A 3C-3D seismic survey at a new field research station near Brooks, Alberta

Don Lawton, Malcolm Bertram, Kevin Bertram, Kevin Hall, and Helen Isaac

ABSTRACT

A high-resolution 3C3D seismic survey was undertaken in May, 2014 as a baseline seismic survey for a new field research station (FRS) being developed by CMC Research Institutes, Inc. and the University of Calgary in Newell County, Alberta. The goal of this research station is to develop and calibrate various monitoring technologies for CO_2 detection thresholds at relatively shallow depths (300 m and 500 m) and for assessing and monitoring cap rock integrity. CREWES has access to the seismic data collected at the site for continuing research in multicomponent seismology. The baseline data were collected over a 1 km x 1 km grid with 100 m shot and receiver line intervals and shot and receiver intervals both of 10 m. Shot line and receiver line spacings were reduced to 50 m within the inner 500 m x 500 m of the site in order to image the shallower zone of interest. PP data quality is excellent over the two shallow zones of interest and PS data are noisy and currently still being processed. Time-lapse studies are planned over the next 5 years.

INTRODUCTION

Carbon Management Canada (CMC) has established CMC Research Institutes, Inc. with a mission to accelerate the commercial uptake and widespread implementation of industrial greenhouse gas mitigation technologies through establishment of a series of research institutes. The first of these, the Containment and Monitoring Institute (CaMI), in collaboration with the University of Calgary, is developing a comprehensive Field Research Station (FRS) to facilitate and accelerate research and development leading to improved understandings and technologies for geological containment and storage of CO_2 and monitoring of fossil fuel production and environmental mitigation. Unconventional fossil fuel extraction (e.g. shale gas and in-situ oil sands) and carbon capture and storage (CCS) require new approaches and innovative technologies to be developed for sampling, measurement and monitoring methodologies in order to provide comprehensive models of the subsurface and to ensure containment and operational and environmental conformance and to alleviate public concerns about technical safety.

To address these challenges, CaMI is establishing the FRS to undertake research into the efficacy and evaluation of monitoring technologies in a realistic field setting. The facility will be used to test new measurement, monitoring and verification (MMV) technologies as they are developed and commercialized (e.g. fibre optic devices, slim wells, new analytical instruments for air and water analyses) as well as new approaches to the integration of low-resolution volume-based datasets (3D seismic volumes) with high resolution point measurements (wells).

The specific objectives being assessed at the FRS are sensitivity of monitoring systems for early detection of loss of conformance and in mapping temporal changes in cap rock that may lead to loss of containment. The FRS is being constructed on lands ~25 km southwest of Brooks, Alberta (Figure 1), and the site will operate for at least 10 years. Capital investment for development of the site is estimated to be $10 million. Construction has begun on an array of wells, sensing stations, and surface facilities that will be monitoring fluid injection and cap rock behaviour at depths of 300 m and 500 m below surface. Technologies being evaluated will include time-lapse surface and borehole seismic surveys, microseismic surveys, geochemical, cross well, electrical resistivity, electromagnetic, gravity, geodetic and geomechanics surveys. The layout of the surface facilities of the FRS are shown in Figure 1.

CREWES will have an active role in processing and undertaking research on seismic data collected at the FRS in order to advance time-lapse seismic imaging and full-waveform inversion for monitoring subsurface fluid flow, including containment and conformance monitoring.

