develops horizontal. Computation in the time slice plane may well enhance lithology distributions patterns without a prior knowledge of velocity and/or density.

METHODOLOGY

The reflection seismic amplitude is an attribute related to the physical properties of the subsurface as a function of the reflectivity at the acoustic boundaries:

$$A = A(\rho, V_p, V_s, \theta, t)$$

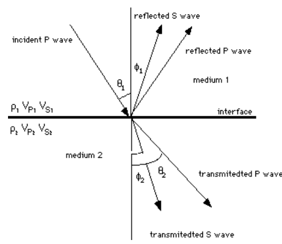


Figure 1 Principle of energy partition at an elastic interface.

$$p = \frac{\sin\theta_1}{V_{P1}} = \frac{\sin\theta_2}{V_{P2}} = \frac{\sin\varphi_1}{V_{S1}} = \frac{\sin\varphi_2}{V_{S2}}$$

with ρ (density), V_P (compressional velocity) and V_S (shear velocity) important lithological identifiers. Numerous relations have been developed to calculate from seismic velocities rock properties as porosity, fluid saturation, lithology, etc. Without neglecting these important contributions of, we try to relate the same rock properties to seismic attributes as they are defined by Bracewell (1965) and Tanner (1976).

The complex seismic attributes: reflection strength (RS)

$$A = |F(t)|\ ,$$

instantaneous frequency (IF)

$$\omega(t) = d\theta(t)/dt\ ,$$

and instantaneous phase (IP)

$$\theta = \tan^{-1}[f(t) / f^*(t)]\ .$$

These attributes completely characterize the complex seismic trace

$$F(t) = f(t) + j f^*(t)$$

with the real seismic trace

$$f(t) = A(t) \cos\theta(t)$$

and imaginary seismic trace (the Hilbert transform of the real trace)

$$f^*(t) = A(t) \sin \theta(t) .$$

The complex seismic trace attributes are found in some instances to correlate with lithological changes and historically have been used to characterize hydrocarbon reservoirs. All the seismic attributes should be considered and evaluated simultaneously. The 3-D seismic technique allows for a better understanding and use of these parameters as lithology changes develop spatially.

An assumption is made that any lithology change has a seismic response which might or not be directly measurable by seismic attributes of the compressional data. For the multicomponent seismic data there is higher chance that at least one attribute is sensitive with that change. The seismic attribute analysis consists in defining that set of attributes being sensitive to lithological variation affecting the reservoir rock hosting properties: lithology, pore volume, permeability and water saturation.

In our case studies, we find that the instantaneous frequency seems to be sensitive to reservoir lithology. The thick slice technique, the sum of selected attribute slices, needs geological refinements to accurately interpret lithological changes.

The seismic attribute computation is implemented on all current seismic workstations and is straightforward. From the attribute volume time slices are constructed unflattened or flattened on stratigraphic markers. Amplitude extraction and horizon computation is performed on the attribute 3-D volume. 2-D filtering prior computation is performed in Matlab or Ermapper environments to enhance the output. The advantage of the ERmapper is that we can interactively select the number of inputs and customize processes individually; lowpass, highpass and median filters are easy to be applied in the ERmapper environment.

In the relation

$$V_P / V_S = 2\, T_p / T_s - 1$$

we substituted T with the corespondent seismic attribute value and generated ratio maps comparable to the isochron ratios. Different ratios were compared with the P-P and P-S isochron ratios and we find the instantaneous frequency correlating well. The amplitude envelope ratio is also correlatable but we prefer the instantaneous frequency.

With isochron and seismic attribute time slice inputs reservoir character map are produced. The following examples illustrate our approach.

SIERRA 3-D SURVEY

The Sierra gas field is one of the largest gas accumulations in Western Canada located in northeast British Columbia, 80 km east of Fort Nelson. Gas is produced from the Upper Keg River carbonate buildup.

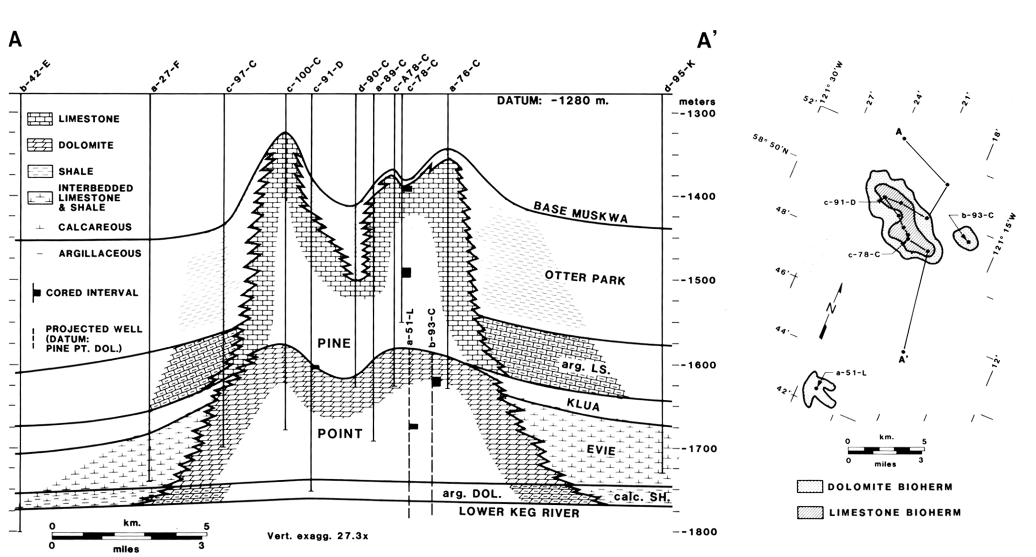


Figure 2. Structure-section and location map depicting the dual lithology of the Sierra reef complex.

The field was discovered in 1966 with c-78-C/94-I-14 and eight development wells have been drilled to dat to exploit the field. In 1989, Mobil Oil Canada acquired a 3-D seismic survey to assist in the development work and identify new drilling locations. The Middle Devonian Sierra buildup is a reef complex part of a cluster of bioherms in the Otter Park shale basin. These bioherms developed from paleohighs on the Lower Keg River platform. The Sierra structure lies 1400 m sub sea, has an ellipsoidal shape (7 km in NW-SE and 3 km in SW-NE direction) with 250 m of Slave Point tight limestone overlying 150 m of Upper Keg River dolomite (Collins and Lake, 1989). The reservoir rock is a secondary dolomite with 10% porosity and a maximum 83 m pay above the gas-water contact measured at -1656 m. Interval velocities for the dolomite are in the range of 5500 m/s. The estimated gas reserves in place are 2 Tcf with 1.2 Tcf produced to date. Average well production is 10 MMcf/day with 35 m^3 water cut.

The 3-D seismic data set was donated to the University of Calgary by Mobil Oil Canada. We created a set of three attribute volumes: amplitude envelope, instantaneous phase, and instantaneous frequency. The amplitude envelope and instantaneous phase are used tools for correlation and stratal evaluation. The instantaneous frequency correlates with the porous dolomite and could be a potential indicator for dolomite / limestone content. A set of thick instantaneous frequency at the limestone/dolomite interface (1200 ms) was calculated to assess for pore volume within the buildup.

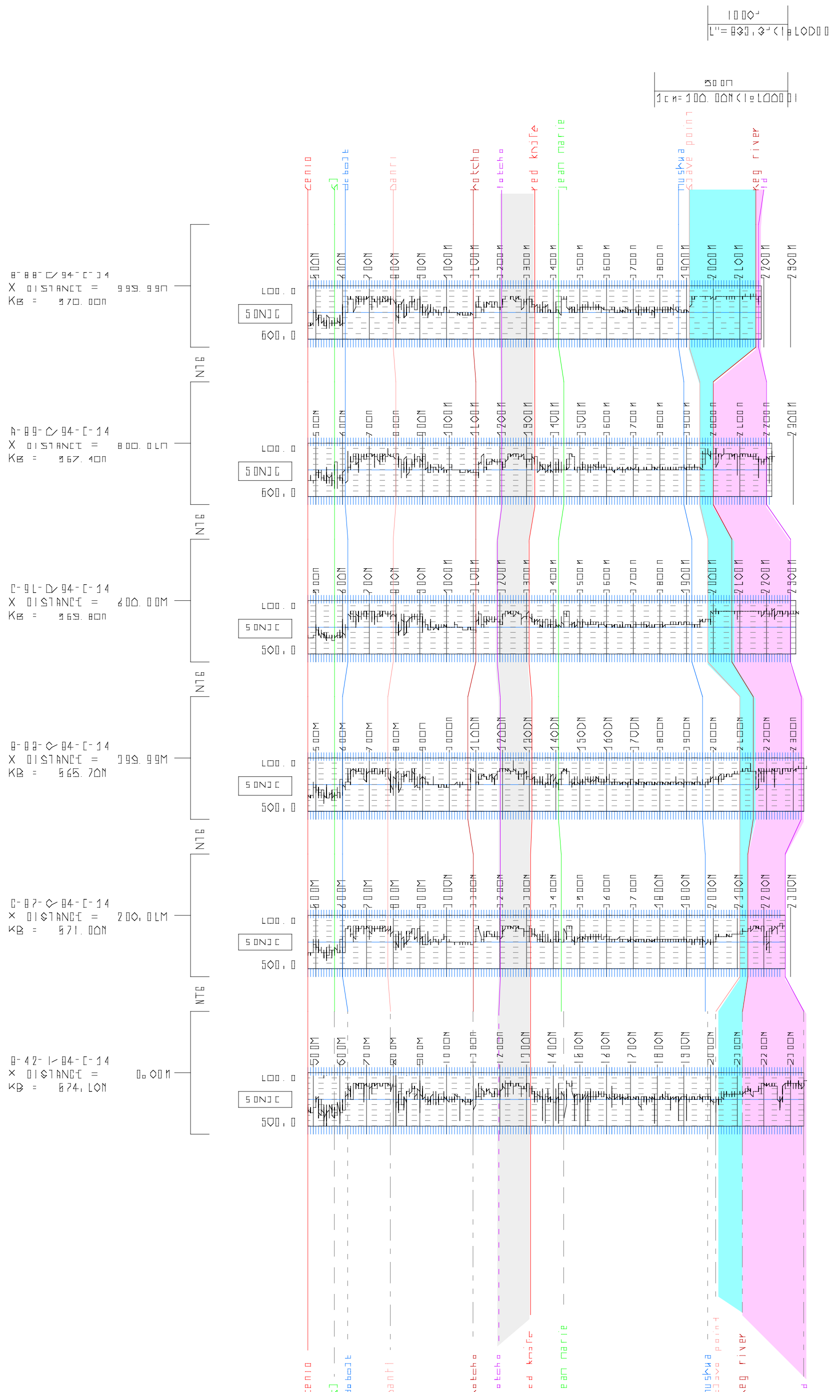


Fig. 3 Sierra reef:well cross section

In Figure 2, a geological cross section depicts the nonporous Slave Point limestone cap overlying the Keg River dolomite. In Figure 3, a sonic cross section duplicates the geological section in Figure 2, and shows the acoustic response of the Sierra reef dual lithology.

In Figure 4 to 13, a set of IF time slices, from the 1150 ms - 1500 ms interval, illustrates the limestone and dolomite signature.

