Design review of the Blackfoot 3C-3D seismic program

Don C. Lawton, Robert R. Stewart, Andreas Cordsen[1], and Stacey Hrycak[2]

ABSTRACT

Design of the Blackfoot 3C-3D seismic program was reviewed by evaluating pre-survey and post-survey fold plots, and comparing predicted fold with the stacking fold extracted from the processed data volume. The survey was designed initally using asymptotic binning and Flexi-bin® acquisition geometry with a sub-bin interval of 10 m for the *P-S* data. The survey consisted of 1395 sourcepoints and 903 receivers, recorded in 2 fixed patches with up to 700 receivers per patch. Processed stacking fold distribution matched closely the pre-survey depth-variant fold distribution computed using an offset range of up to 2300 m for the *P-S* data. Maximum fold for 30 m x 30 m bins at the Glauconitic target level reached 100 in the centre of the Glauconitic patch, and greater for later events. Fold distribution was good, with relatively minor bin-to-bin and sample-to-sample variations within the volume from the Glauconitic patch. Some fold striping parallel to the receiver lines was noticeable over the Beaverhill Lake patch where a receiver line interval of 495 m was used.

INTRODUCTION

In this paper, we review the design of the Blackfoot 3C-3D survey, which was recorded in October, 1996. The initial design was presented at the CREWES Consortium Meeting last year (Lawton, et al., 1996) and was a collaborative effort between The University of Calgary, Boyd Exploration Consultants, Geophysical Exploration & Development Corporation, and the Technical Advisory Team for the Blackfoot Project. We show the geometry actually used for the survey, discuss the shooting strategy developed, and assess the predicted subsurface *P-S* fold in relation to the actual depth-variant stacking fold determined from the processed *P-S* volume. Interpretation of the processed data volume is discussed later, in Chapter 46 (Yang, et al., 1996).

During the initial design stage of the Blackfoot survey, it was noted that, in previous studies (Lawton, 1993, 1994) it had been shown that empty bins occur for asymptotic *P-S* mapping when $Vp/Vs = 2$ and if the shot-line spacing is an even integer spacing of the group interval. In this case, empty bins occur in every fourth row in the crossline direction; i.e. parallel to the shot lines. The concept of the *optimum bin size* was developed, based on the natural separation of conversion points at the reflector. This bin dimension, Δr, is given by $\Delta r = \Delta g/(1.0 + Vs/Vp)$, where Δg is the group interval. As an example, for $Vp/Vs = 2$ and $\Delta g = 60$m, the normal CMP bin dimension for *P-P* data would be 30m, whereas the optimum bin dimension for *P-*

[1] Geophysical Exploration & Development Corporation.
[2] Boyd PetroSearch

S data would be 40m. While this provides smooth *P-S* fold with no empty bins, it is undesirable to have different numbers of traces in the *P-P* and *P-S* data volumes for interpretation, particularly when trace-by-trace computations are undertaken, such as *Vp/Vs* analysis. It was found that it was also possible to avoid empty bins by setting the shot line interval to an odd integer multiple of the group interval. This was shown (Lawton, 1994) to produce a high frequency variation in the fold and that the fold in adjacent

To better overcome high frequency P-S fold variations, an alternative design strategy using the Flexi-bin® concept was proposed by Geophysical Exploration and Development Corporation (GEDCO), in which the conversion points are distributed at even 10m intervals in both the in-line and cross-line directions. This approach resulted in a more even fold distribution for *P-S* data assuming asymptotic conversion points. It also resulted in distributed midpoints for *P-P* data which could be stacked at the same 30 m x 30 m bins as the *P-S* data. This approach to survey design was implemented for the Blackfoot program.

BLACKFOOT 3C-3D SEISMIC SURVEY

Introduction

In the Fall of 1995, Boyd Exploration Consultants Ltd and the CREWES Project recorded a 3C-3D seismic survey to evaluate the effectiveness of integrated *P-P* and *P-S* surveys for improved hydrocarbon exploration. The objectives were to demonstrate that 3C-3D seismic data could build on and improve conventional 3D *P*-wave data, provide additional stratigraphic and structural images of the subsurface, discriminate lithology, and test for anisotropy which may be caused by fracturing and regional stress directions. The site chosen was over the Blackfoot field near Strathmore Alberta (Township 23, Range 23 W4M). The primary target horizon for the 3C-3D survey was the Glauconitic Member of the Mannville Group. Glauconitic sandstones and shales fill valleys which were incised into the regional Lower Mannville stratigraphy. In particular, the Ostracod and Bantry Shale Members of the Lower Mannville Formation were truncated by the valleys. Older valley-fills also occur in the Sunburst and Detrital Members. The Glauconitic reservoir sands occur at a depth of 1550 m.

In the Blackfoot area, a Glauconitic valley-fill was interpreted from wells and a previous 3D *P*-wave seismic survey conducted by PanCanadian Petroleum Ltd. The interpreted trend of the valley, based on the well information, is shown in Figure 1. Good channel sands were encountered in wells in the southern part of the area shown (e.g. 08-08 well), but the channel-fill facies appears to be a shale plug to the north at the 12-16 well. Primary objectives of the 3C-3D survey were to discriminate channel and regional seismic signatures, and to distinguish between sand-fill and shale-fill within the channel. A secondary objective of the 3C-3D survey was to characterize the *P-S* response of deeper Paleozoic carbonates.

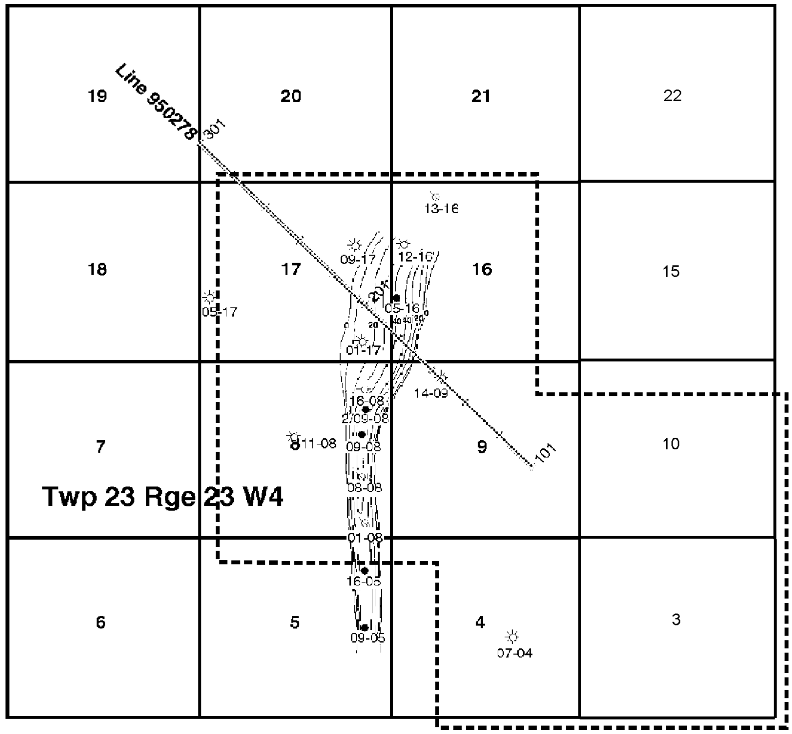

Fig 1. Base map of Blackfoot area. The 3C-3D survey area is shown by the dashed line.

Design

Table 1 shows the acquisition parameters used for the final design. The acquisition geometry was established in order to maintain the number of sourcepoints to less than 1400, and record an active patch of up to 700 geophones (2100 channels). An additional benefit of this geometry was that it provided smooth asymptotic fold for *P-S* data using the standard 30 m x 30 m bin dimension, with an average fold of 36 at the Glauconitic level, for planned source-receiver offset ranges of 300 m to 1700 m. The receiver effort was reduced over the deeper target area in order that imaging of the Glauconitic target was not compromised with the available budget. The pre-survey layout for the design is shown in Figure 2. Because of the extra care required to lay out 3-component geophones, it has been decided to not have a rolling patch, but to shoot the survey into two patches, one over the Glauconitic target ("Glauconitic patch") in the northwest part of the survey, and the other over the deeper carbonate target ("Beaverhill Lake patch") in the southeast part of the survey. The pre-survey field layout for the survey is shown in Figure 2. Generally, most planned source and receiver locations were occupied, but with some departures in the central region of the Glauconitic Patch, and near the eastern boundary of the Beaverhill Lake Patch, (Figure 3). Figure 4 and 5 show the sources and receivers which were live for the Glauconitic and Beaverhill Lake patches, respectively.

Table 1. Acquisition parameters for Blackfoot 3C-3D design.

Source parameters:

Line orientation:	North-south
Source interval:	60 m
Source line interval:	210 m
Number of source lines:	24
Total number of sourcepoints:	1395

Receiver parameters:

Line orientation:	East-west
Receiver interval:	60 m
Receiver line interval:	255 m (Glauconitic); 495 m (Beaverhill Lake)
Number of receiver lines:	18
Total number of receivers:	903

Patch #1 (Glauconitic)

Receivers

All receivers on lines R2 - R18, R22, R26, R30 (42 per line).
All receivers on lines R20, R24, R28 west of and including shot line S13 (62 per line).
Total number of live receivers = 690

Sources

All shots on shot lines S31 - S47 (60 shots per line).
All shots on shot lines S25, S27, S29 north of receiver line R30; i.e. SP 101- SP 160 on these lines, for a total of 60 shots per line).
Total number of shots = 720

Patch #2 (Beaverhill Lake)

Receivers

All receivers on lines R12 - R36 inclusive
Total number of live receivers = 693

Sources

All shots on shot lines S1 - S23 (50 shots per lines)
All shots on shot lines S25, S27, S29 south of receiver line R30; i.e. SP 161 - SP 185 on these lines (25 shots per line).
All added shots on shot lines S25, S27, S29 between receiver lines R18 and R30 (12 shots per line,).
Total number of shots = 711