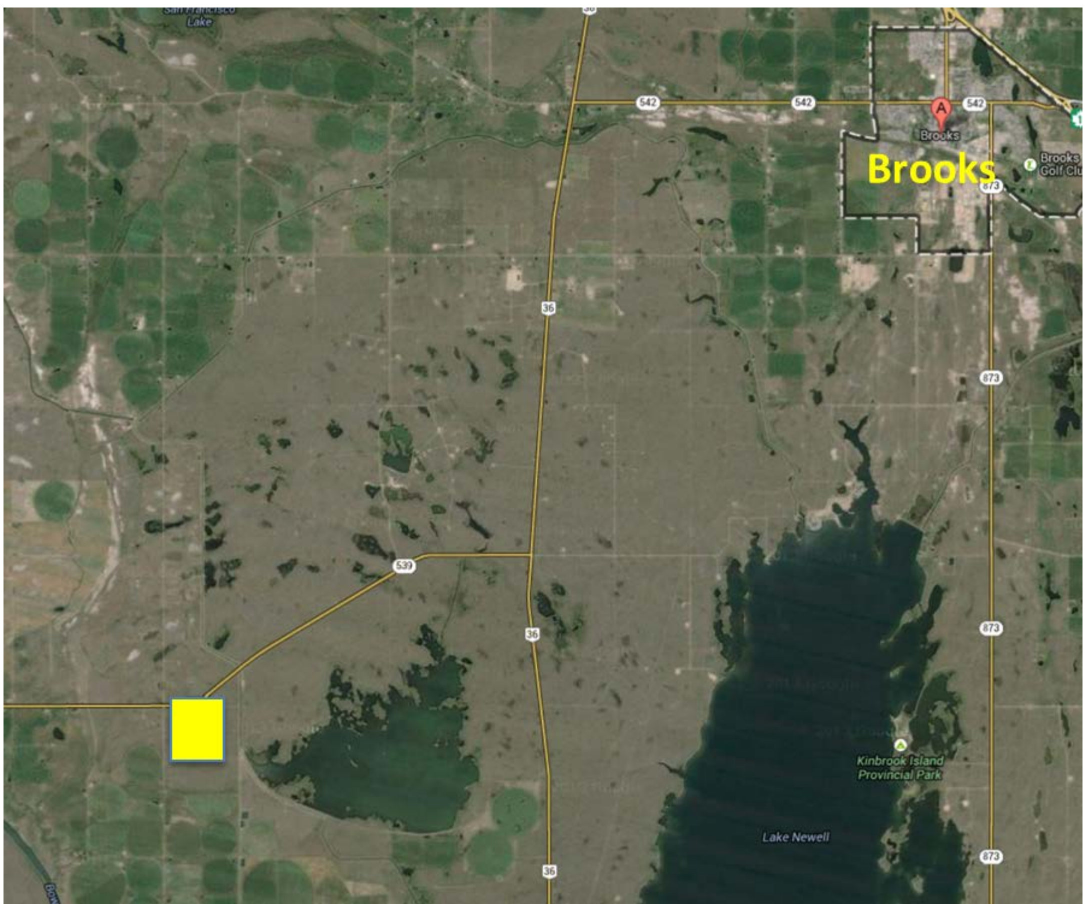

FIG.1. Location of the FRS (yellow rectangle) southwest of Brooks, Alberta.

Figure 2 shows the 1 km x 1 km site and a schematic diagram showing the layout of the surface facilities. Construction is scheduled to be completed in 2015. The baseline seismic program was undertaken in May, 2014 in order to build the geostatic model of the site

(Dongas and Lawton, 2014) and to characterise the zones of interest (Isaac and Lawton, 2014a).