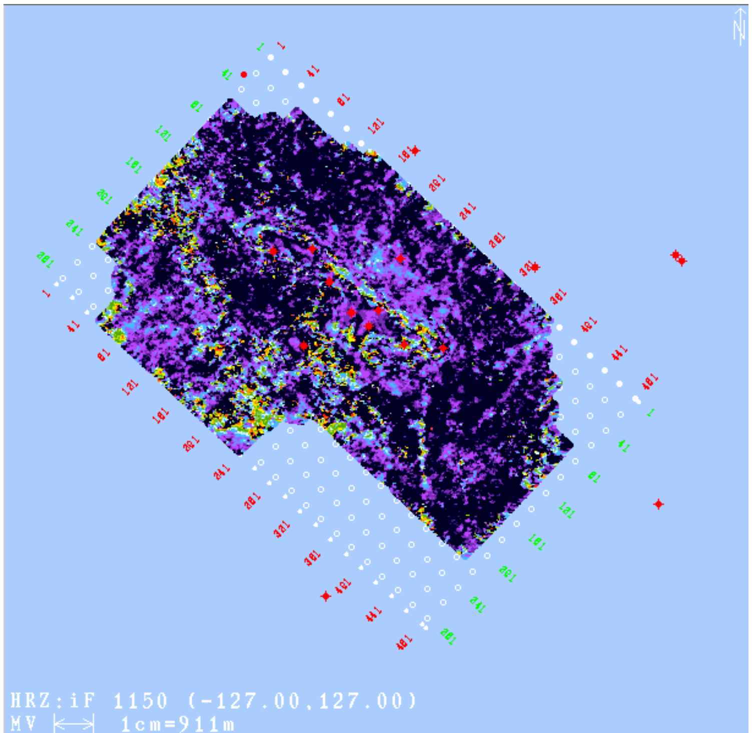


Figure 4. Sierra instantaneous frequency at 1150 ms

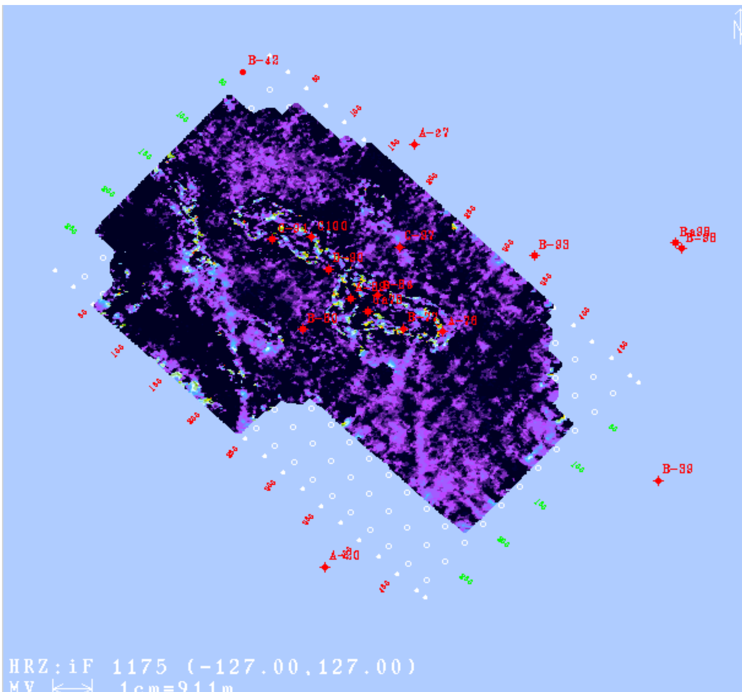


Figure 5. Sierra instantaneous frequency at 1175 ms

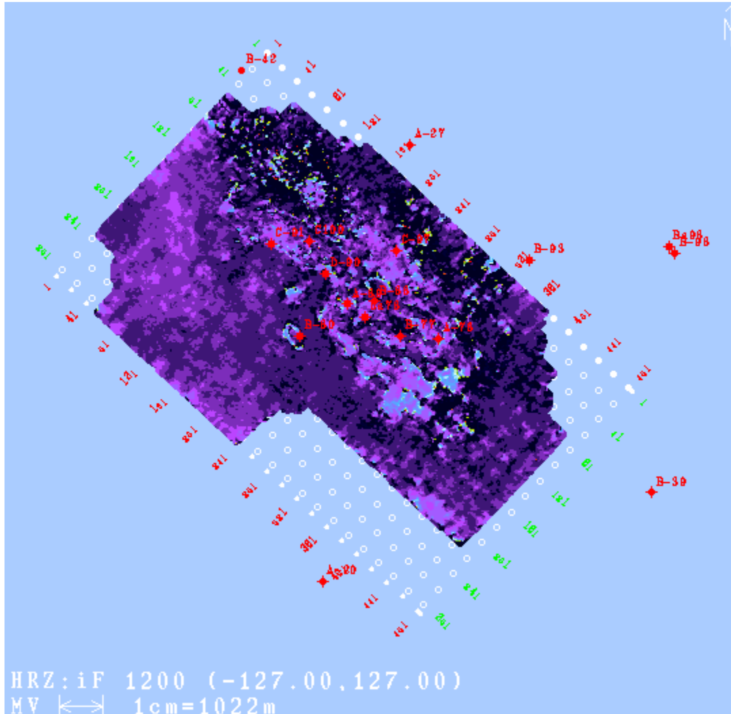


Figure 6. Sierra instantaneous frequency at 1200 ms

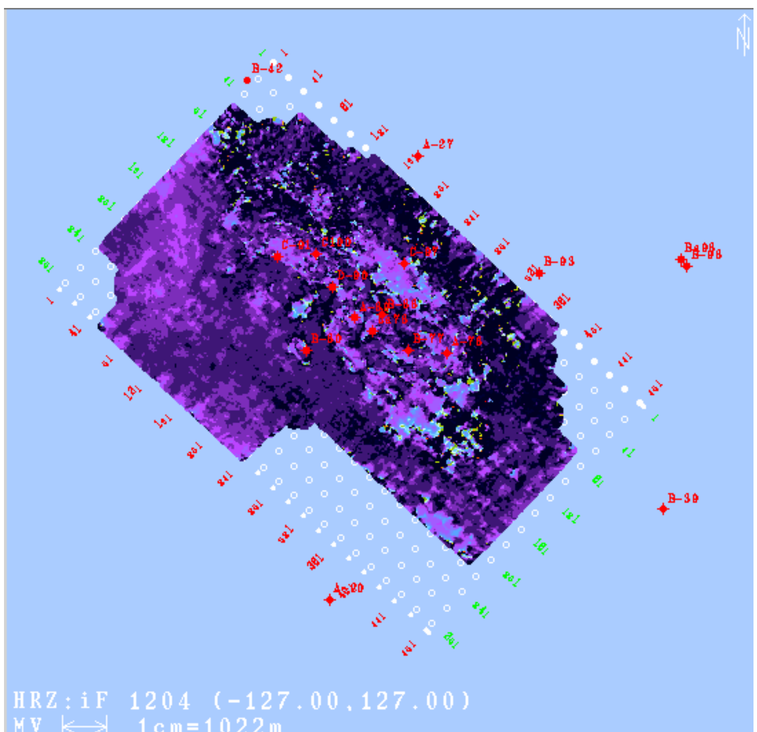


Figure 7. Sierra instantaneous frequency at 1204 ms

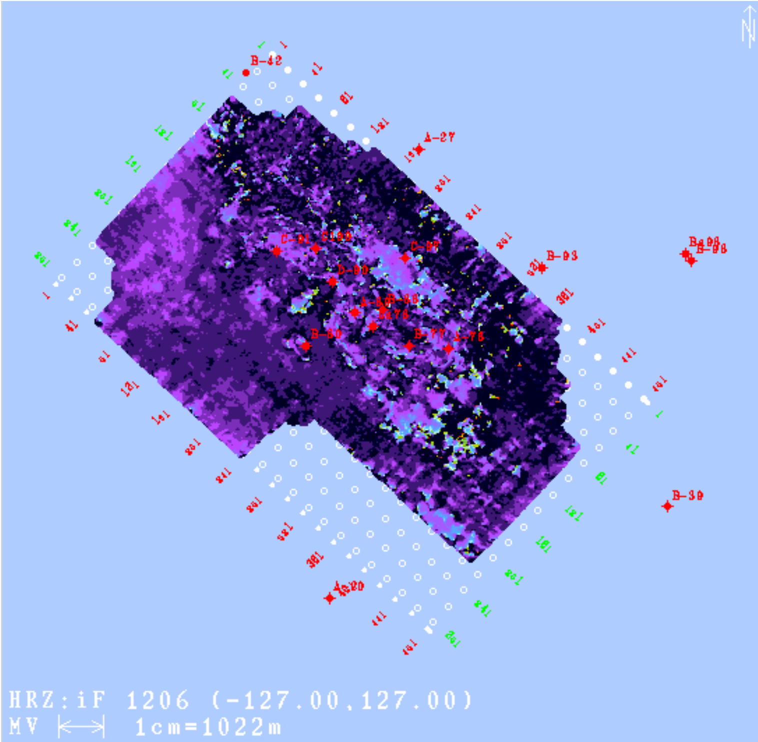


Figure 8. Sierra instantaneous frequency at 1206 ms

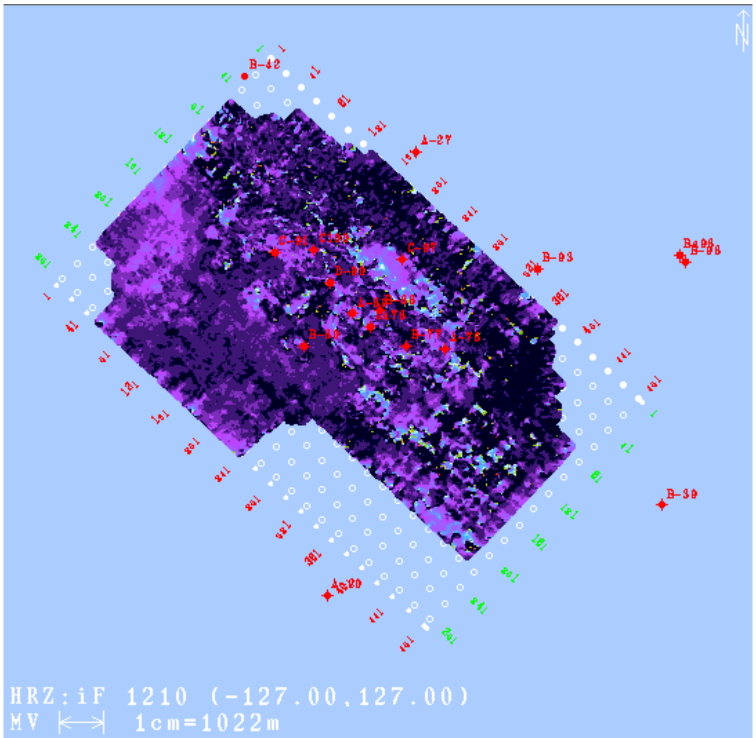


Figure 9. Sierra instantaneous frequency at 1210 ms

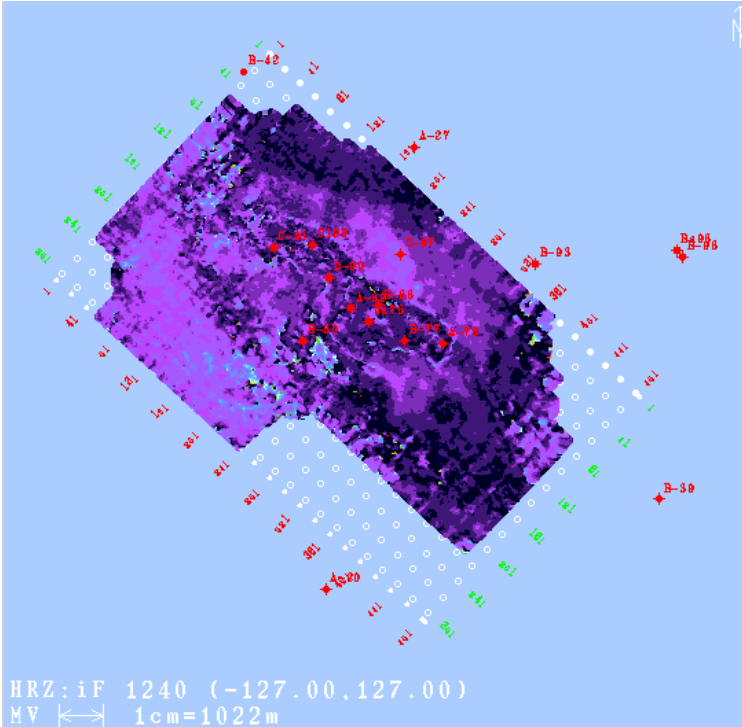


Figure 10. Sierra instantaneous frequency at 1240 ms

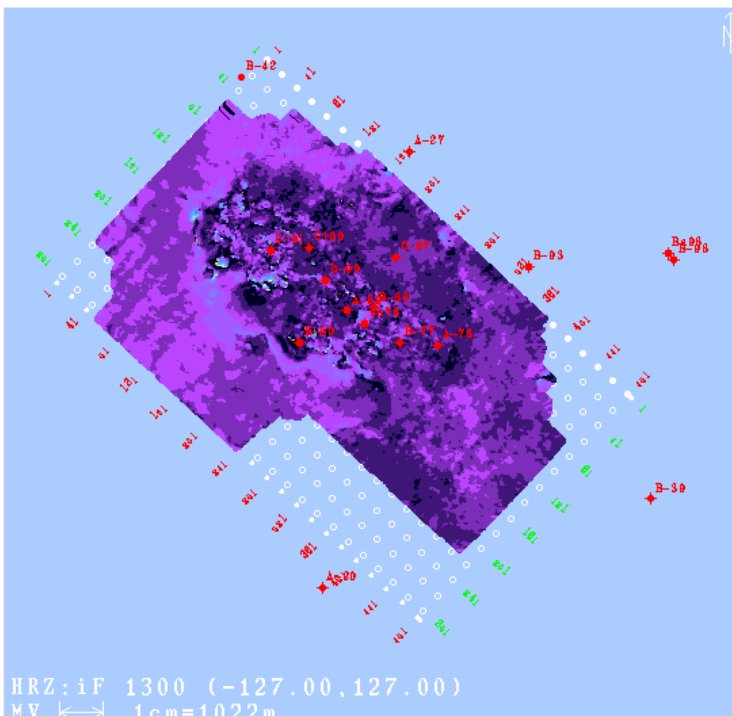


Figure 11. Sierra instantaneous frequency at 1300 ms

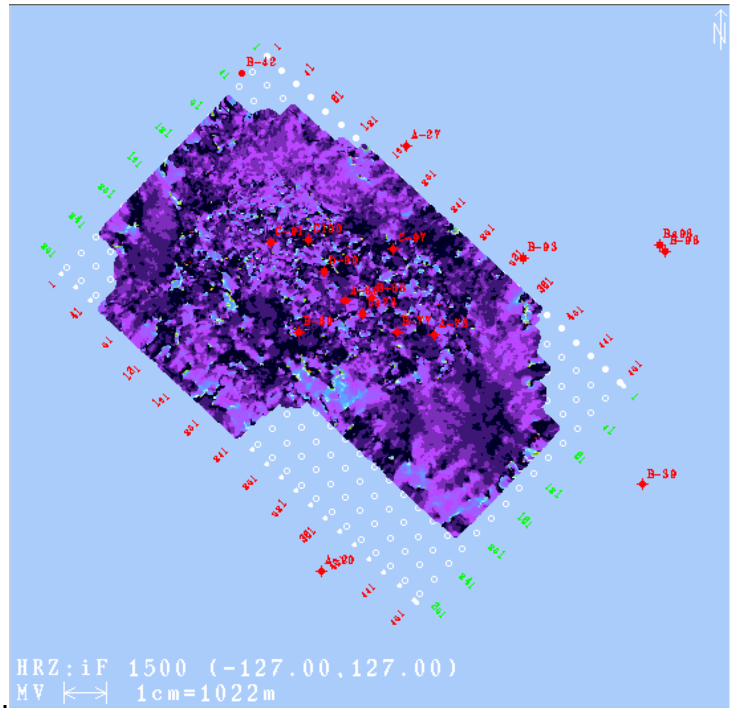


Figure 12. Sierra - instantaneous frequency at 1500 ms

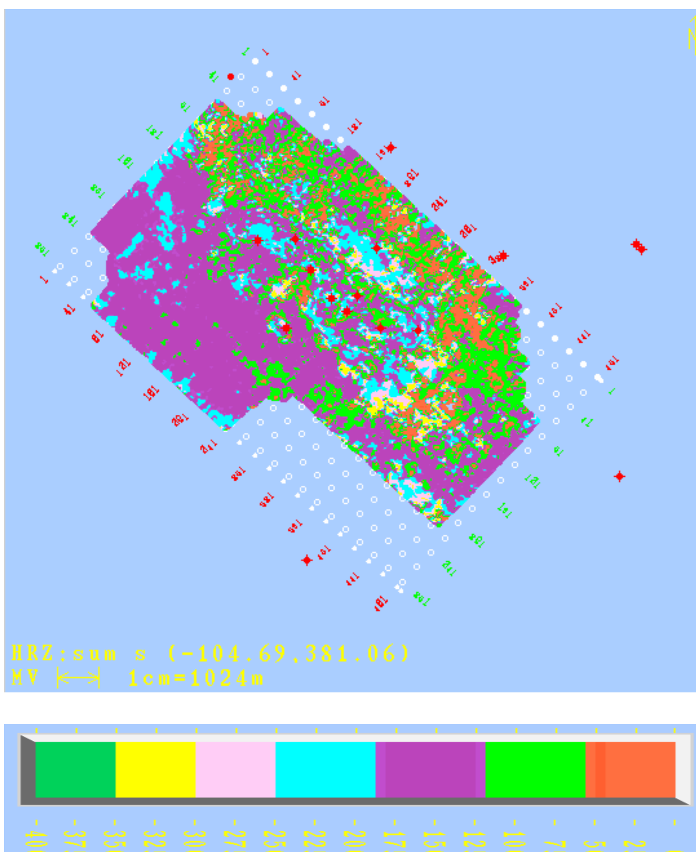


Figure 13. Sierra instantaneous frequency sum: 1200 ms to 1212 ms.

The instantaneous frequency value and the texture of the time slice are characters we will analyze. The IF time slice also enhances tectonic features otherwise masked on the conventional time slice displays. Figure 4, 5, are IF time slices displaying the Slave Point limestone and Otter Park shale lithologies. The shale/limestone contact is sharply defined wiyh the exception of the north site where the Slave Point limestone might interfinger with the Muskwa and Otter Park shales. Observe two faults crossing the Sierra reef.

Figure 6 is the instantaneous frequency slice tangent at the dolomite structure as estimated from well data. The dolomite appear present at several locations indicating random occurrence. The image texture change with the change of the instantaneous frequency value. The light areas suggest limestone as it appears mapped on the shallower slices. In the south central part a circular feature is observed on all subsequent slices, Figure 7, 8, 9 and 10. This represent a pinnacle reef, tested in 1990 by Mobil Oil with b-80-C / 94-I-14 well. In Figure 11 the instantaneous frequency slice beneath the reef, delineates a large elliptical shadow, an observation mention in literature for large gas reservoirs (Tanner, 1976).

At 1500 ms on the verical seismic sections there are still correlatable reflections but the IF slice displays little variation.