Total number of shots in program = 1431

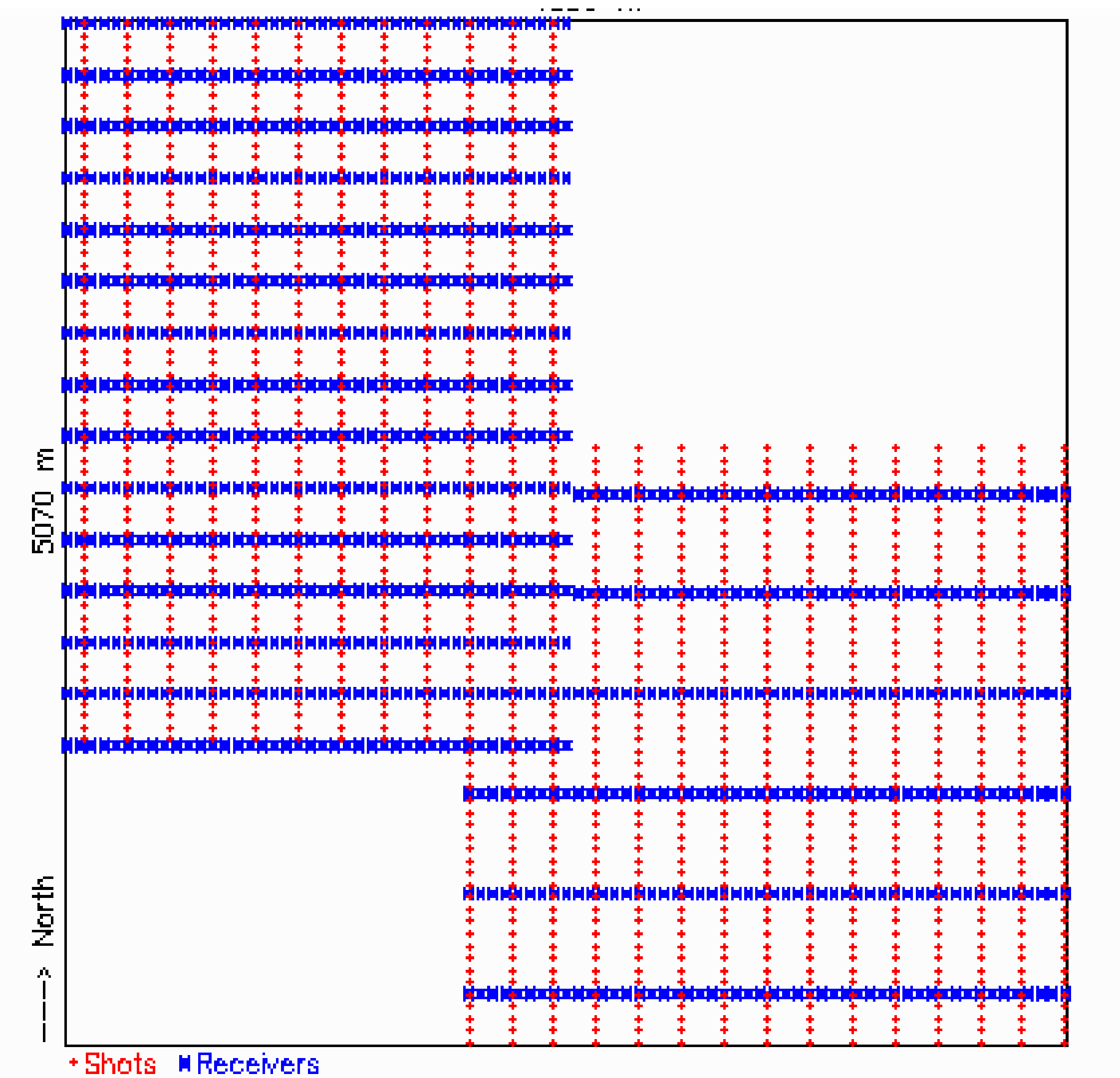

Fig. 2. Pre-survey source and receiver line geometry for Blackfoot 3C-3D program

Offset Ranges

Design of the 3C-3D survey was in part based on the results obtained from the 3C-2D survey which was recorded in the area of the 3D survey in 1995. Examination of *P-P* and *P-S* common-offset stacks of these data showed optimum offset ranges at the target level (Glauconitic) of up to 1500 m for *P-P* data, and up to 1700 m for *P-S* data. However, processing of the 3C-3D data volume included offsets of up to 2300 m for the P-S data. This increase in useable offsets is attributable to a significantly weaker reflection being obtained from the top of the Shunda Formation (Mississippian) and less apparent phase distortion.

The seismic program was recorded in early November 1996. Conditions initially were frozen, but thawed part-way into the program which required replanting of most geophones. Single geophones were planted in holes augered 0.5 m deep.

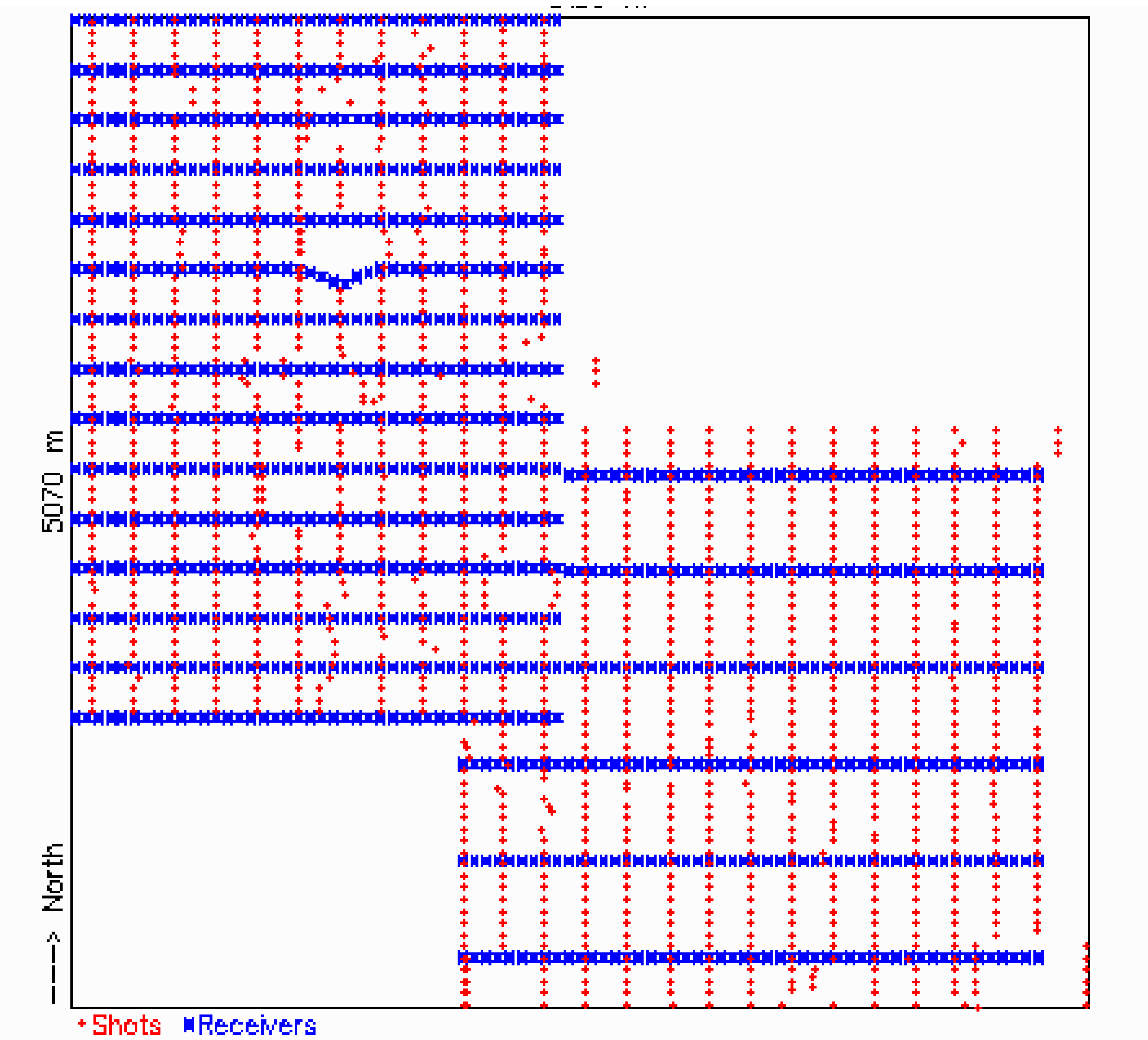

Fig. 3. Field survey source and receiver line geometry for Blackfoot 3C-3D program

Fold Maps

Figures 6 and 7 show pre-survey and post-survey *P-P* fold maps at the Glaucontic level, based on source-receiver offsets to 1500 m (mute). Maximum fold is about 40, and the fold distribution for the actual survey (Figure 7) is very similar to that for the pre-survey (Figure 6). Equivalent, fold maps for the *P-S* data (asymptotic mapping) are shown in Figures 8 and 9 respectively. Offset range for these data were extended to 2300 m, as discussed previously. This increase in maximum allowable offset from the initial design of 1700 m resulted in significantly higher fold (> 80) in the central part of the Glauconitic patch. Using the 2300 m maximum offset, the pre and post survey fold displays are very similar.