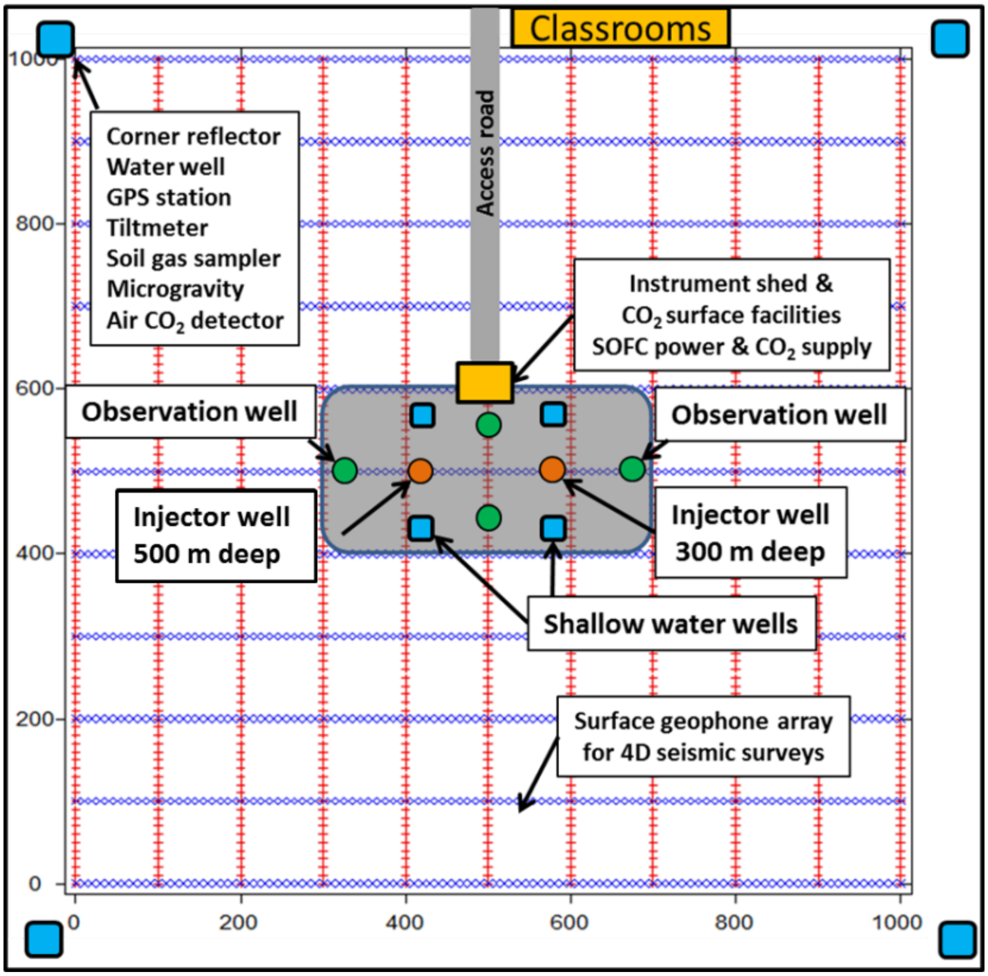

FIG. 2. Schematic layout of facilities at the CaMI-University of Calgary Field Research Station.

PRE-SURVEY DESIGN

The design of multicomponent land seismic surveys has been extensively assessed in the literature (e.g. Stone, 1994; Cordsen et al., 2000; Vermeer, 2002; Meier, 2009; Zuleta and Lawton, 2011). Initial survey design assumed asymptotic conversion points, i.e. an assumption of a large depth-to-offset ratio which generated highly variable fold when binned using CMP-based binning (e.g. Eaton and Lawton, 1992; Cordsen and Lawton, 1996). Yang and Lawton (2002) examined the influence of VTI on the conversion point location and Lawton and Hoffe (2000) reviewed binning issues for marine ocean-bottom recording.

In the current study, the design issue was a compromise between very shallow imaging (300 m depth) and total cost. Final acquisition parameters chosen for the seismic baseline program are listed in Table 1. Nominal, source and receiver line intervals of 100 m was used in an orthogonal pattern, reducing to 50 m spacing for more detailed shallow imaging in the centre part of the survey area.

Table 1. Acquisition parameters for the baseline 3C3D seismic program at the FRS.

Parameter	Value
Source line interval (outer)	100 m
Source line interval (inner)	50 m
Receiver line interval (outer)	100 m
Receiver line interval (inner)	50 m
Source spacing	10 m
Receiver spacing	10 m
Source	2xEnvirovibes
Source sweep	8 – 150 Hz
Sweep length	16 s; 0.2 s taper
Receivers	3-C SM-7 geophones
Recorder	Hawk nodes
Sample interval	1 ms
Binning (CDP and CCP)	5 m x 5 m

The pre-survey geometry for the seismic program is shown in Figure 3. The injection wells will be placed in the centre of the survey area, hence the denser shot and receiver grid within the inner part of the survey.