The instantaneous frequency slice in Figure 13 is a sum of seven (1200 ms to 1212 ms) instantaneous frequency slices. The summation was performed to evaluate the correlation, if any, between the dolomite content and IF. Two distinct circular regions can be contoured on this figure. We are favorable to the idea of interpreting this areas as higher dolomite content than the surrounding localities.

BLACKFOOT 3C-3D SURVEY

The Blackfoot area Twp 23, R 23 W4M located 15 km southeast of town of Strathmore, Alberta is explored for Lower Cretaceous incised valley channel sandstone reservoirs. The fluvial / estuarine Glauconitic Formation deposits range from sandstone to shale distributed in a braided channel system with a northwesterly drainage.

A type Glauconitic sandstone reservoir is found at 600 m sub sea level depth, has an average thickness of 40 m, length of several kilometers and width of 200 m. Porosity varies 0 % up to 30%. The interval velocity in clean sandstone is 3900 m/s. The Blackfoot area has hydrocarbon reserves in place in excess of 400 MMbbl oil equivalent.

Exploration work conducted by PanCanadian area discovered in section 8-23-23 W4M a NS a Glauconitic channel. P-P 3-D seismic data was acquired to support further exploration and development activities here. Subsequent drilling revealed the complexity of the Glauconitic channel and the of the seismic response ambiguity with lithological variations affecting the reservoir porosity. A reliable exploration tool is desired to more accurate predict Glauconitic reservoir porosity.

The Blackfoot Seismic Project conducted, with the industry participation, a 3C-3D seismic survey in T23 R23 W4 to try 3-D multicomponent seismic technologies for subtle Glauconitic sandstone exploration. Over 20 wells drilled in the area covered by this seismic survey provide reasonable depth control.

From the seismic data processed at Pulsonic, Calgary, six attribute 3-D seismic volumes were created: amplitude envelope, instantaneous phase and instantaneous frequency. As analysis of the Blackfoot data is an ongoing CREWES project at Department of Geophysics, University of Calgary, we will discuss the aspects pertinent to the relation between the seismic attributes and the Glauconitic channel signature.

We research the seismic attribute sensitivity to lithology. A set of two-way-time, isochron and attribute maps for the compressional (P-P) and converted (P-S) data sets are presented to illustrate our results.

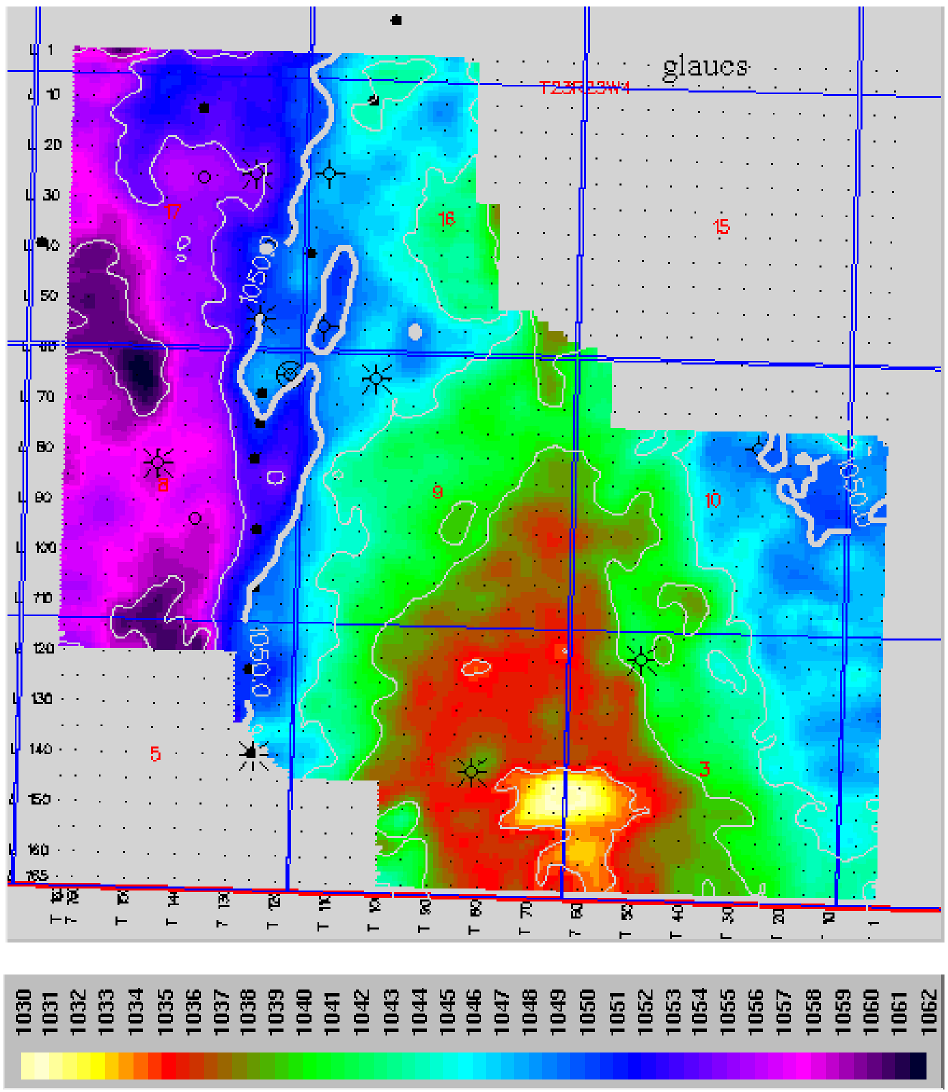


Figure 14. Blackfoot 3C-3D P-P data. Glauconitic - Two-way time map.

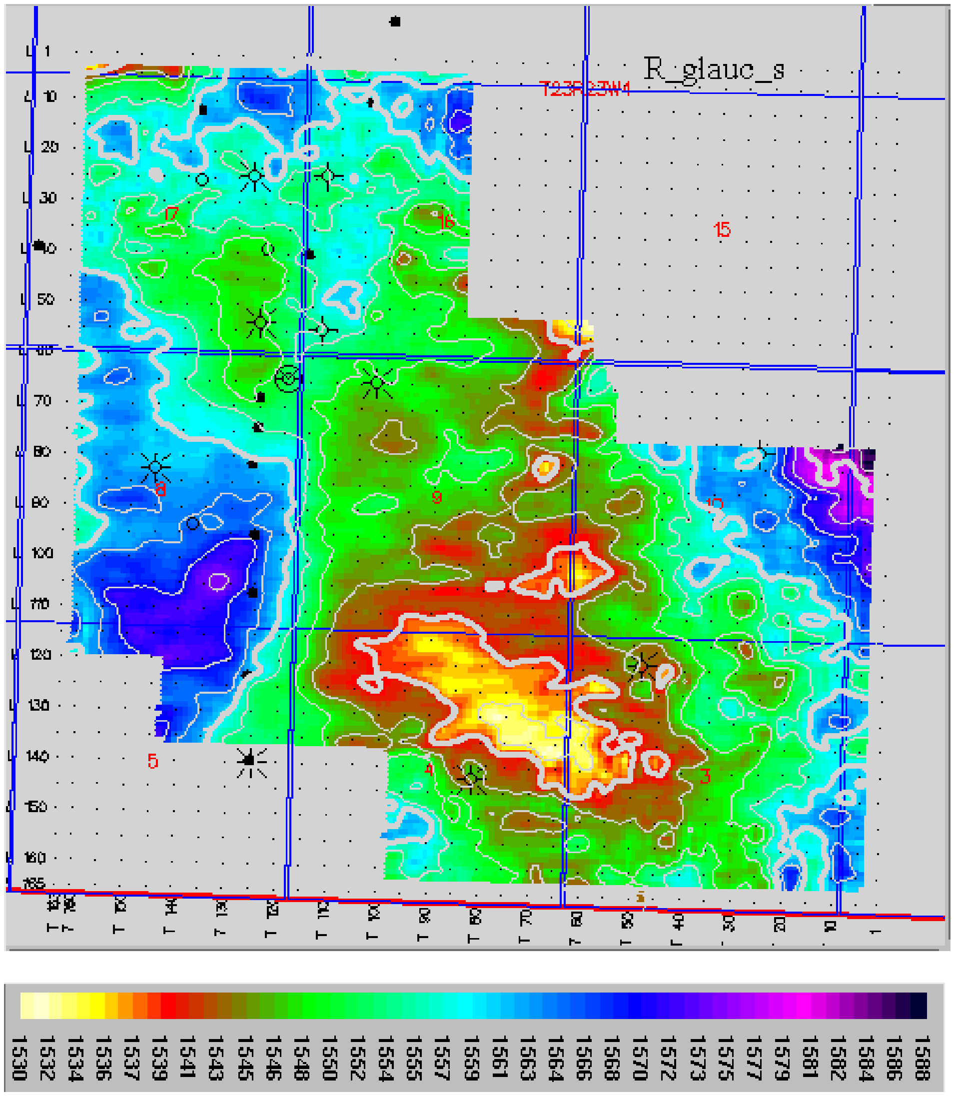


Figure 15. Blackfoot 3C-3D P-S data set. Glauconitic - Two way time map.