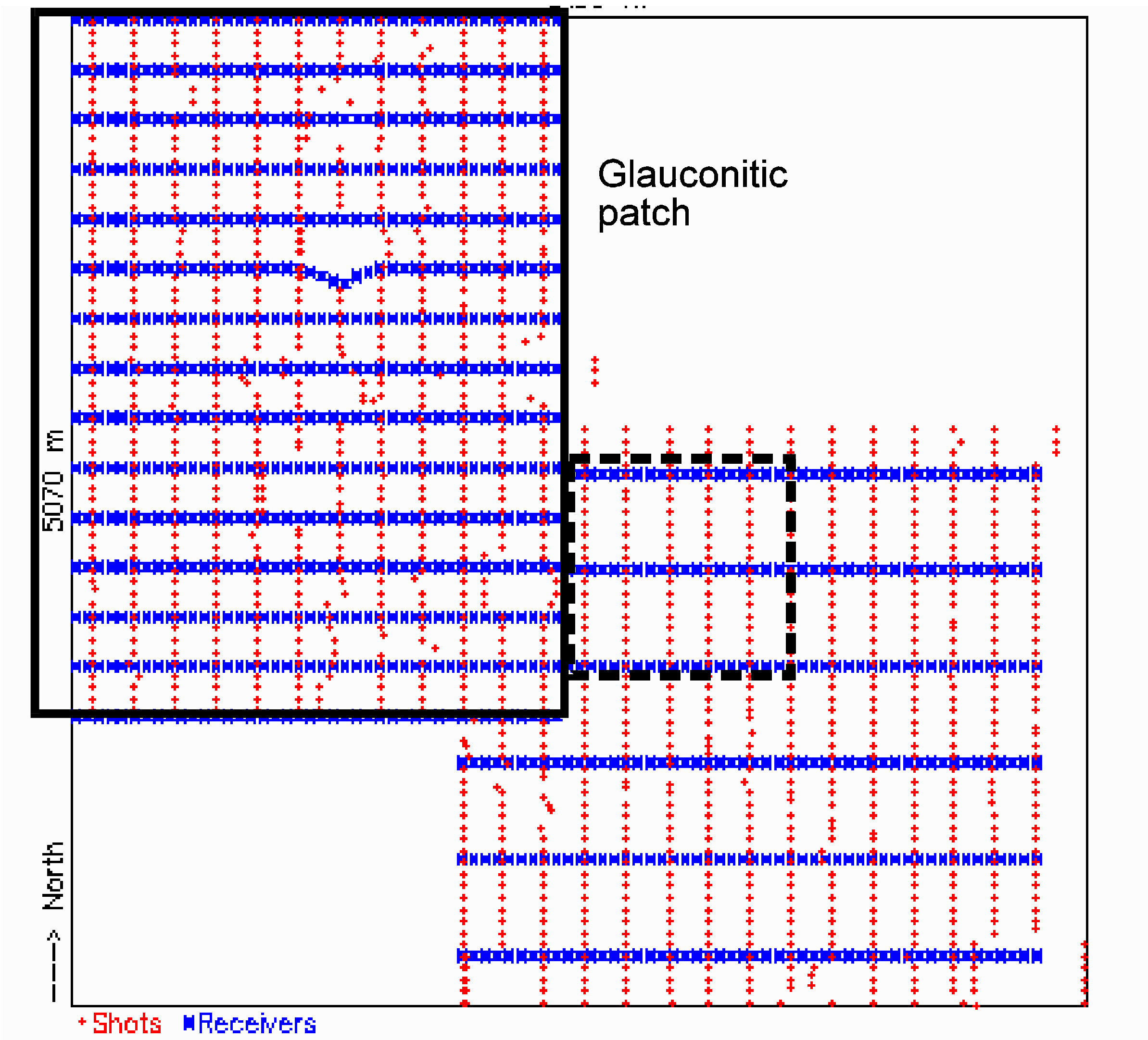

Fig 4. Geometry of Glauconitic path. All shots were fired in rectangle outlined by a solid line; receivers in dashed box were also live.

The asymptotic fold displays for *P-S* data provide only an approximate view of the actual subsurface fold, because of the depth-variant position of the conversion point. The asymptotic maps will provide the most reliable evaluation of fold distribution for small offset to depth ratios; i.e. will best represent the actual conversion point fold distribution for the deepest horizons imaged by the survey. More precise evaluation of *P-S* fold distribution is obtained through depth-variant fold analysis. However, this requires knowledge of *Vp/Vs* as a function of depth (and hence also time).

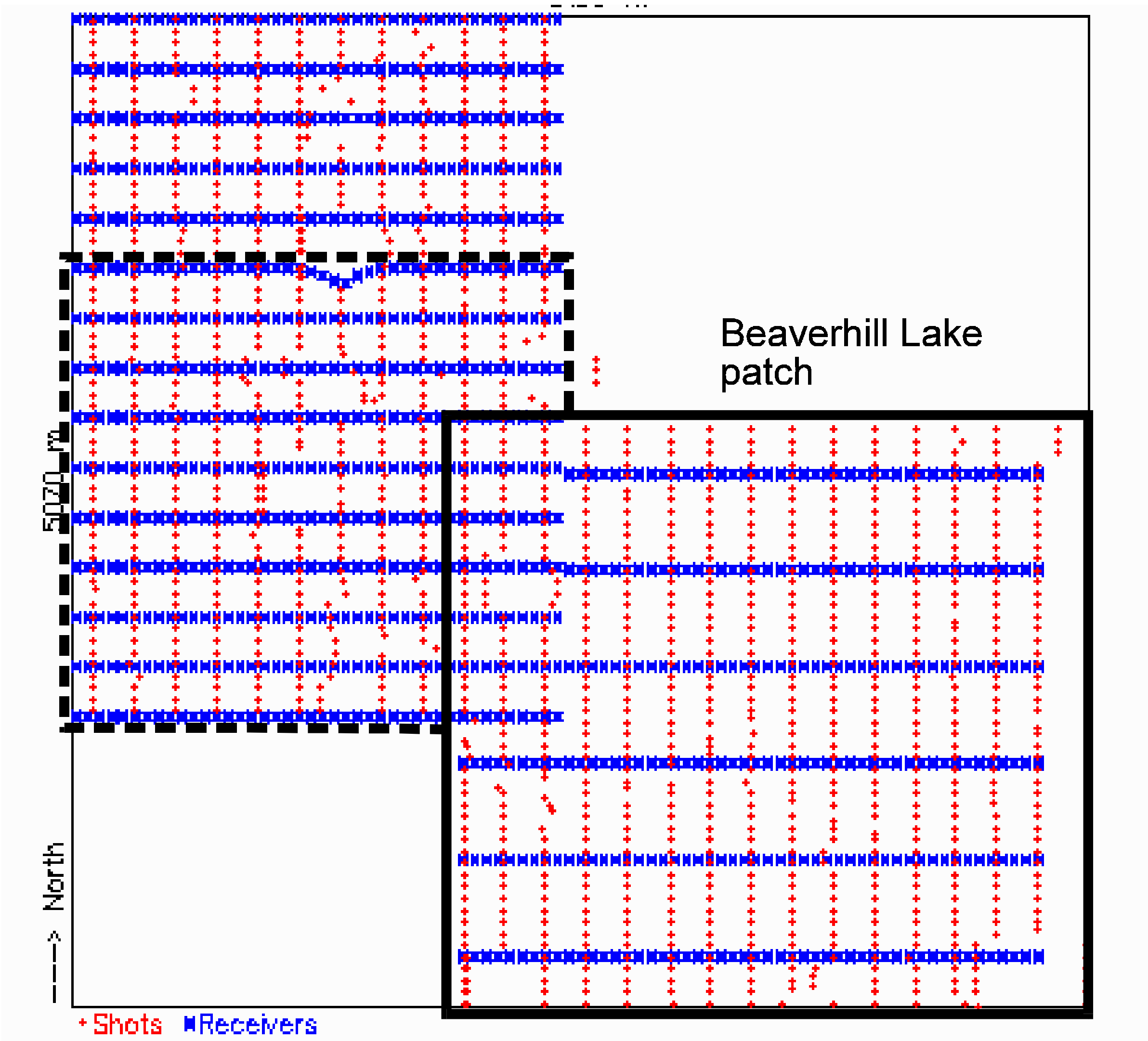

Fig 5. Geometry of Beaverhill Lake path. All shots were fired in rectangle outlined by a solid line; receivers in dashed box were also live.

Depth-variant fold maps for *P-S* conversion points at the Glauconitic level are shown in Figures 10 and 11 for pre and post-survey geometries, respectively. Maximum offsets to 2300 m were again used, and the maps were created assuming *Vp/Vs* = 1.9, which was based on the analysis of the Blackfoot broadband line recorded earlier. Compared with the asymptotic mapping, the depth-variant maps show a more irregular fold distribution, with some higher-fold stripes parallel to the receiver lines, particularly in the Beaverhill Lake patch. Figure 12 shows depth-variant *P-S* fold computed at the Cambrian level.

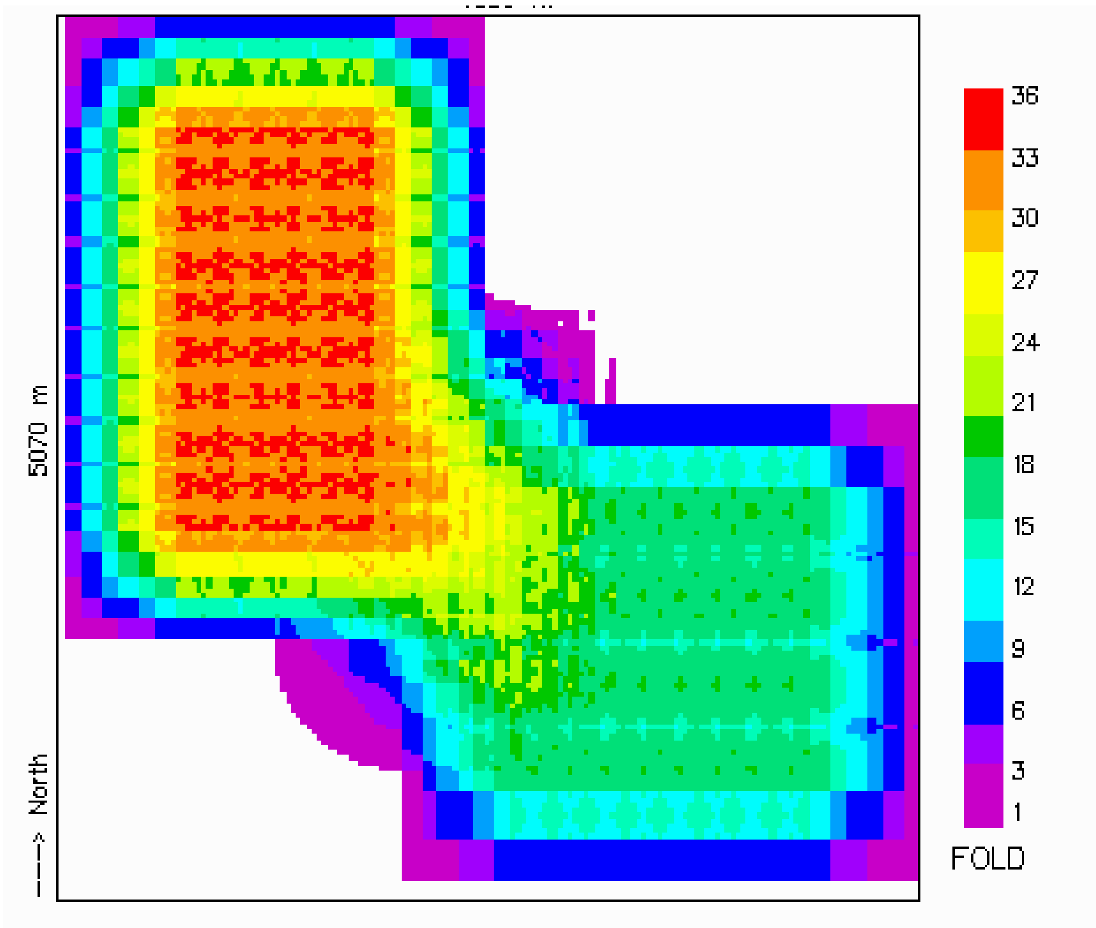

Fig 6. Pre-survey P-P fold distribution. Bin size 30 m x 30 m.