The Glauconitic two-way time maps Figure 14, 15 are comparable with the exception of the NW quadrant (section 17-23-23 W4M).

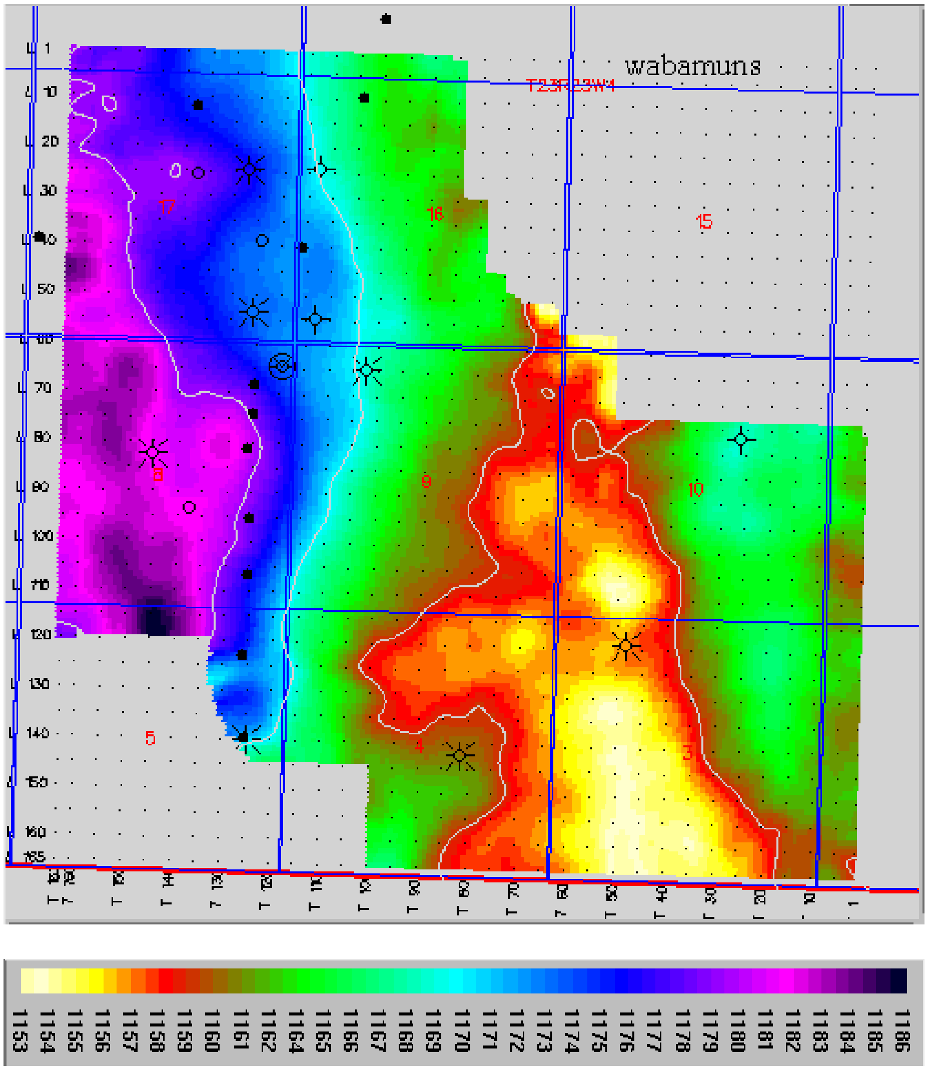


Figure 16. Blackfoot 3C-3D P-P data set. Wabamun - Two-way time map.

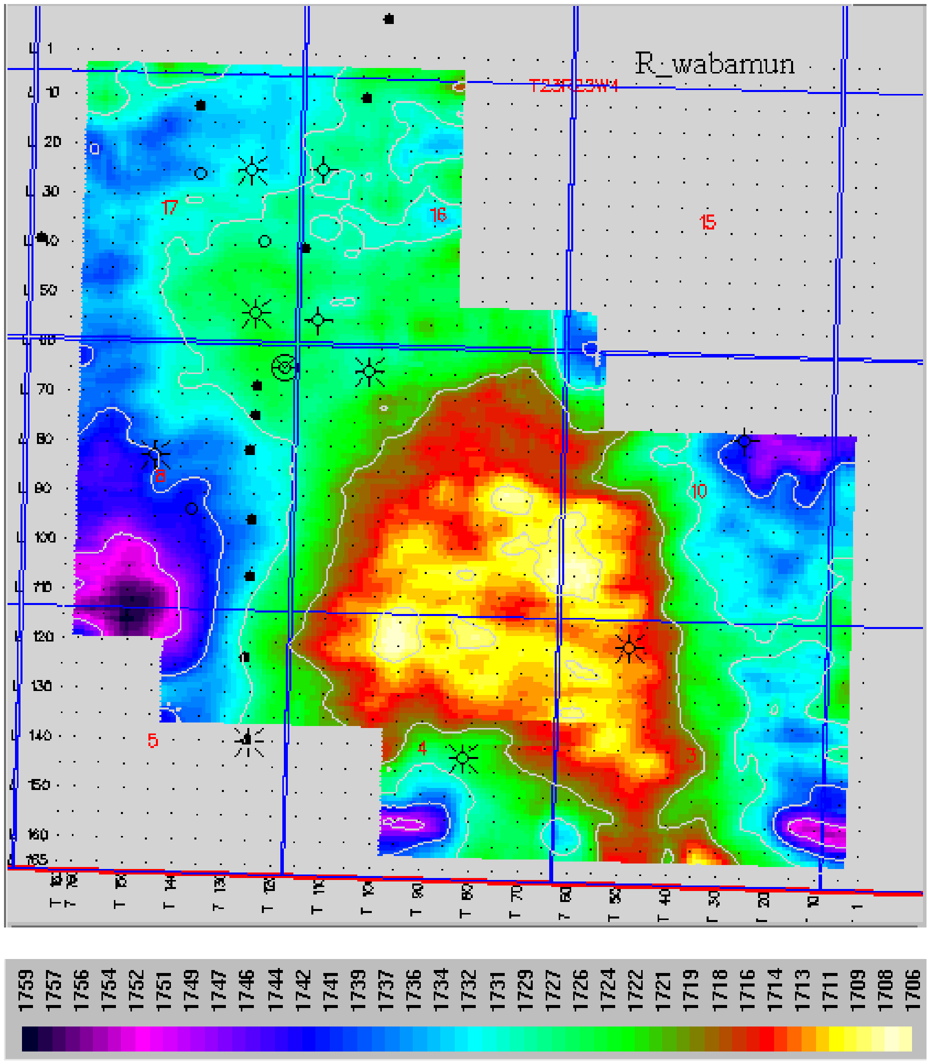


Figure 17. Blackfoot 3C-3D P-S data set. Wabamun - Two way time map.

The Wabamun P-P and P-S two-way time maps, Figure 17, 18, display a major differences in the NW part of the map similar to those observed for the Glauconitic two-way time.

The P-P and P-S data was acquired to identify Glauconitic channels with higher confidence as the sand/shale seismic velocity ratios differentiate between the two lithologies.

The isochron value Glauconitic - Wabamun is considered to be affected by any velocity change within Glauconitic. As the Mississippian Unconformity seismic pick is uncertain we prefer Wabamun to construct a reliable isochron.

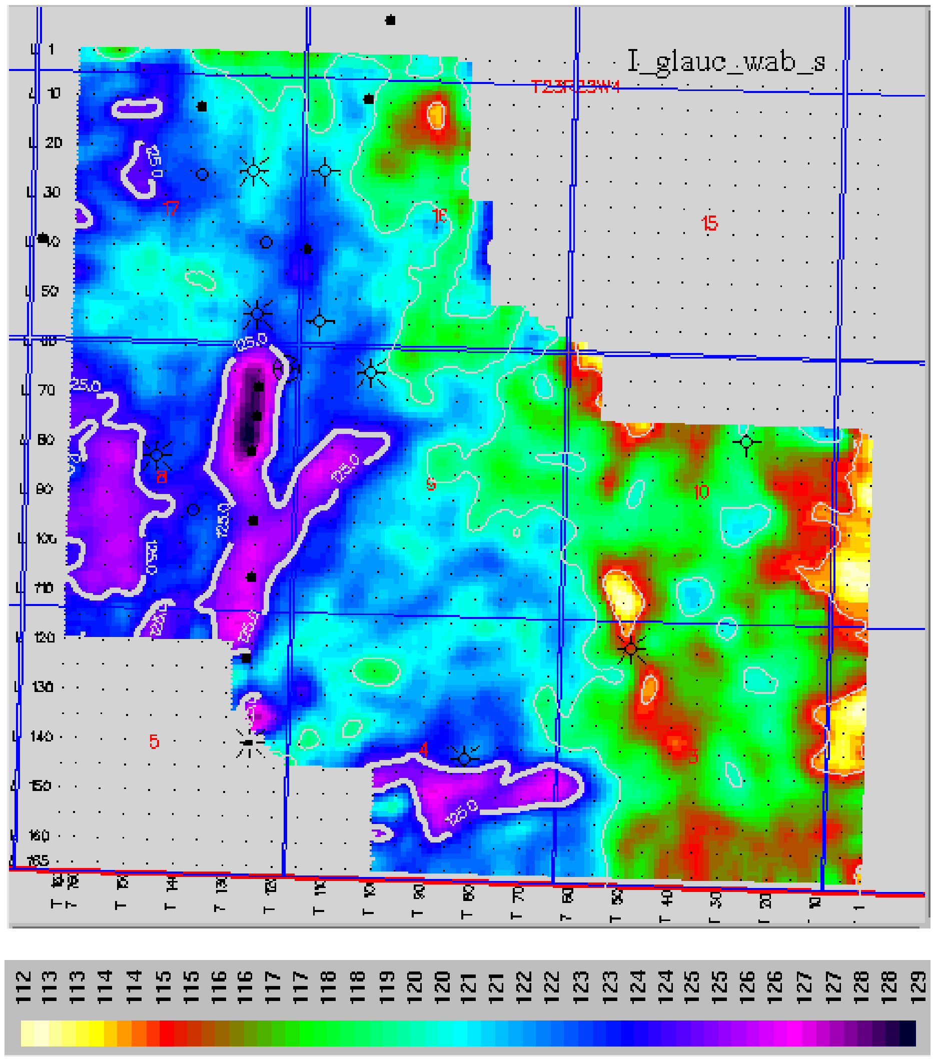


Figure 18. Blackfoot 3C-3D P-P data set. Glauconitic-Wabamun isochron map.

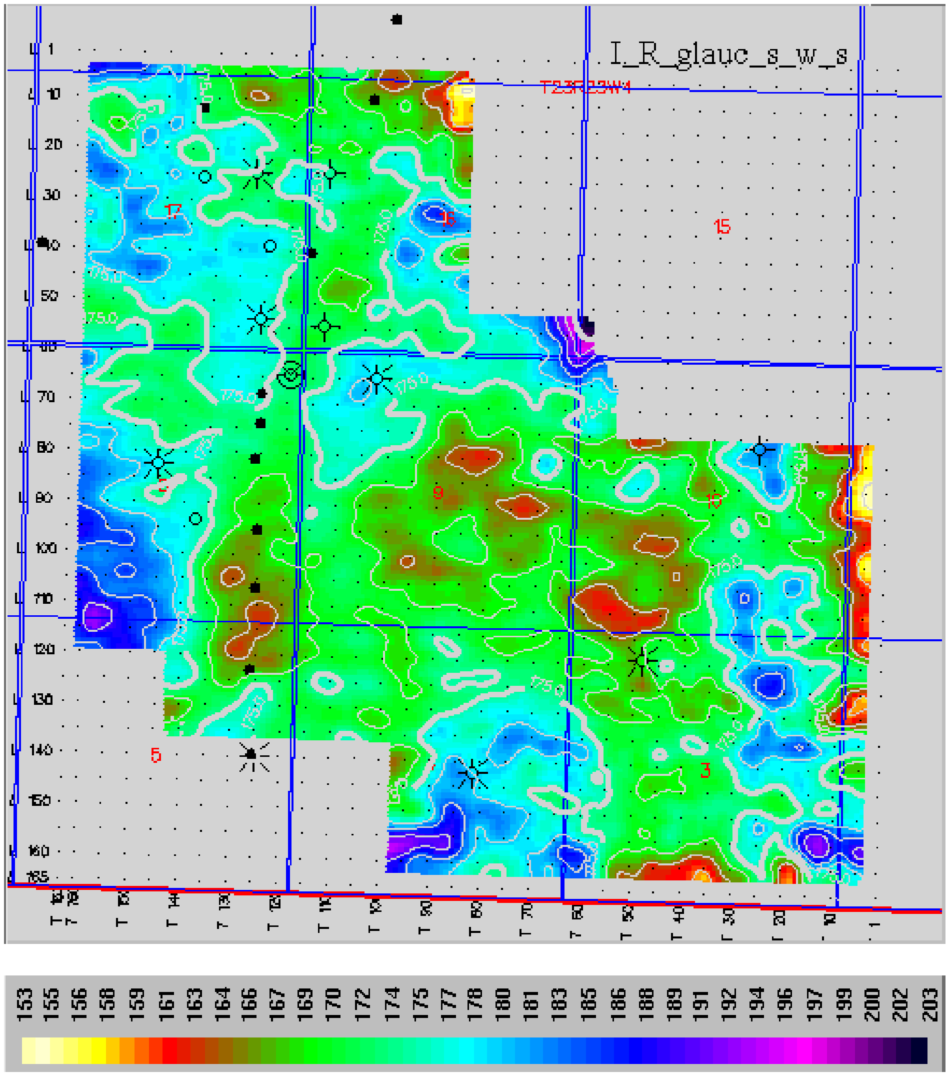
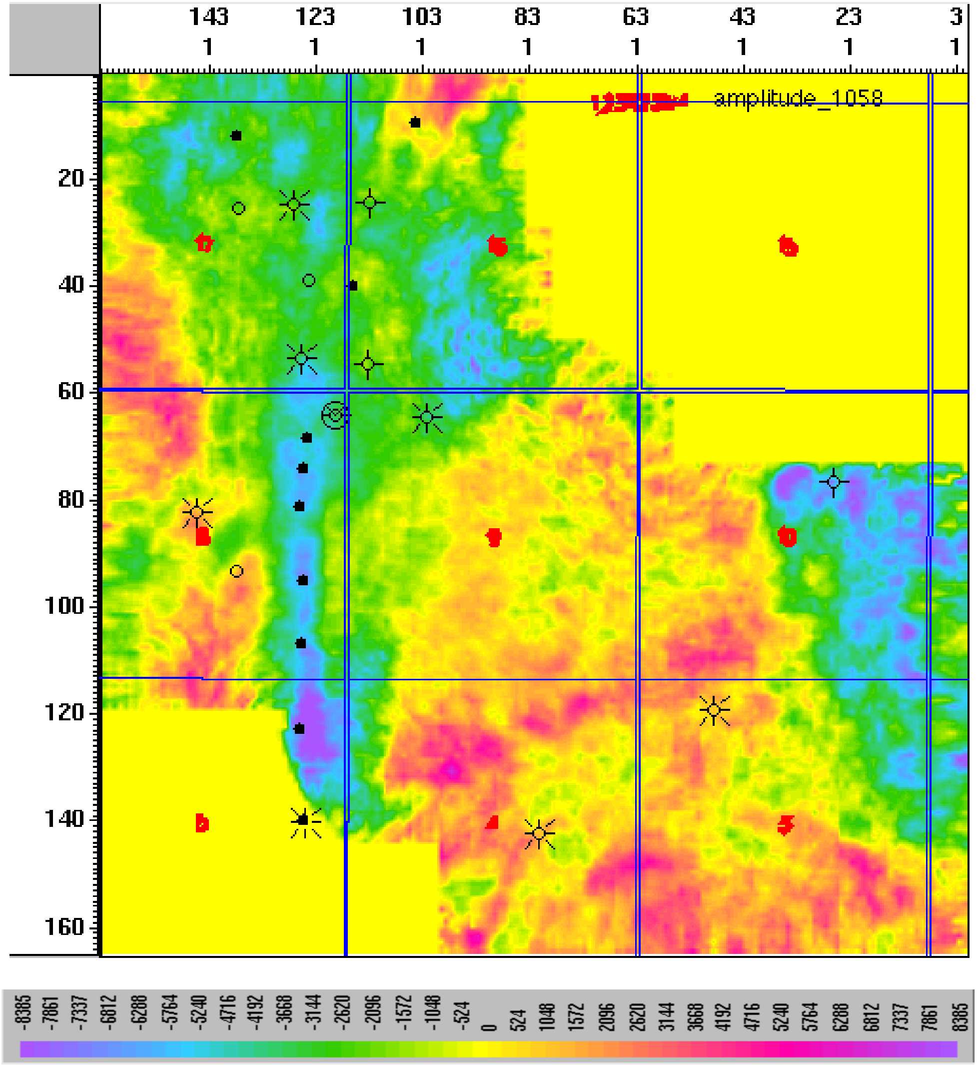


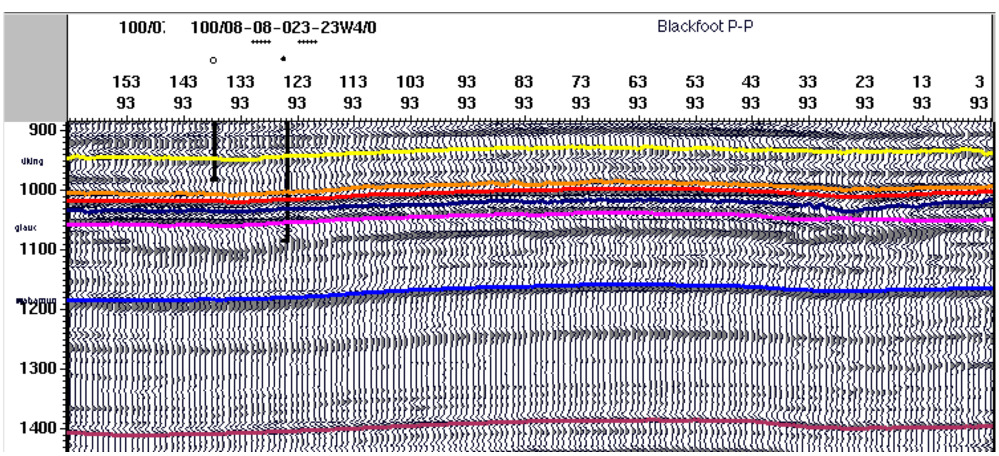
Figure 19. Blackfoot 3C-3D P-S data set. Glauconitic-Wabamun isochron map.

The Glauconitic-Wabamun isochron maps Figure 18 and 19, appear correlatable. Both map the Glauconitic channel in section 8 with closed contours. The P-S isochron suggests the channel continuation to North different than P-P isochron were the channel turns NW.

Seismic amplitude, amplitude envelope, instantaneous phase and instantaneous frequency time slices within Glauconitic, and their vertical section on EW Line 93, are illustrated in Figures 20 to 27. The channel intercepted with 8-8-23-23 W4M well appears distinct on all eight displays.

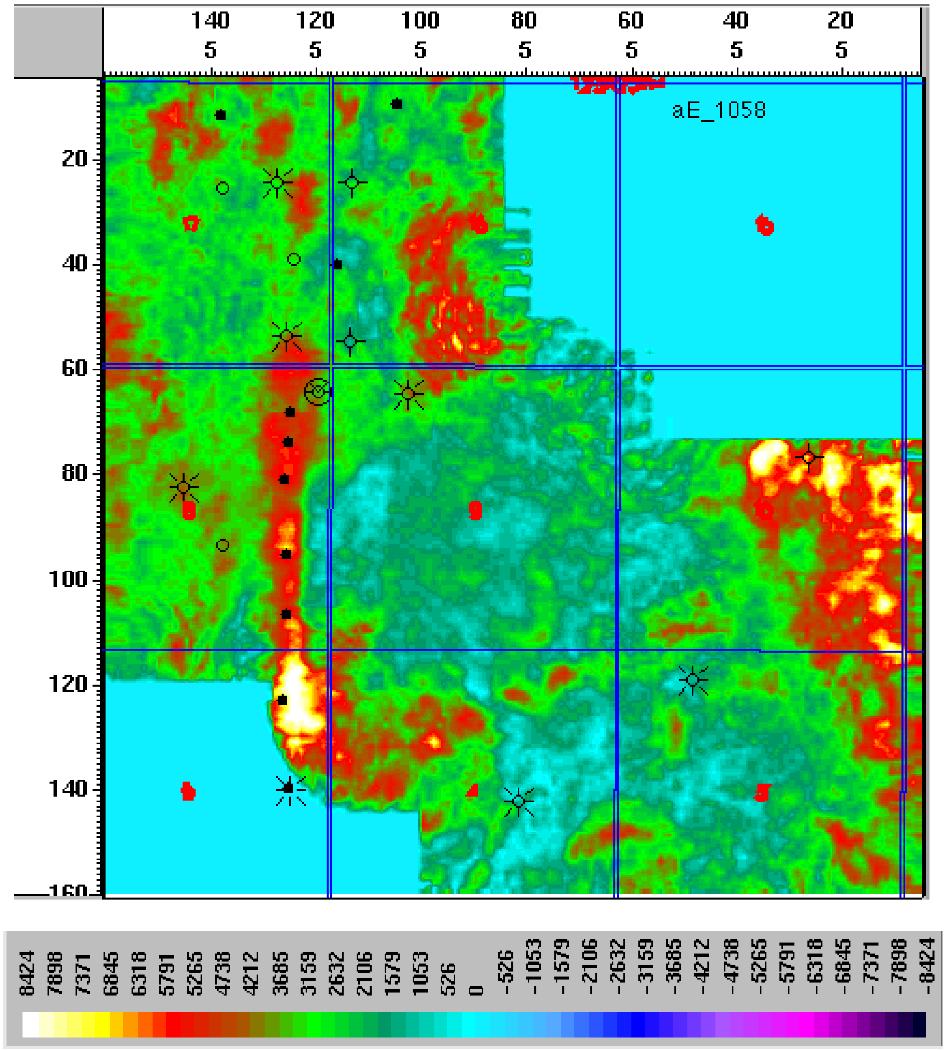


Time slice at 1058 ms

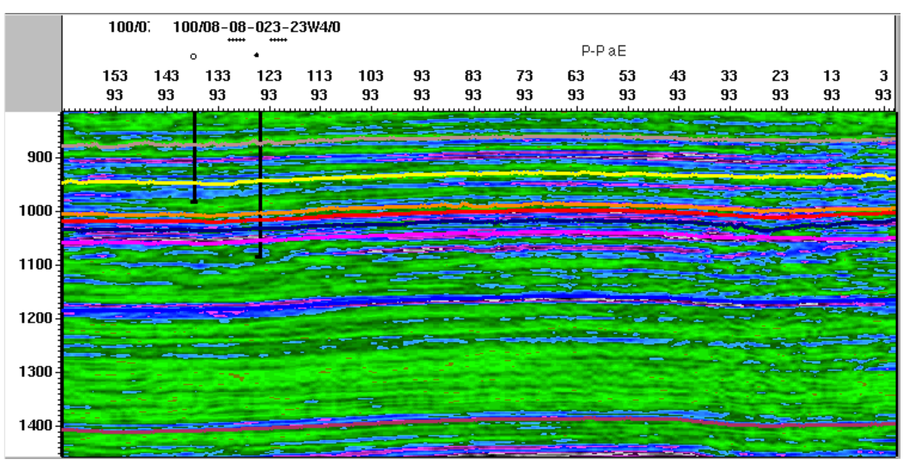


EW Line 93.

Figure 20. Blackfoot 3C-3D P-P data set. Seismic amplitude within Glauconitic.

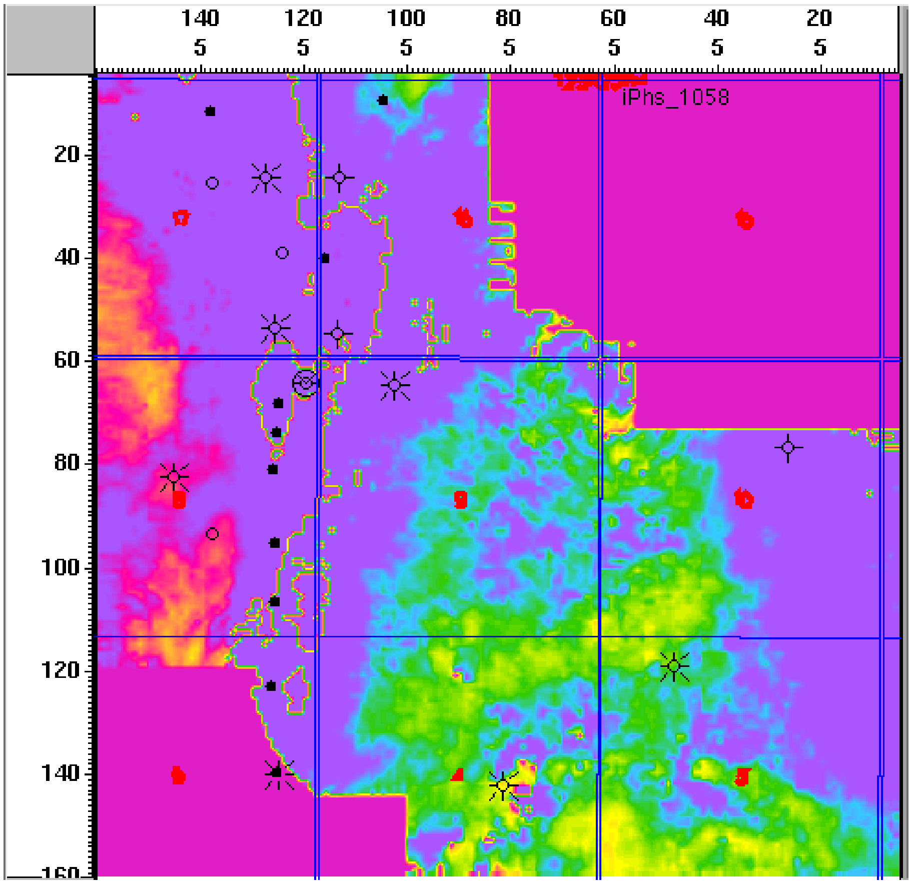


Time slice at 1058 ms.