During the processing of the Blackfoot 3C-3D data, a depth-variant stacking fold volume was created by Pulsonic. This volume sums all non-zero contributions to each bin at each time sample; i.e. the actual stacking fold within the mute zone. Figures 13 through 15 show the processed stacking fold at times of 1500 ms, 1700 ms, and 2200 ms respectively. The fold is seen to increase with time, due to the mute taper, and reaches values in excess of 100 at the 2200 ms fold slice (Figure 15). Higher fold stripes are visible in the receiver-line direction, similar to that predicted from the design maps (Figures 11 and 12).

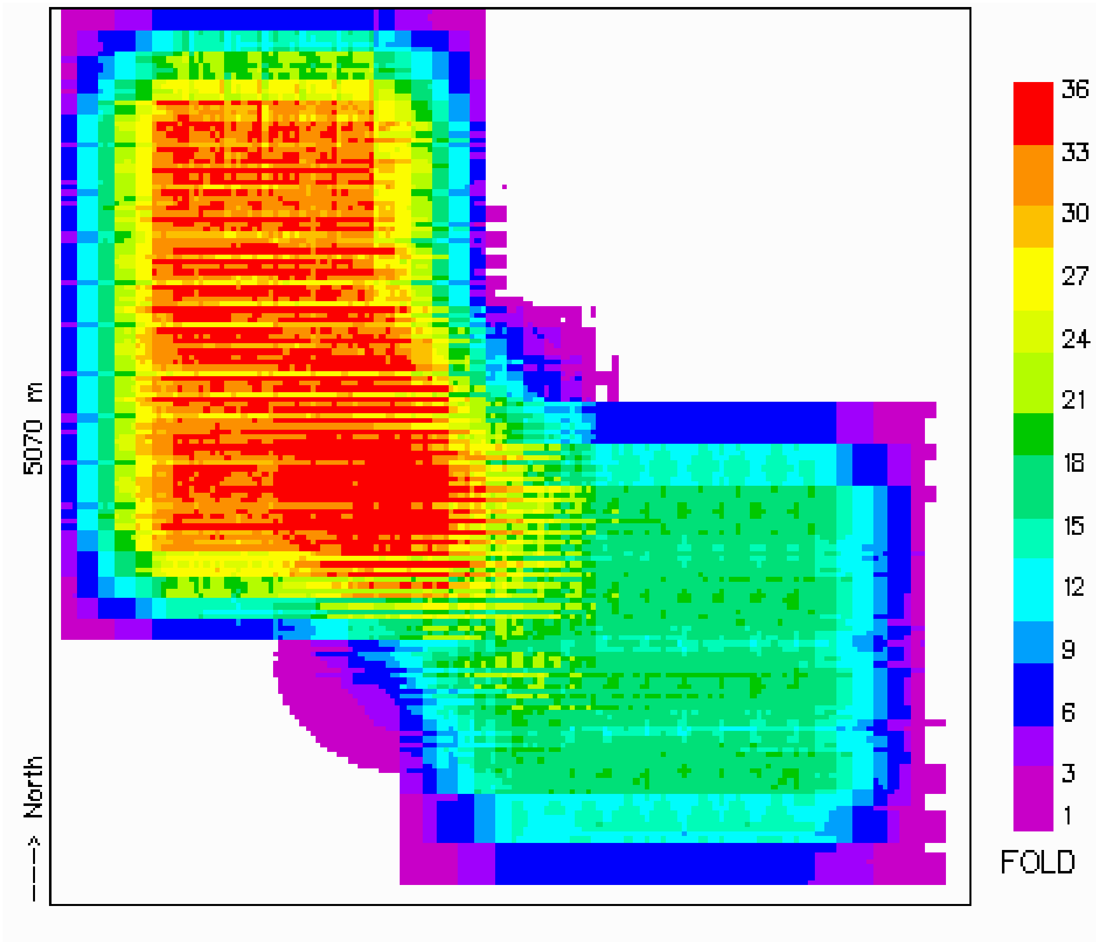

Fig 7. Post-survey P-P fold distribution. Bin size 30 m x 30 m.

Fold sections

The stacking fold was also assessed along sections extracted from the fold volume. Figure 16 shows the stacking fold section along a diagonal section running from the northwest corner of the survey area to the southeast corner. This line intersects a number of wells, as indicated in Figure 16. Stacking fold increases with time, and is higher over the Glauconitic patch than over the Beaverhill Lake patch, as predicted. The Glauconitic reservoir zone occurs at about 1600 ms, which is close to the time where maximum fold is reached. There are some short-wavelength fold variations, but this is not considered to be significant in terms of amplitude footprint in the seismic data, except perhaps at the Glauconitic level within the Beaverhill Lake patch.

Figures 17 and 18 show stacking fold sections along in-line 95 (east-west) and cross-line 125 (north-south) respectively, both of which pass through the 08-08 well. The receiver-line imprint is visible at early times in Figure 18, but variations at the Glauconitic level and later are not considered to be significant. Figures 19 and 20 display detailed blow-ups of the fold sections across the reservoir interval for in-line

95 and cross-line 125 respectively, showing trace-to-trace and sample-to-sample fold variations. Again, these are considered to be small and show no significant imprint on amplitude slices through this interval.

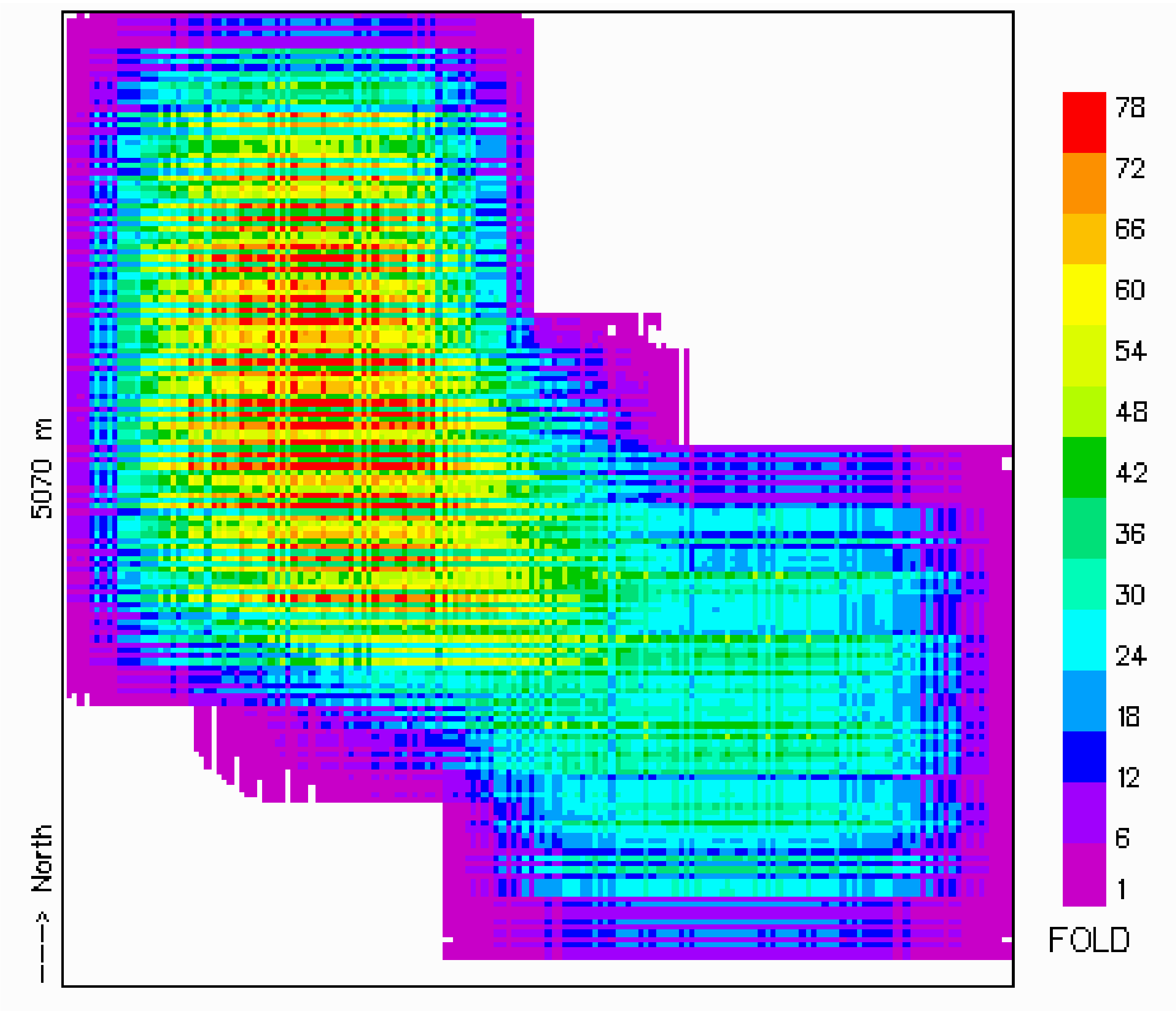

Fig 8. Pre-survey asymptotic P-S fold distribution. Bin size 30 m x 30 m.

CONCLUSIONS

This paper reviews the approach used to design the Blackfoot 3C-3D survey. Comparison of pre-survey, post-survey, and processed *P-S* stacking fold shows that a good fold distribution was achieved using the Flexi-bin® approach. Maximum offset in the processed volume was greater than that anticipated in the initial design, and ranged up to 2300 m for *P-S* data at the level of the Glauconitic reservoir, resulting in stacking fold exceeding 80 in the centre of the Glauconitic patch. Offset and azimuth range were excellent, as predicted from the pre-survey design (Lawton, et al., 1995). Displays of stacking fold, in either time-slice or sections, is a useful means of evaluating acquisition geometry imprint likely to be expected in the processed volume. In the Blackfoot survey, there are no significant fold variations which should lead to amplitude striping in the volume.