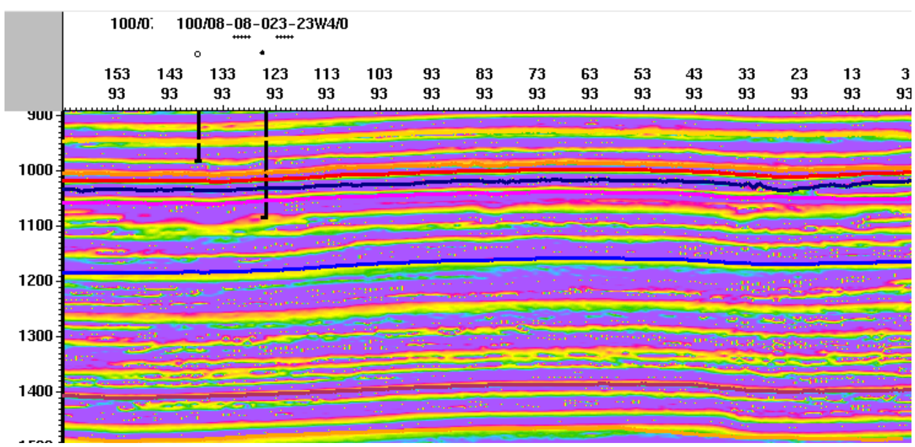


EW Line 93.

Figure 21. Blackfoot 3C-3D P-P data set. Amplitude envelope.

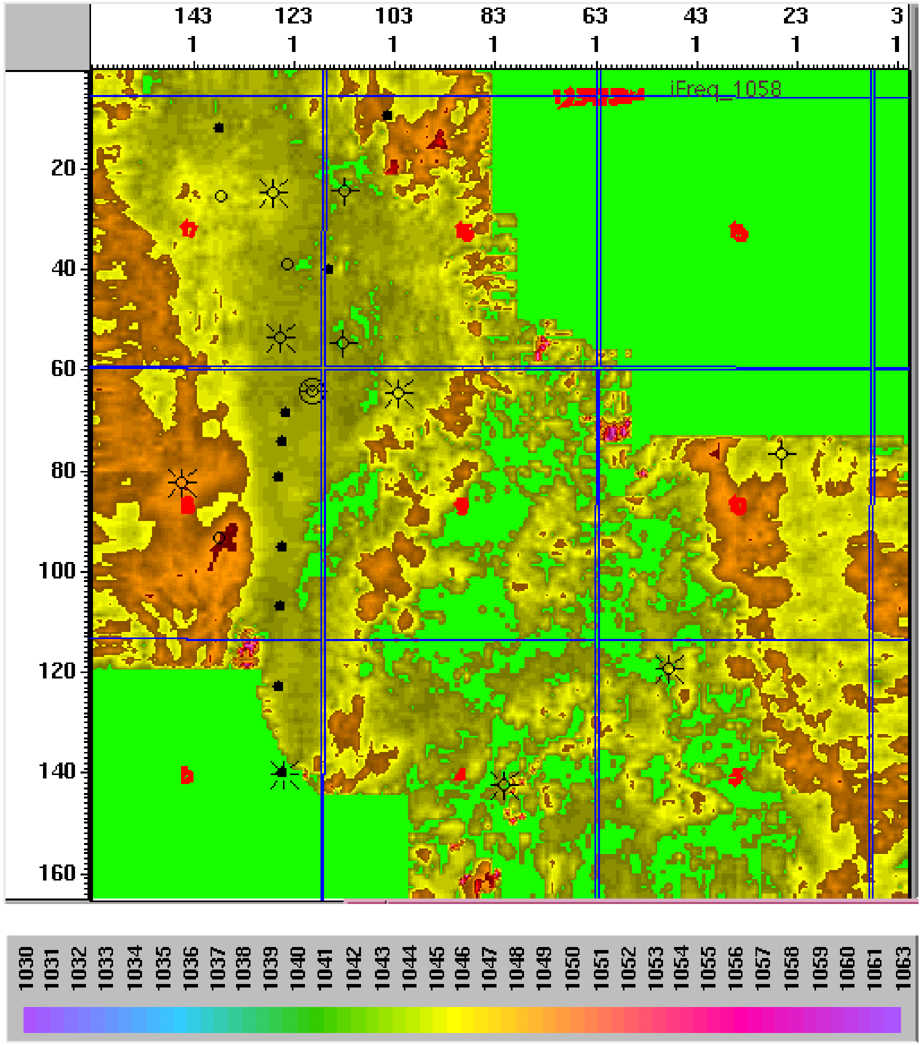


Time slice at 1574 ms.

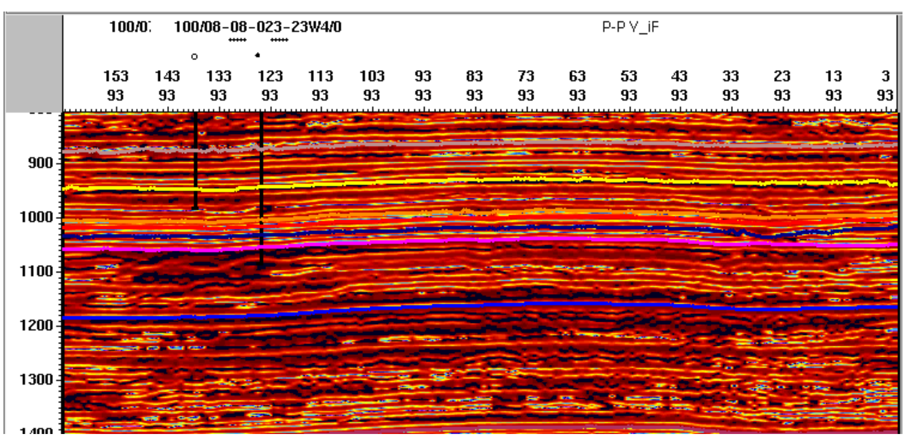


EW Line 93.

Figure 22. Blackfoot 3C-3D P-P data set. Instantaneous phase.

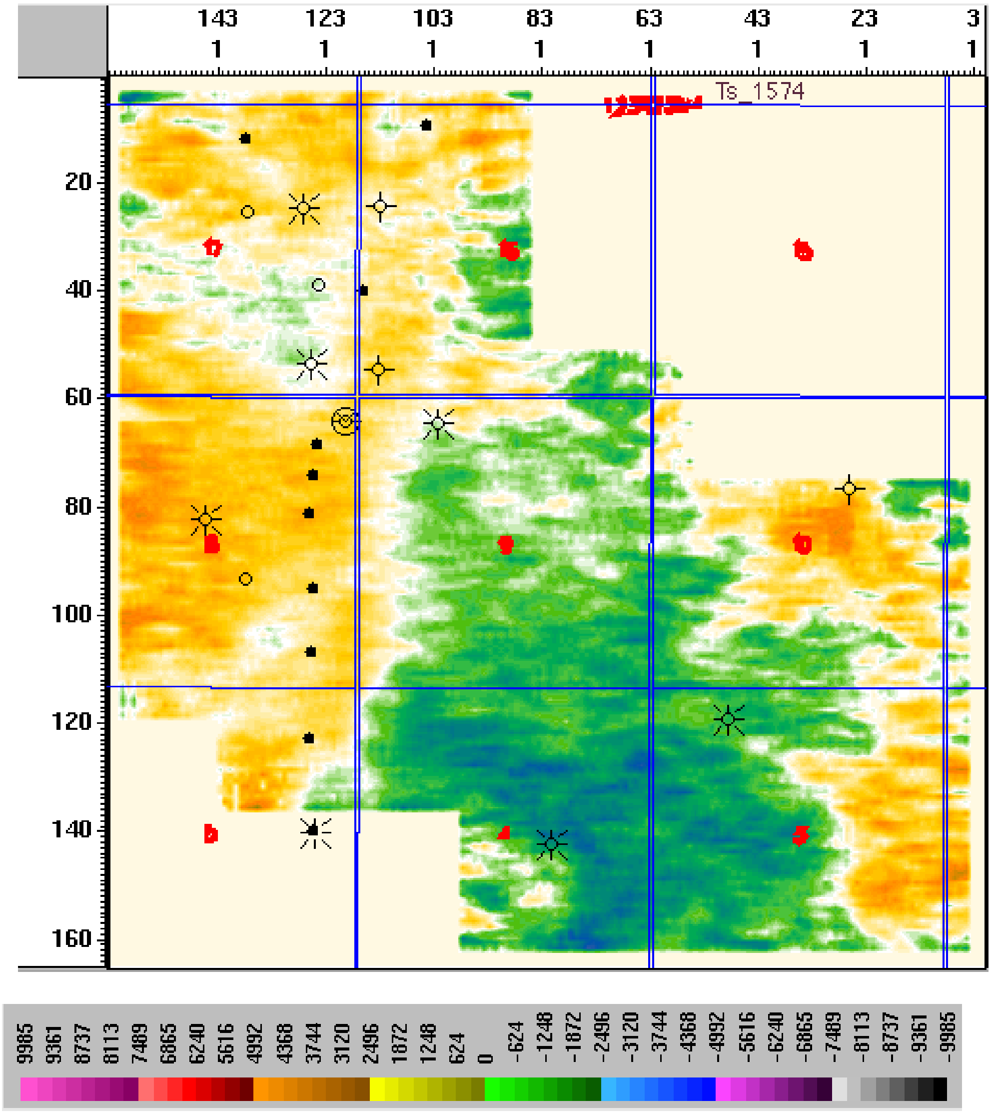


Time slice at 1574 ms

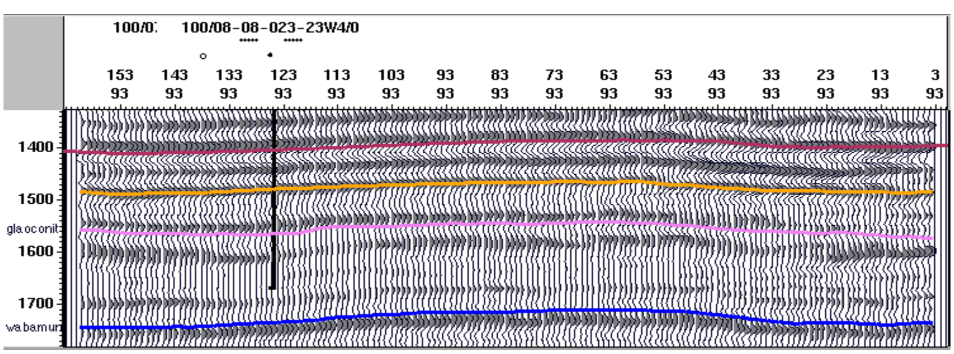


EW Line 93.

Figure 23. Blackfoot 3C-3D P-P data set. Instantaneous frequency.

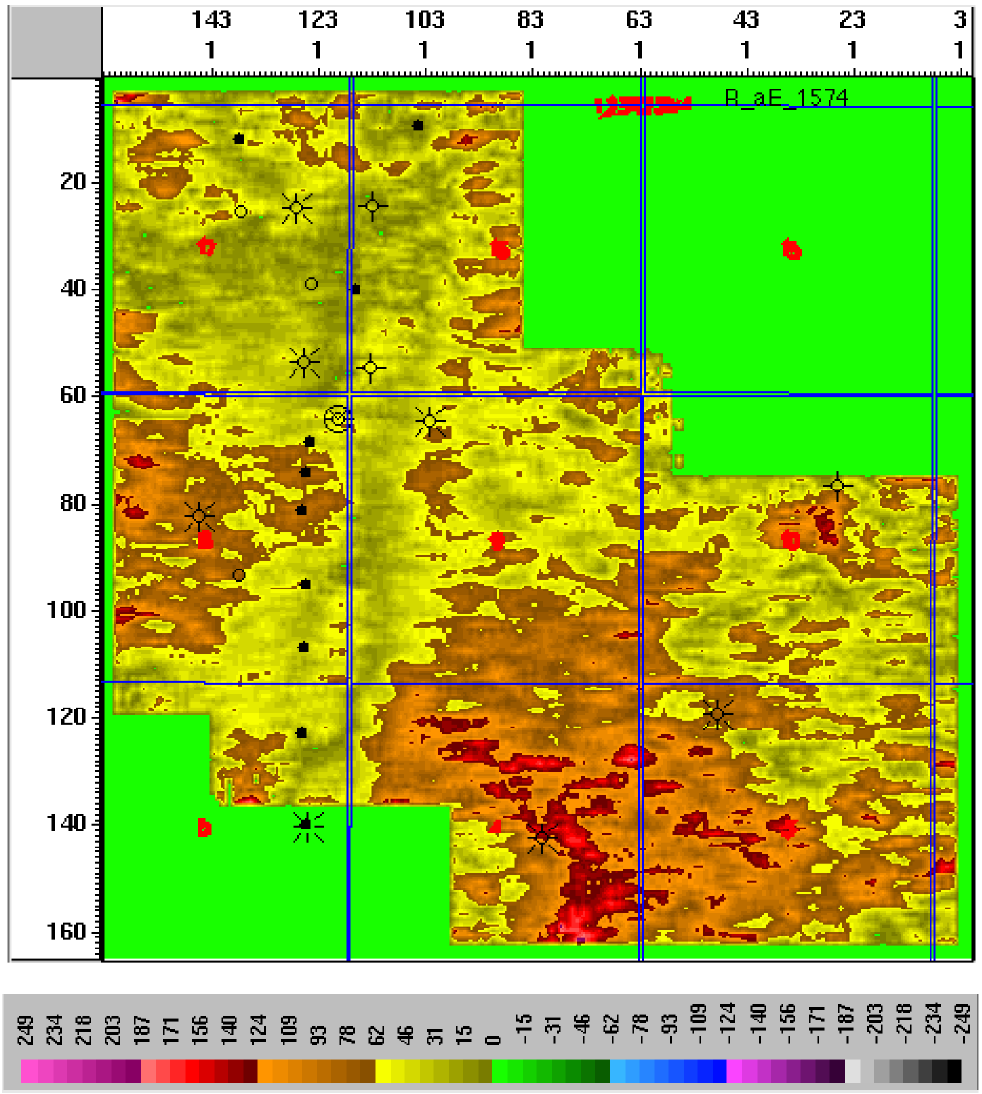


Time slice at 1574 ms..