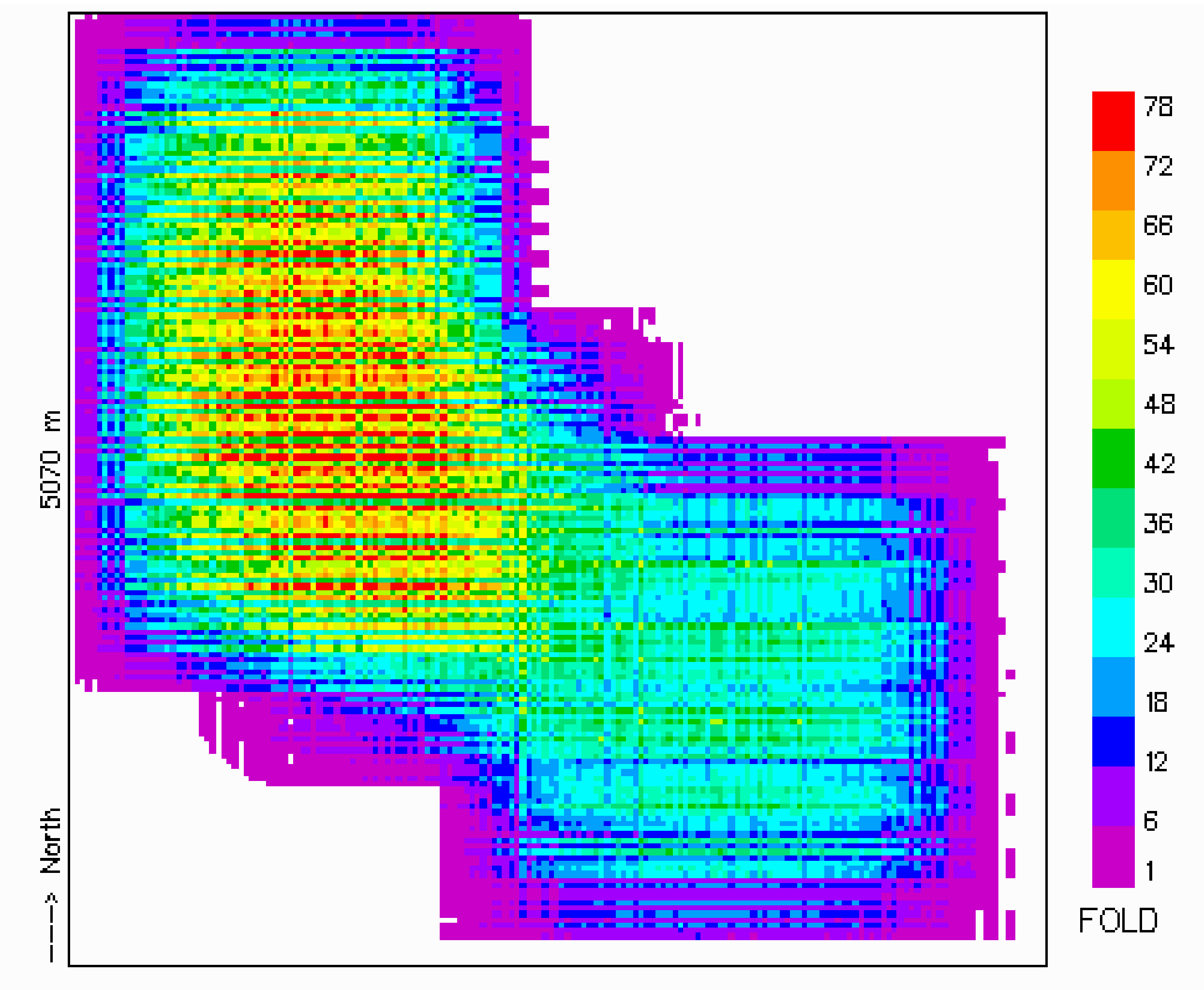

Fig 9. Post-survey asymptotic P-S fold distribution. Bin size 30 m x 30 m.

ACKNOWLEDGEMENTS

We thank the Technical Advisory Group of the Blackfoot Project for valuable input into the design parameters. These people are John Boyd, Louis Blinn, Zig Doborzynski, Larry Mewhort, Darren Kondrat and Garth Syhlonyk. PanCanadian Petroleum Ltd provided geological, well and seismic data from the project area which was useful for assisting in the 3C-3D survey design.

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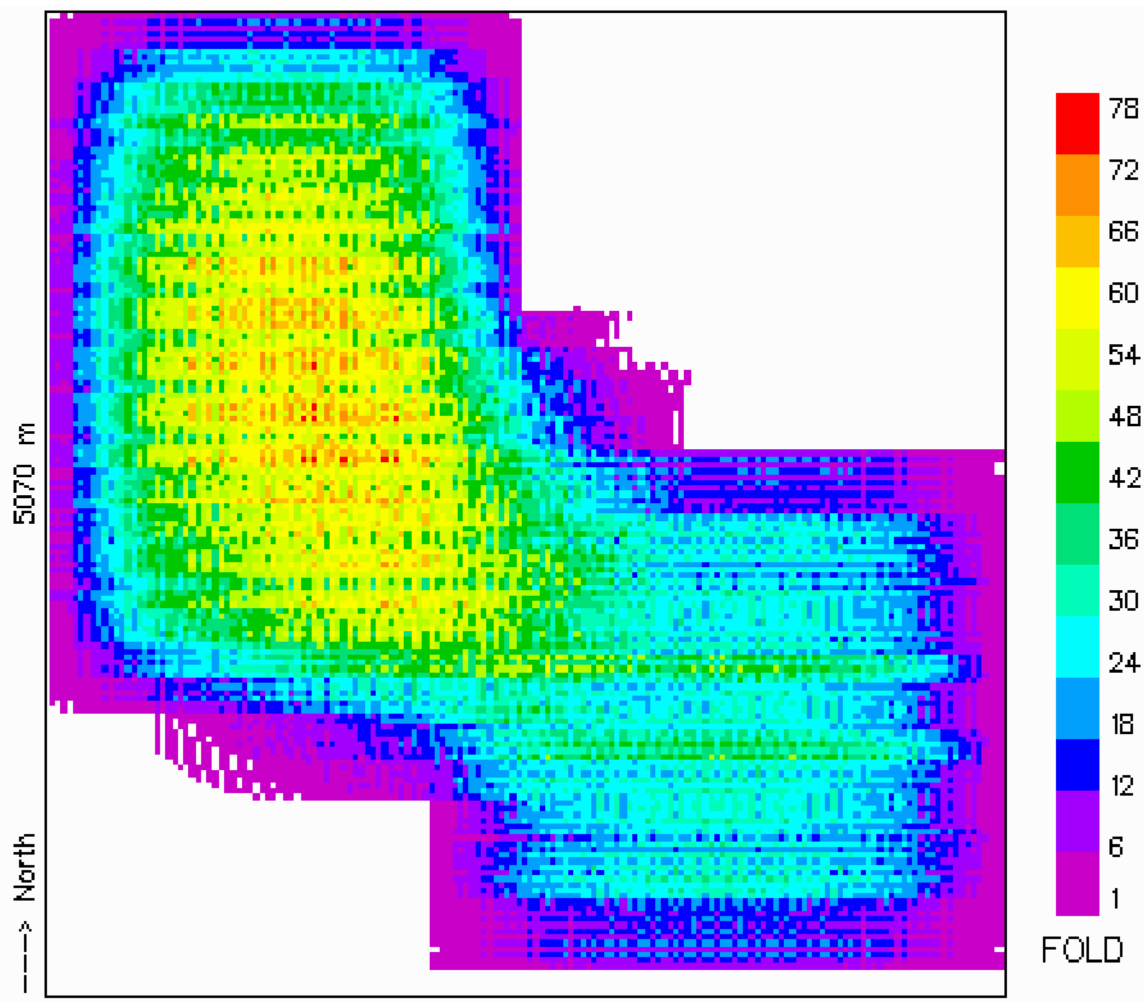

Fig 10. Pre-survey depth-variant P-S fold distribution. Bin size 30 m x 30 m.

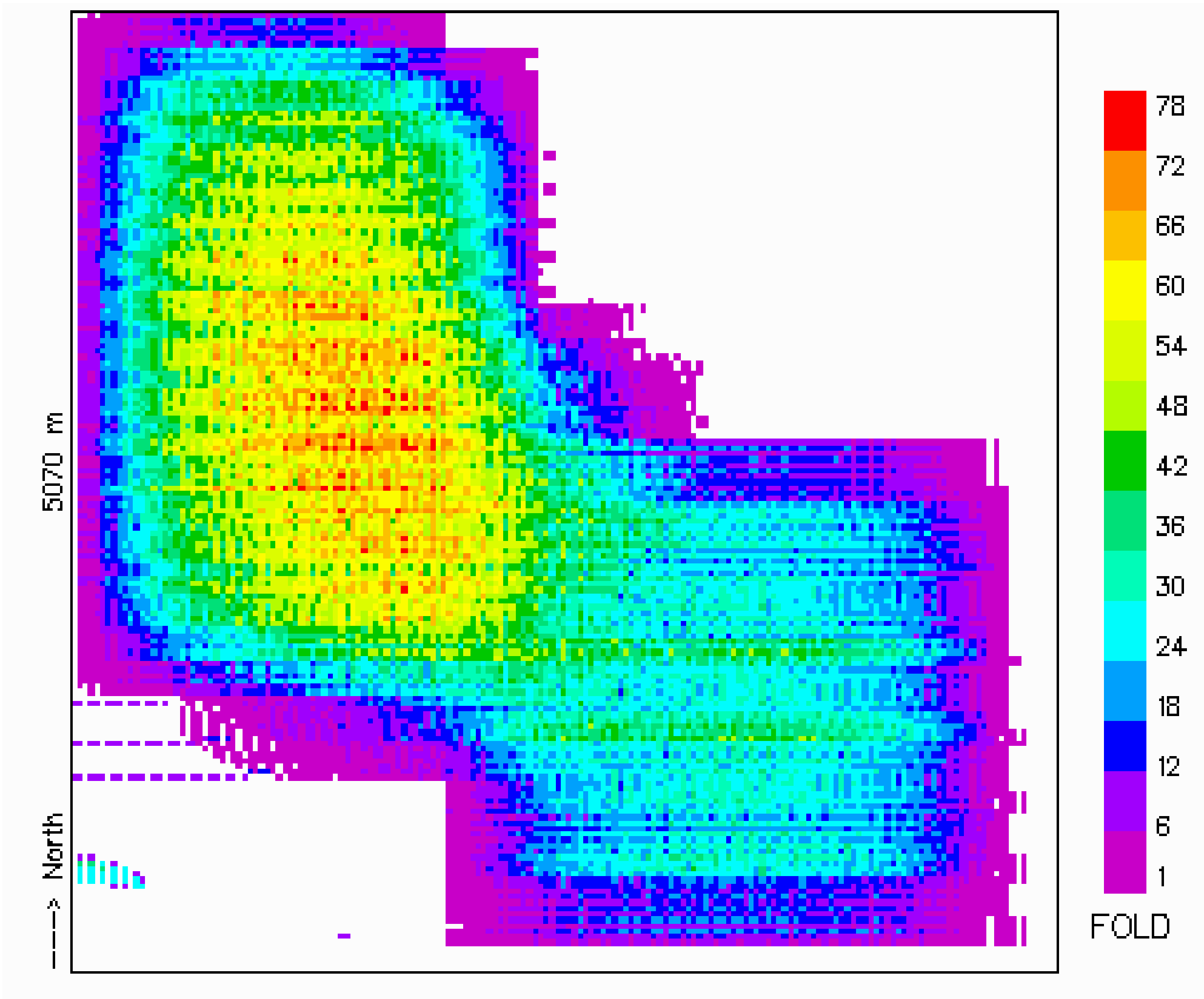

Fig 11. Post-survey depth-variant P-S fold distribution. Bin size 30 m x 30 m. Glauconitic target level.