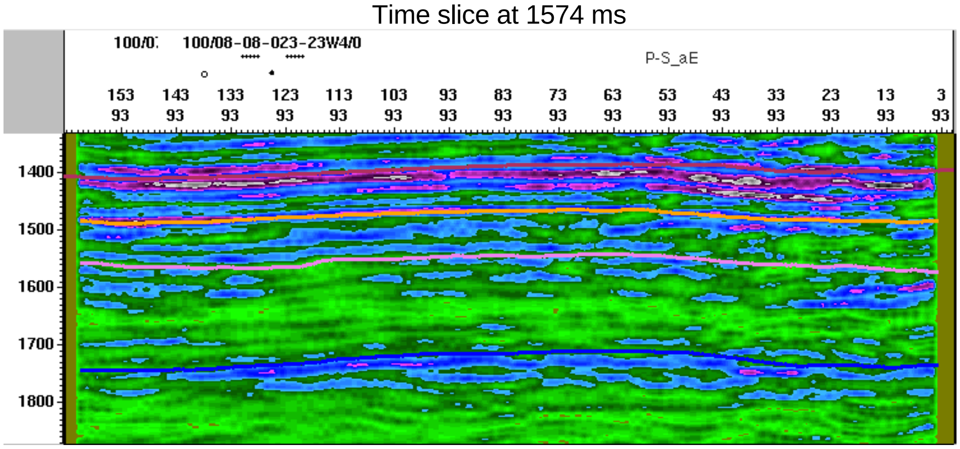


EW Line 93.

Figure 24. Blackfoot 3C-3D P-S data set.

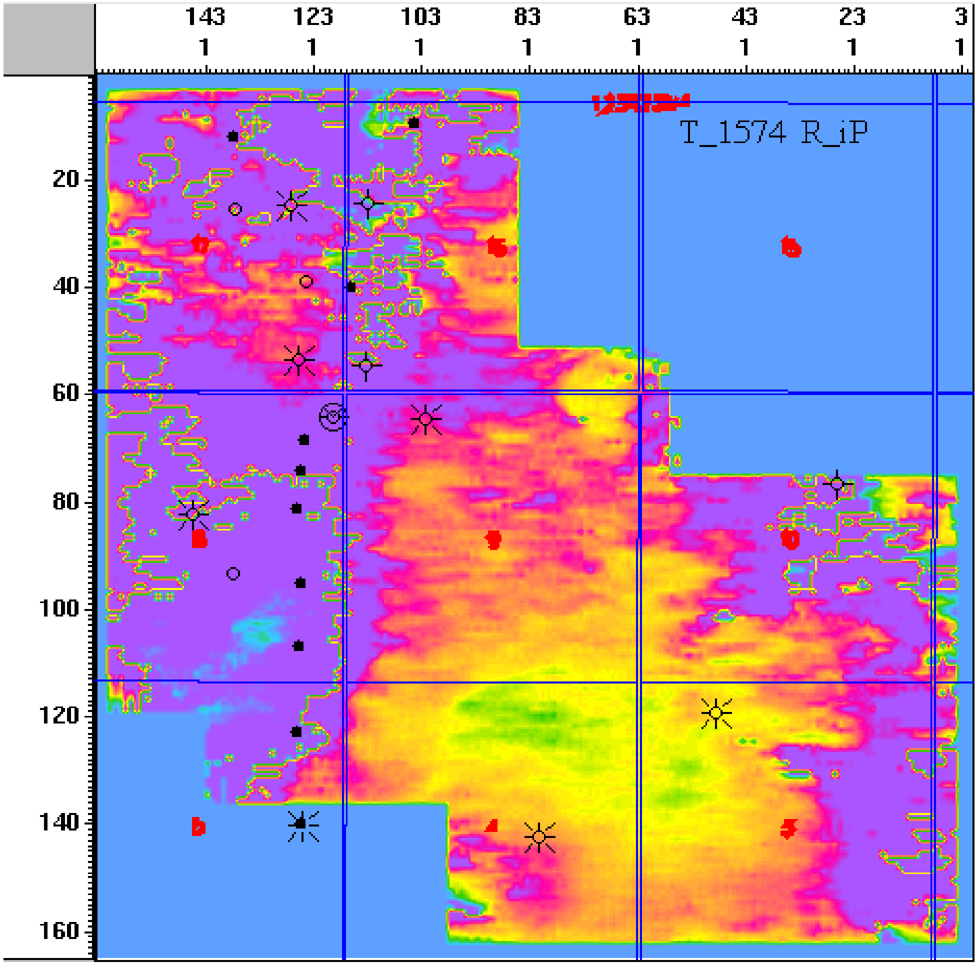


Time slice at 1574 ms

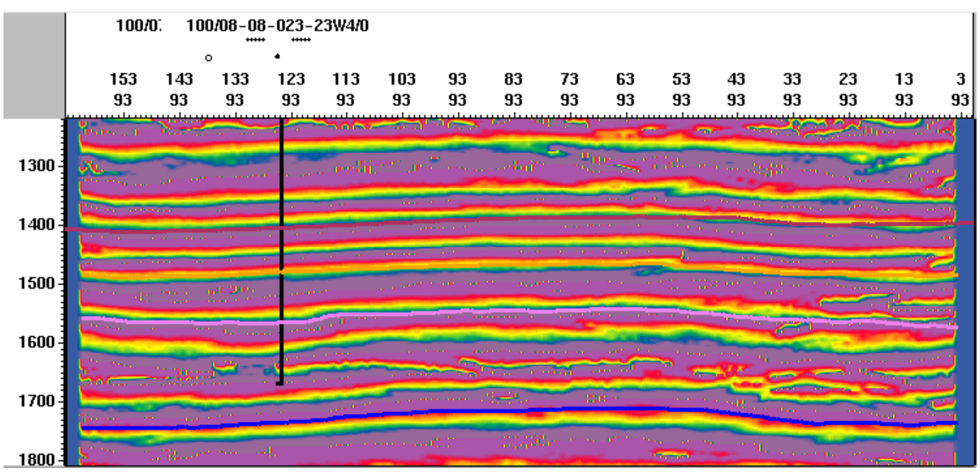


EW Line 93.

Figure 25. Blackfoot 3C-3D P-S data set. Amplitude envelope.

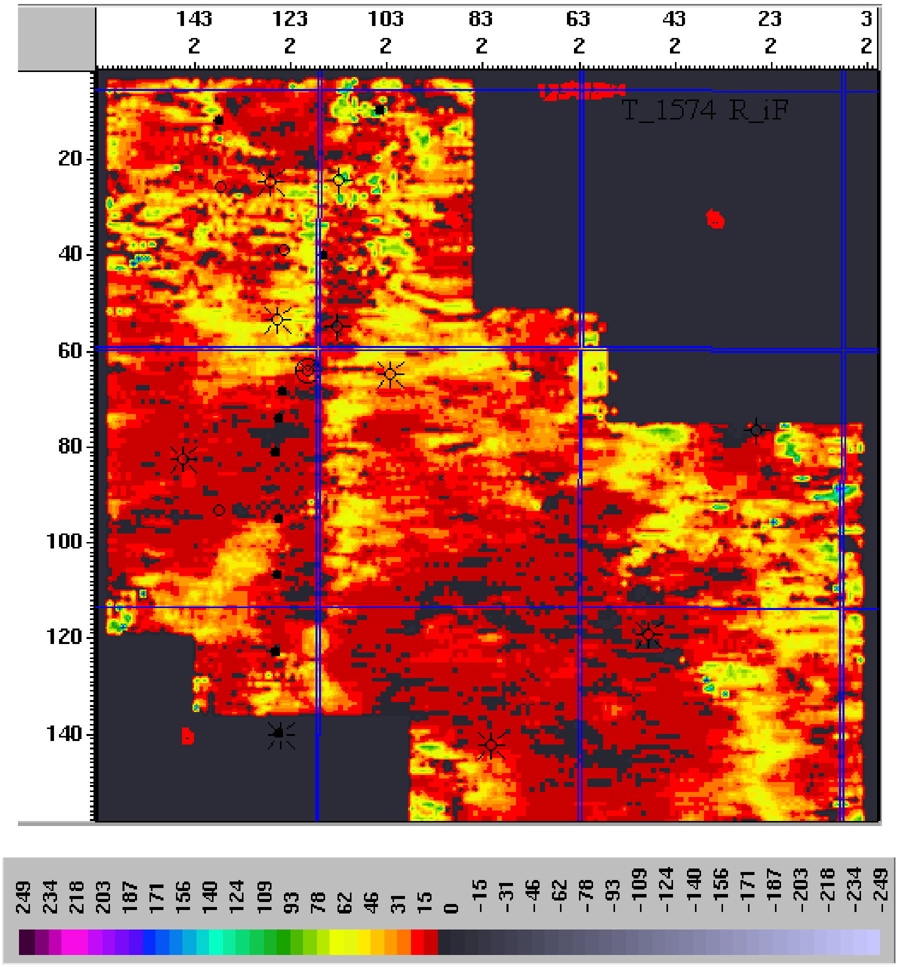


Time slice at 1574 ms.

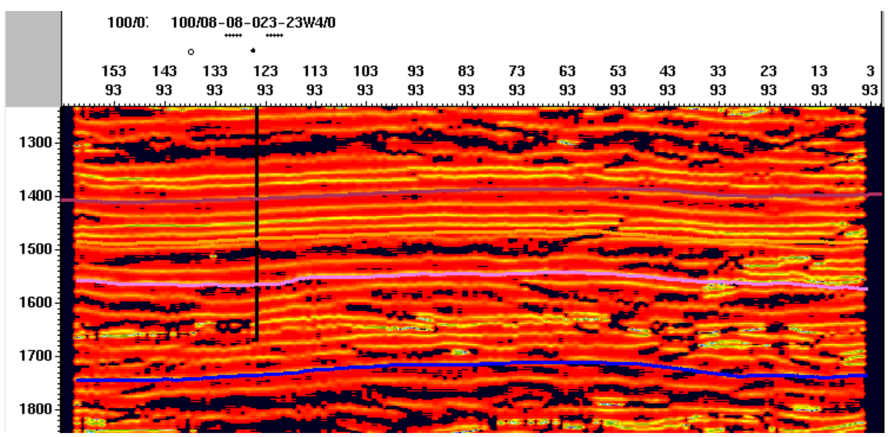


EW Line 93.

Figure 26. Blackfoot 3C-3D P-S data set. Instantaneous phase.



Time slice at 1574 ms.



EW Line 93.

Figure 27. Blackfoot 3C-3D P-S data set. Instantaneous frequency.

On Line 93, Crossline 15 - 35 all the attribute sections indicate another Glauconitic anomaly. As 10-10-23-23 W4M well is at the margin of the survey at this time we do not speculate further.

Two thick IF slices were computed for the two data sets. For 12 ms interval on the P-P waves data we chose 20 ms interval on P-S data Figure 26, 27.

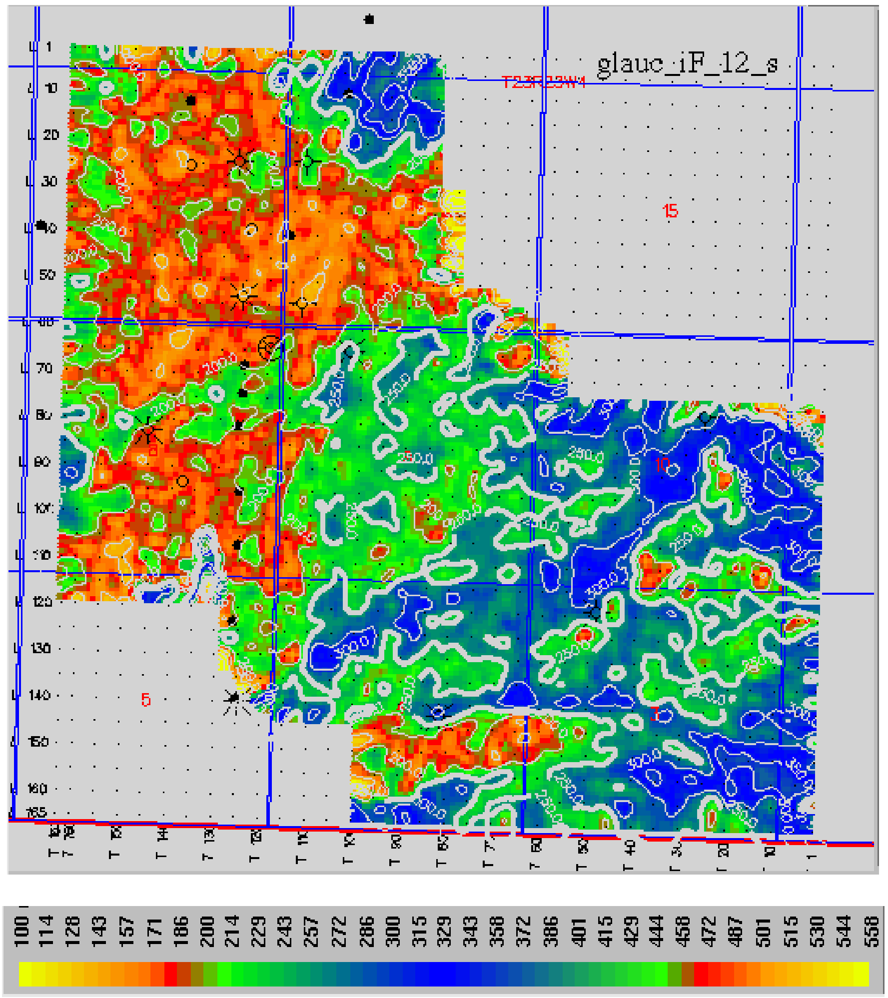


Figure 28. Blackfoot 3C-3D P-P data set. Instantaneous frequency - Top Glauconitic +12ms.

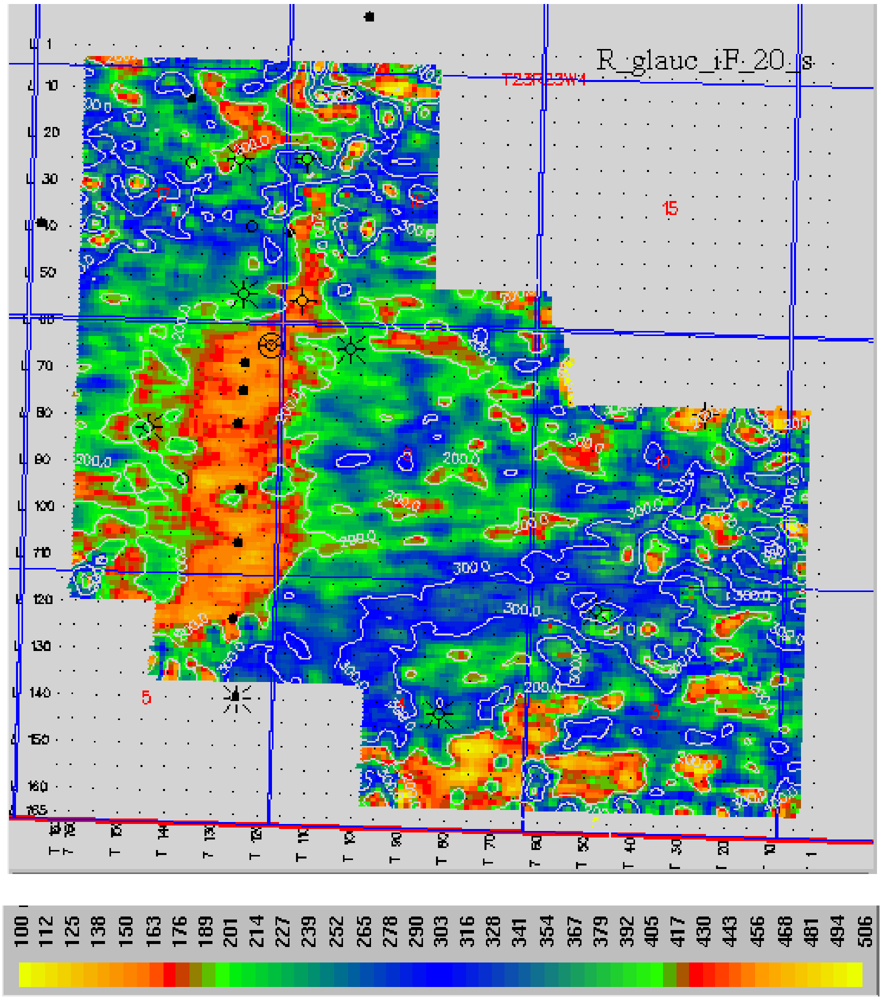


Figure 29. Blackfoot 3C-3D P-S data set.

Instantaneous frequency - Top Glauconitic + 20 ms.

The Glauconitic channel is highlighted by this (time slice) map relatively better than any other map, however in the well 4-16 the reservoir is poor.

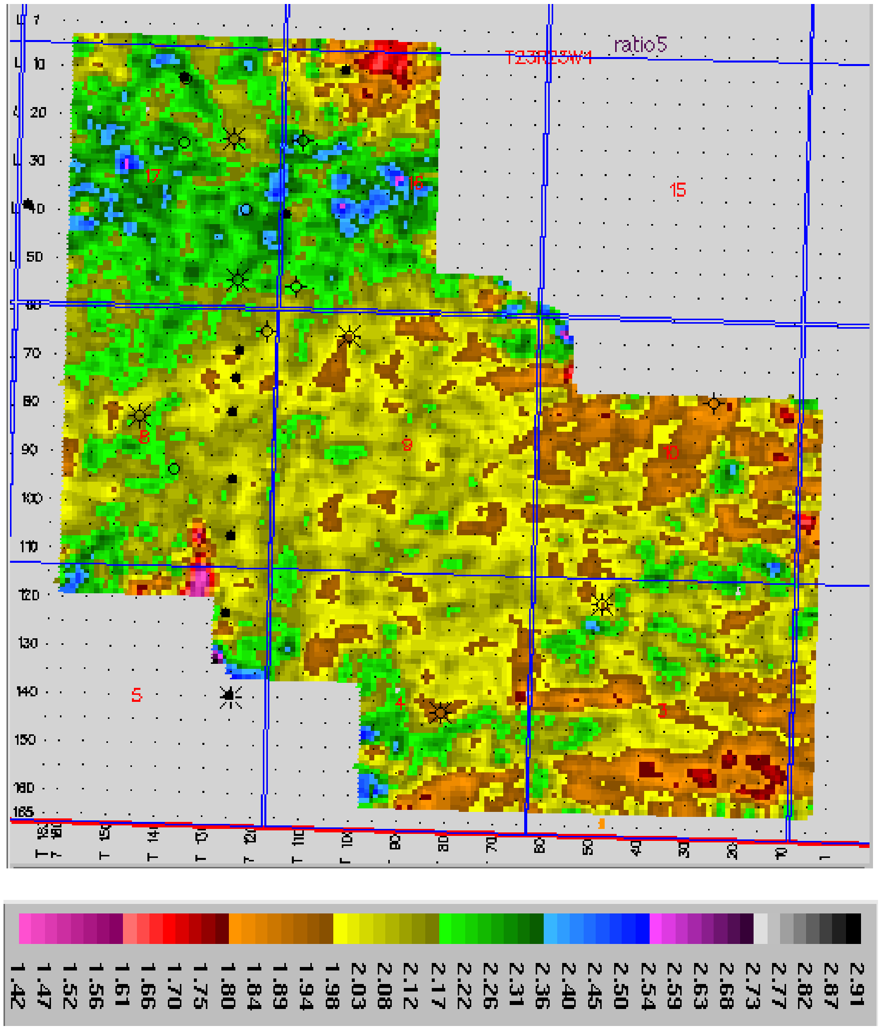


Figure 30. Glauconitic - Instantaneous frequency ratio.

For the thick IF slices instantaneous frequency ratio maps were constructed using various weights. The map in Figure 30 is calculated with the weights 1, 3/5. The ratio map separates the northwest quadrant of the surveyed area. A trend NE -SW could be the expression of deep tectonics.

An attribute ratio map for the IF is computed using the expression:

$$A_{iF} = 2\ A_{iF\_pp} / A_{iF\_ps} - 1$$

with A_{iF} being the calculated instantaneous frequency ratio, A_{iF_pp} the instantaneous frequency of P-P thick time slice and A_{iF_ps} the instantaneous frequency of P-S thick time slice. The calculated IF ratio together with the isochron ratio should map the Glauconitic sand within the seismic resolution.

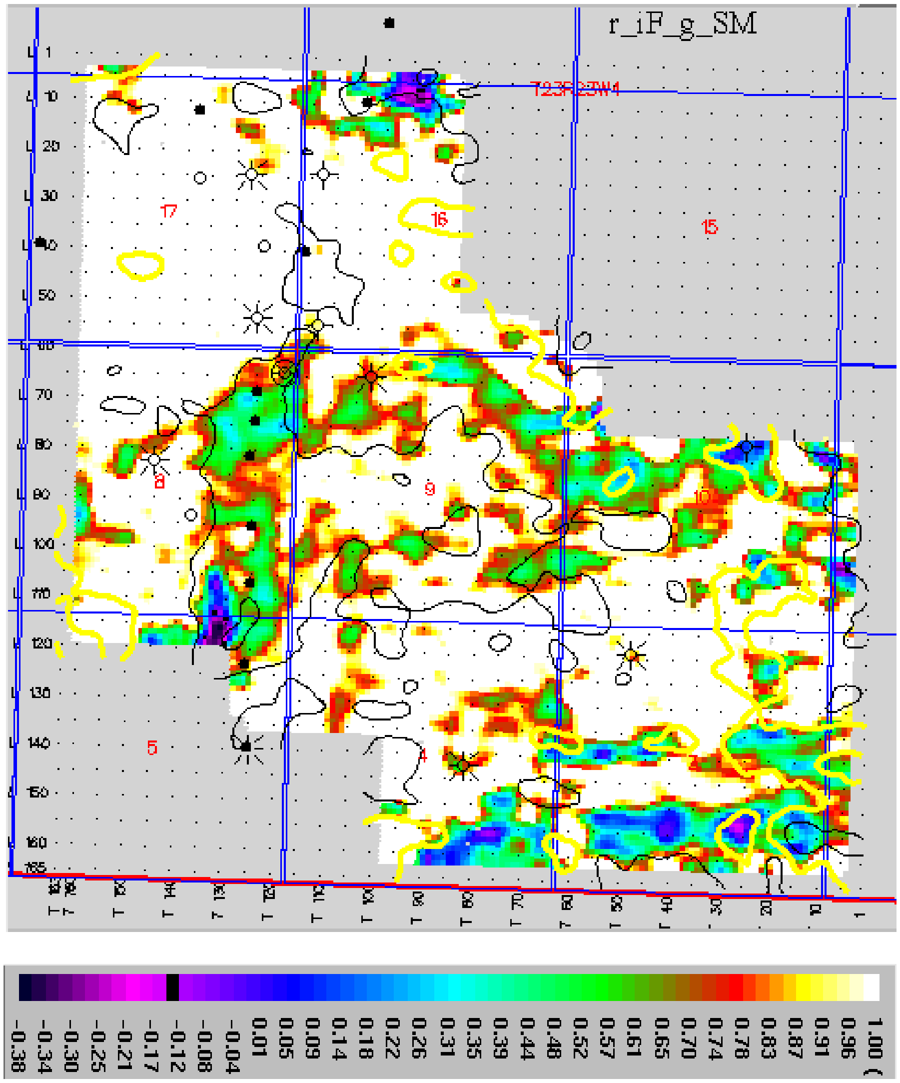


Figure 31. Blackfoot 3C-3D

Channel sand map.

The Glauconitic-Wabamun isochron ratio contours are superimposed on the ratio of the thick instantaneous frequency slices A_{iF}. The map in Figure 31 shows good correlation between the two data inputs. As the isochron ratio approximates Vp/Vs it is implied that the instantaneous frequency indicates the sand presence and together with the time attribute highlights the channel sand distribution.

CONCLUSIONS

The seismic attribute analysis and processing in the time slice plane is a viable stratigraphic approach.

The complex 3-D seismic attributes are considered lithological indicators for hydrocarbon reservoirs. The thick instantaneous frequency slice detects lateral lithological changes and quantitative evaluation might be experimented with detailed well control.

The benefits of 3-C 3-D data sets are promising. Seismic attributes extracted from P-P and P-S seismic data appear to correlate with lithologies.

The ratio of instantaneous frequency thick slices chosen carefully can be used to map calitatively different rock parameters, in this example sand.

Color selection is critical in enhancing subtle features.

Large volume of data computed for surveys like Blackfoot require modern computer technologies, large disk storage and intense analysis.

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