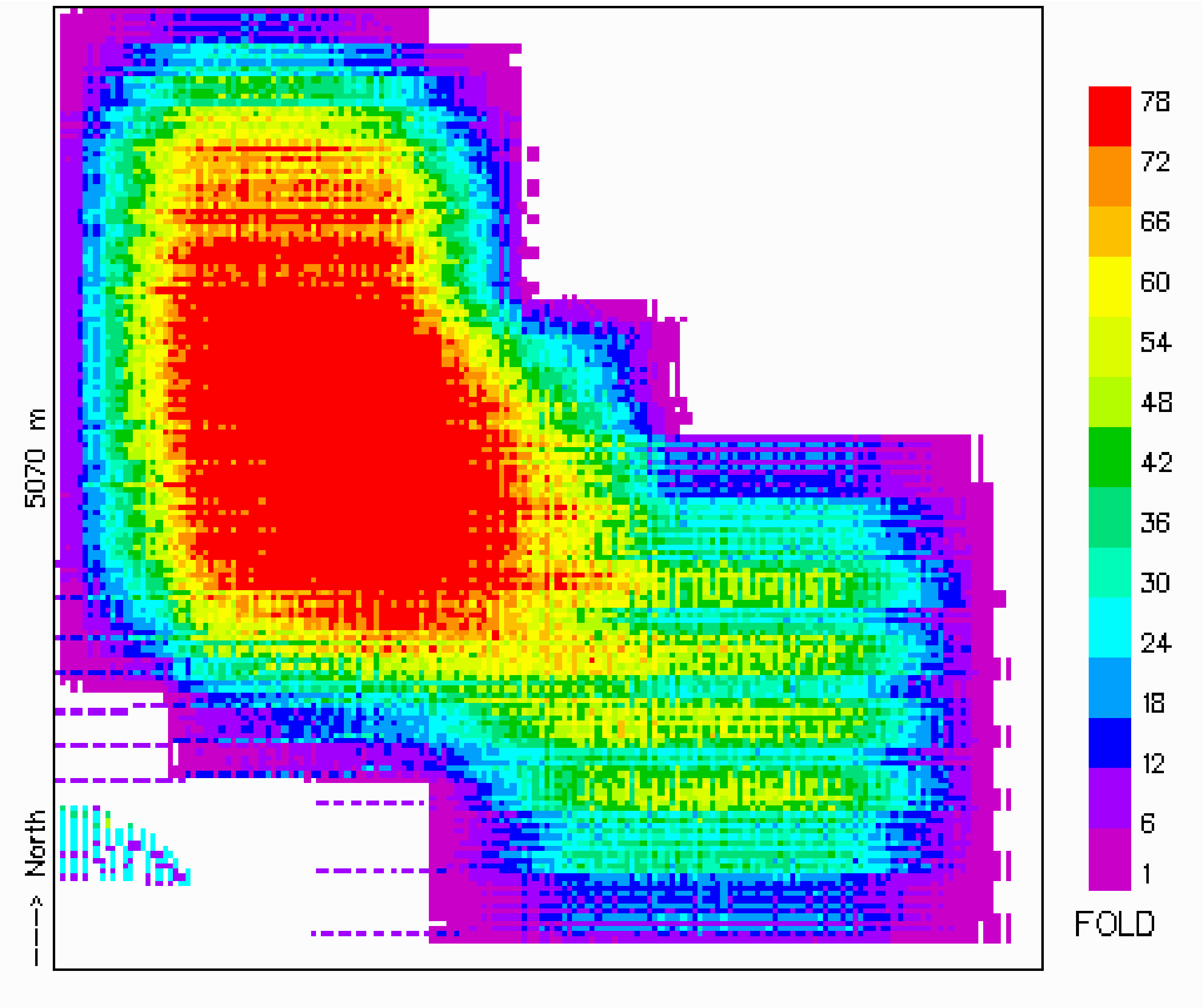

Fig 12. Post-survey depth-variant P-S fold distribution. Bin size 30 m x 30 m. Beaverhill Lake target level.

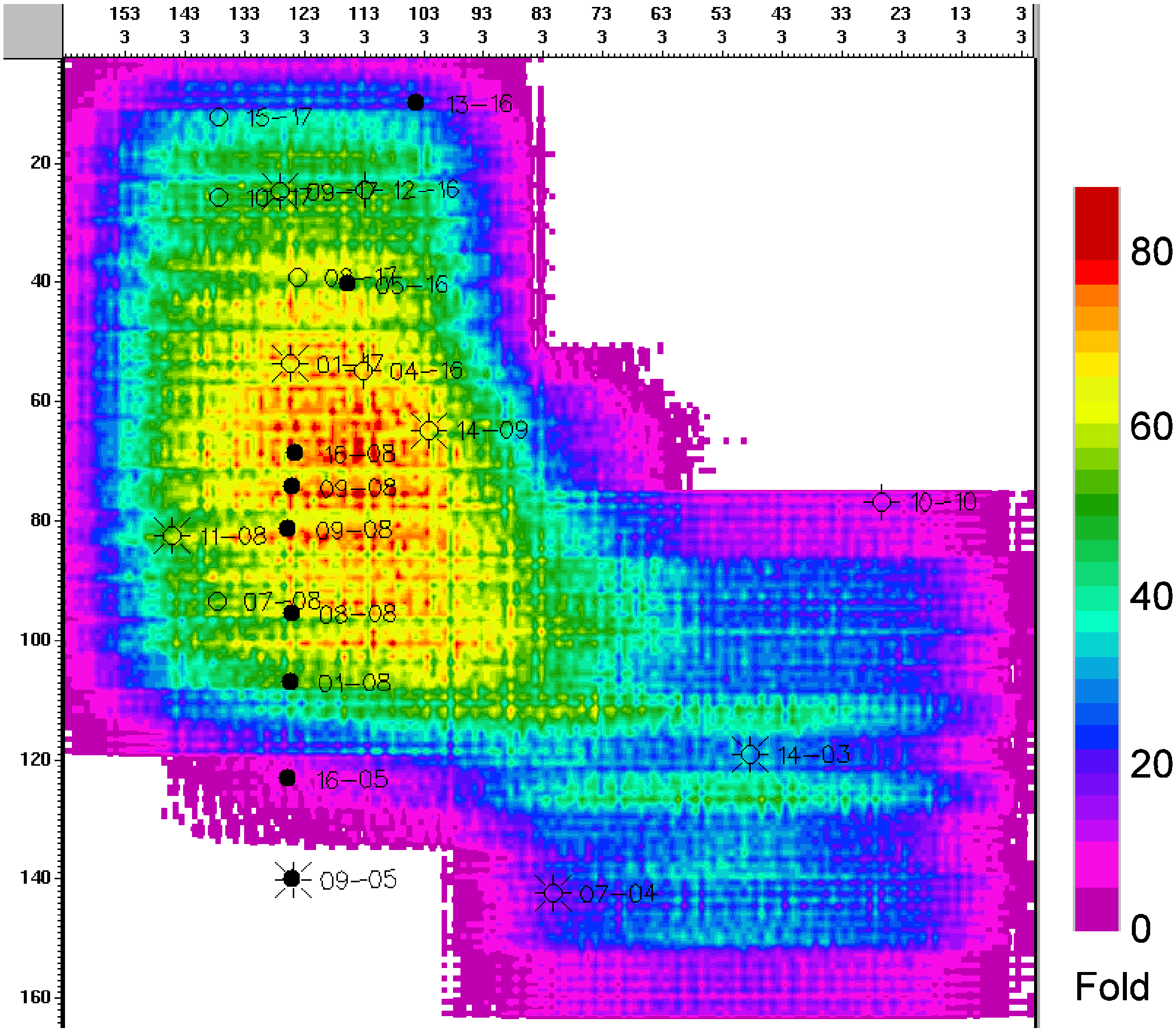

Fig 13. Processed stacking P-S fold distribution at 1500 ms. Bin size 30 m x 30 m. Glauconitic target level.

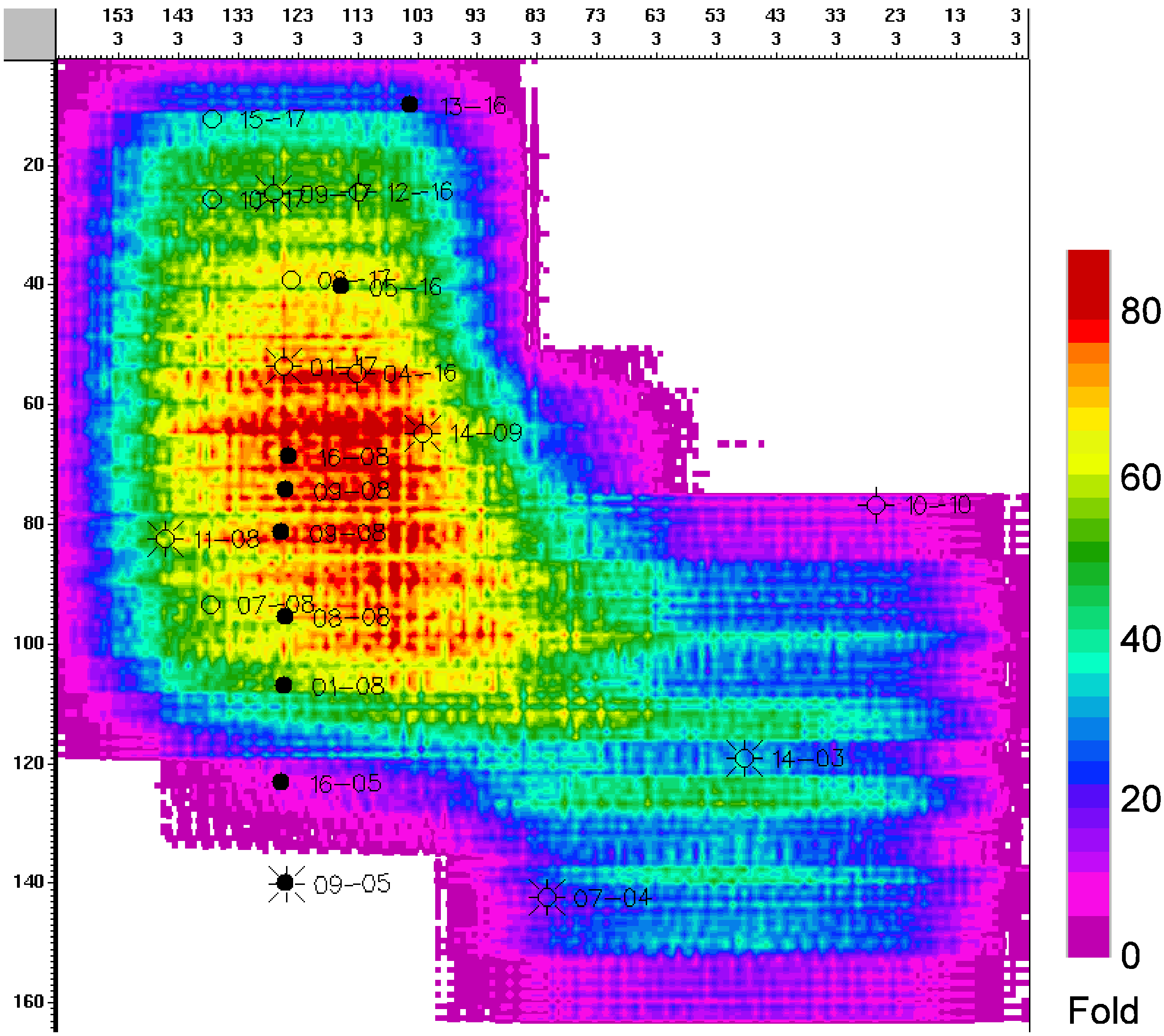

Fig. 14. Processed stacking P-S fold distribution at 1700 ms. Bin size 30 m x 30 m. Glauconitic target level.

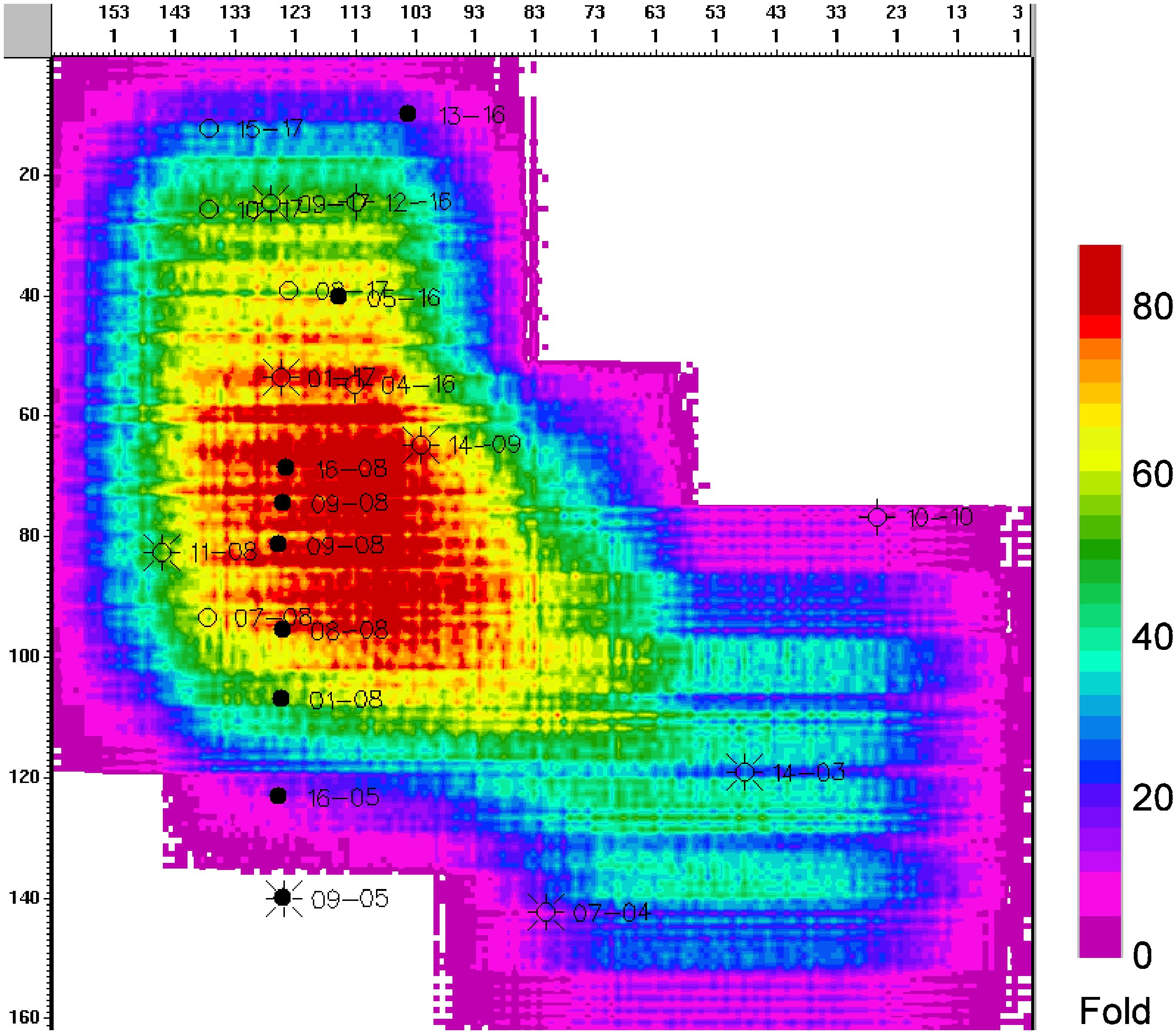

Fig. 15. Processed stacking P-S fold distribution at 2200 ms. Bin size 30 m x 30 m. Beaverhill Lake target level.

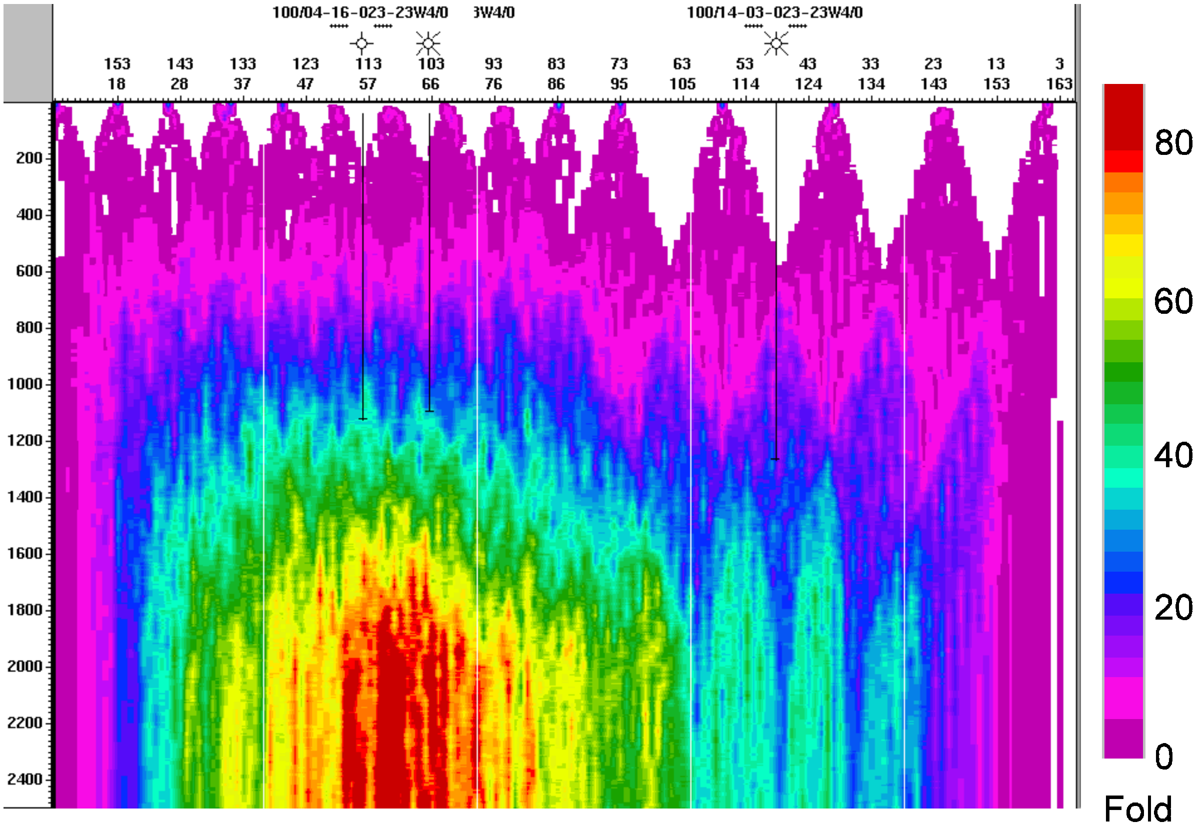

Fig. 16. Processed stacking fold for P-S data from NW-SE diagonal line through survey volume. Trace spacing is 30 m.

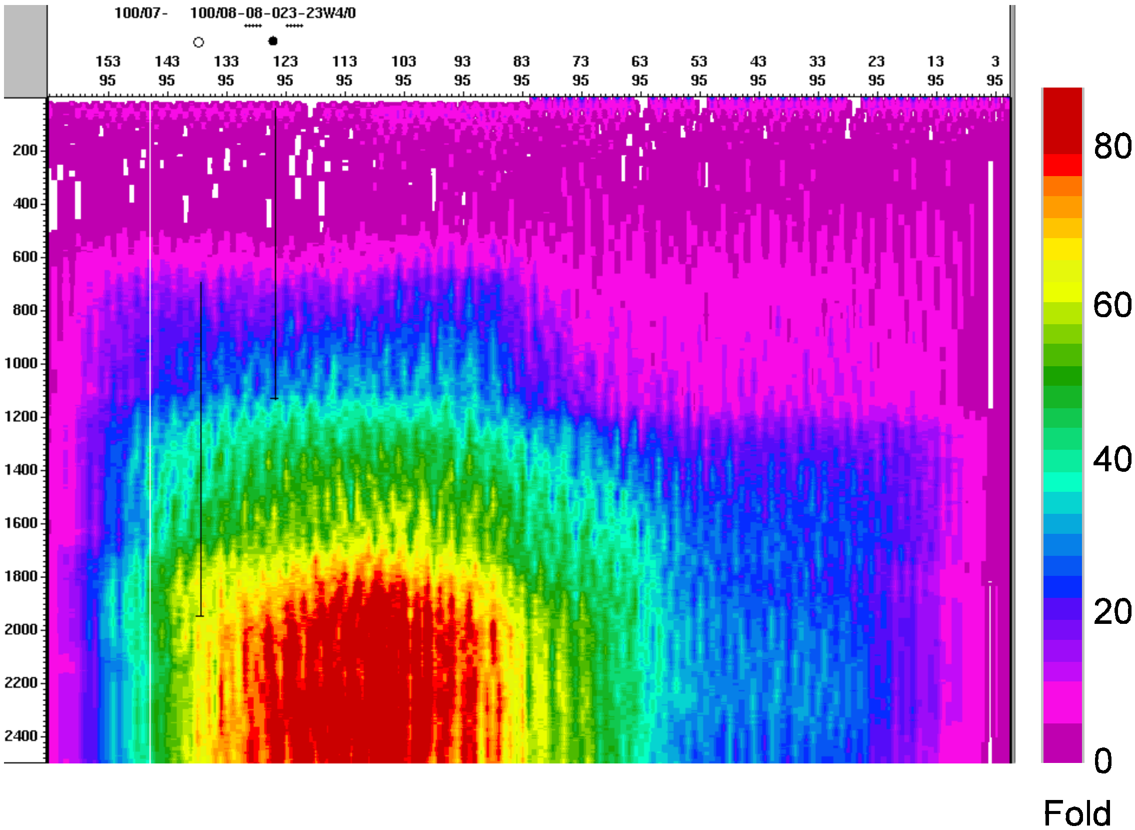

Fig. 17. Processed stacking fold for P-S data from in-line 95 through survey volume. Trace spacing is 30 m.

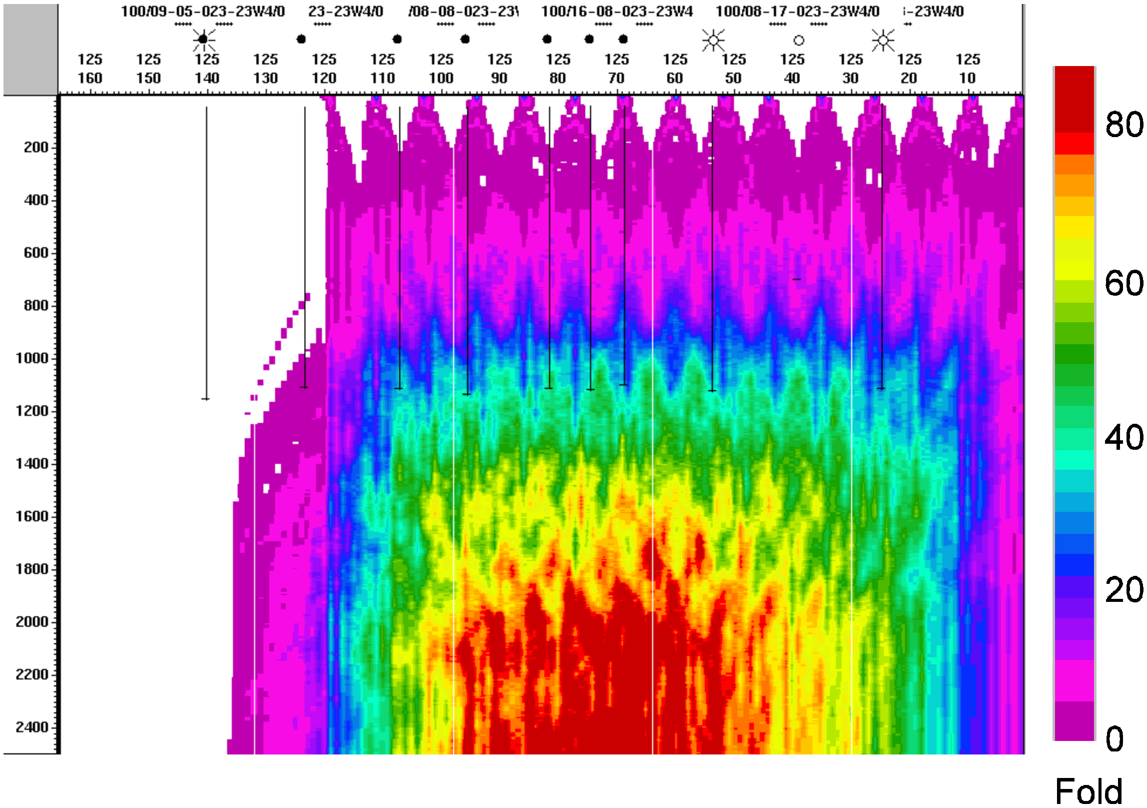

Fig. 18. Processed stacking fold for P-S data from cross-line 125 through survey volume. Trace spacing is 30 m.

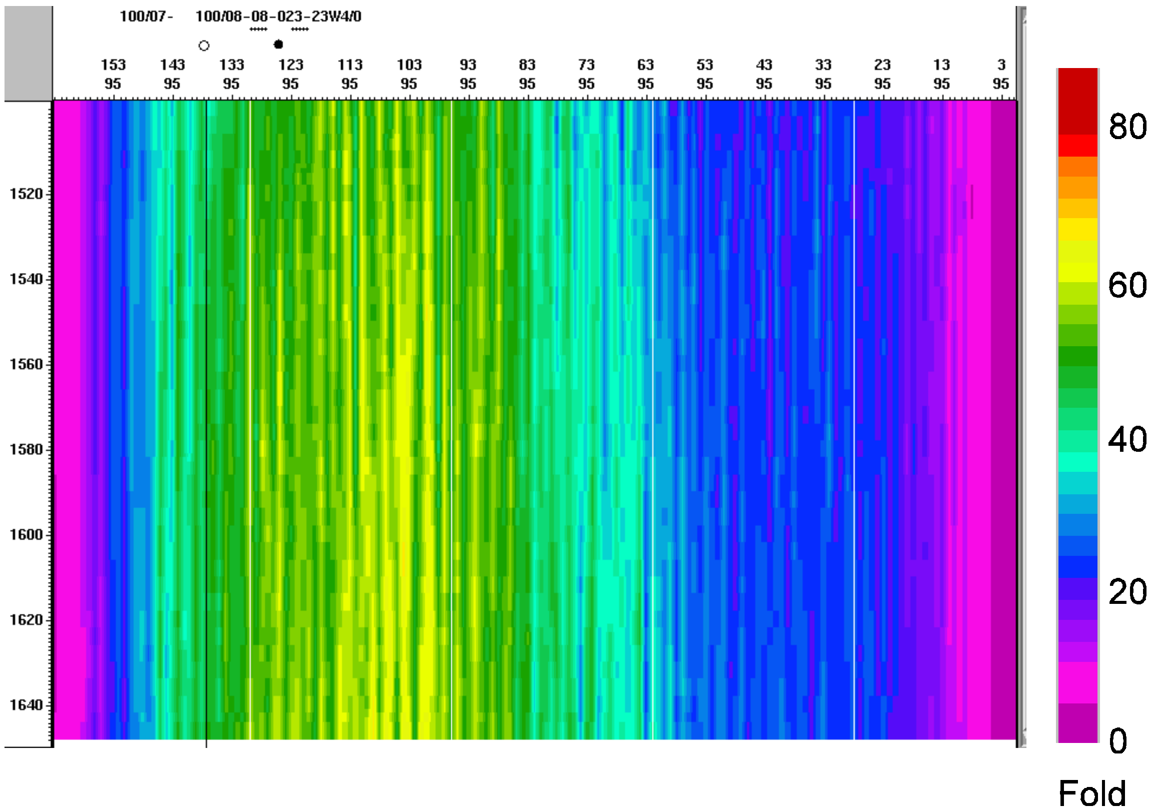

Fig. 19. Detail of processed stacking fold for P-S data from in-line 95 through survey volume at Glauconitic reservoir level. Trace spacing is 30 m.

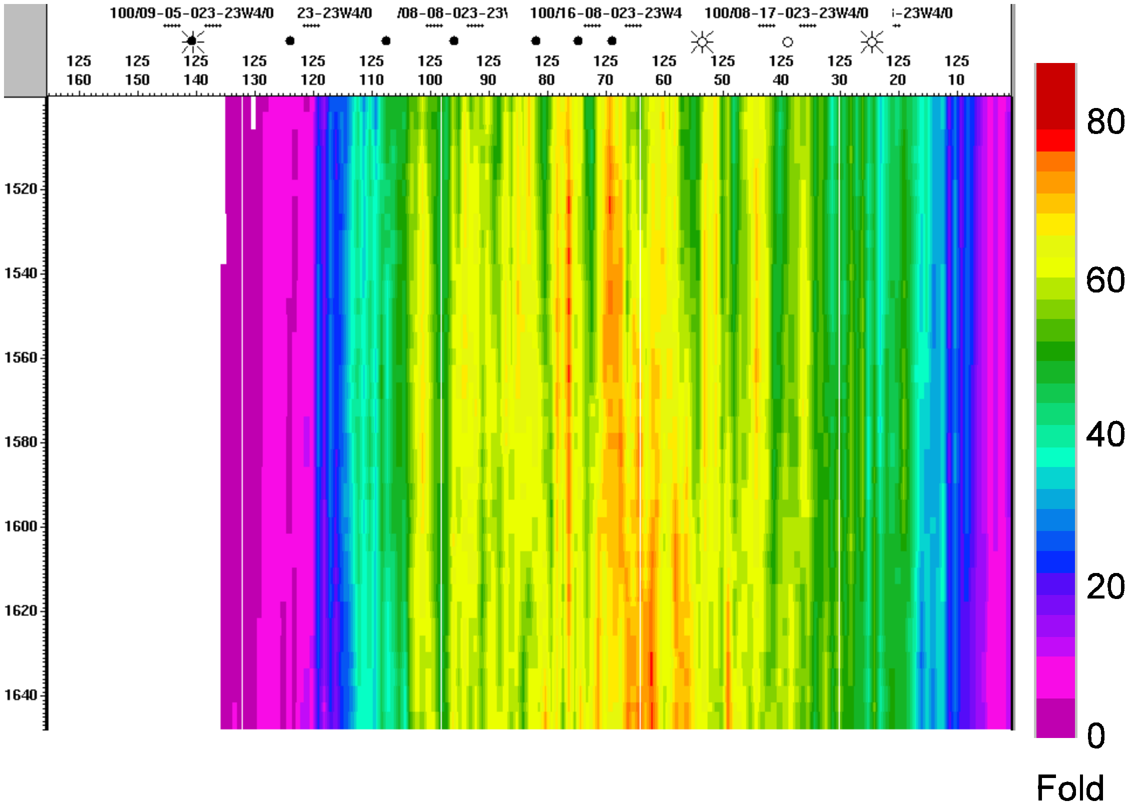

Fig. 20. Detail of processed stacking fold for P-S data from cross-line 125 through survey volume at Glauconitic reservoir level. Trace spacing is 30 m x 30 m.