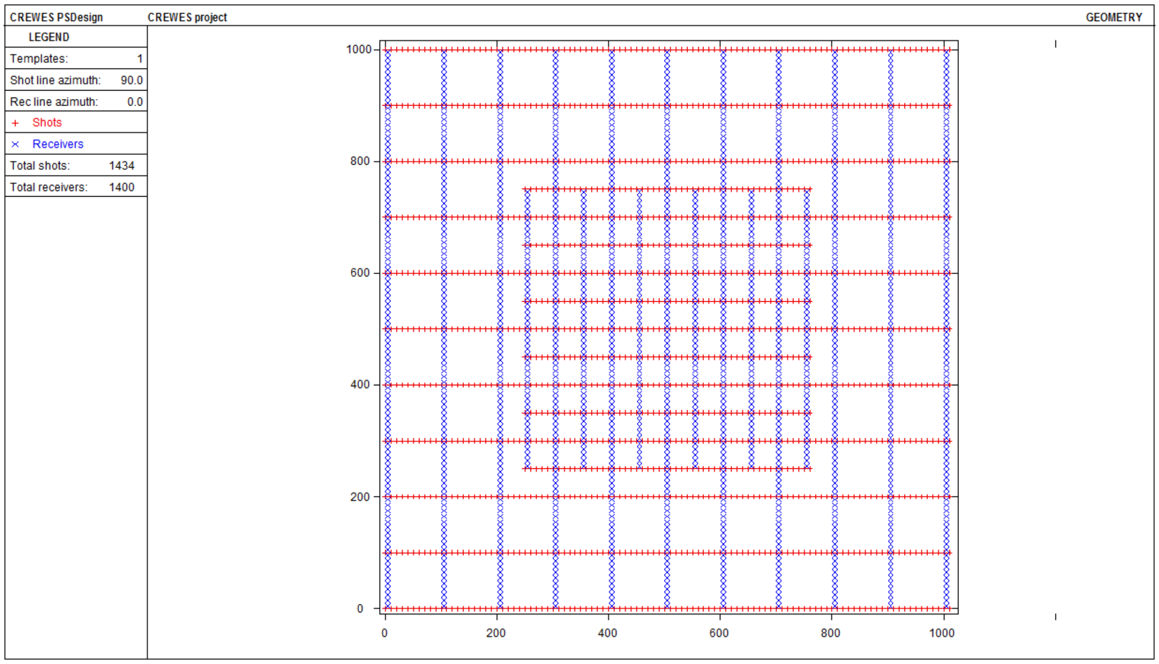

FIG. 3. Pre-survey geometry for the FRS baseline seismic program.

Nominal PP fold is shown in Figure 4, calculated from recording all shots into all receiver, regardless of source-receiver offset. This totalled 1434 shots into 1400 receivers,

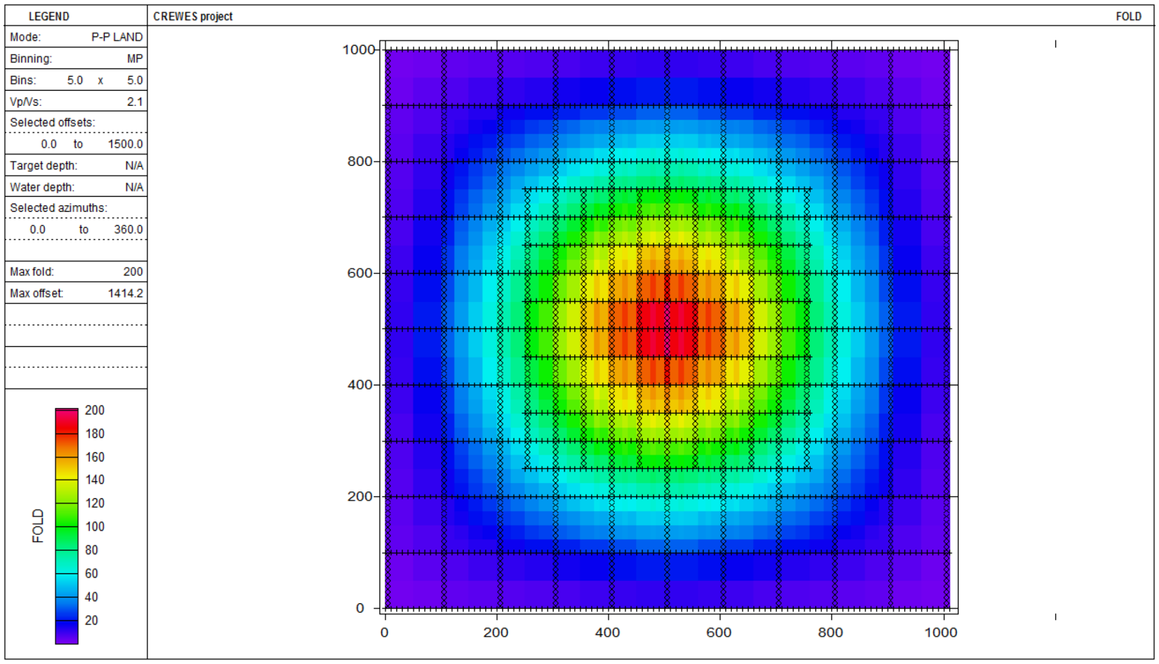

FIG. 4. Nominal pre-survey PP fold for the FRS baseline survey

yielding a total of just over 6 million traces for the program,. Maximum fold in the centre of the survey is 200, and exceeding 80 fold within the boundaries of the inner dense grid (Figure 4).

On order to map PS fold for various target depths, some knowledge about Vp/Vs for the region is required. A database search yielded a dipole sonic log from well 01-07-18-15W4M, about 20 km north of the FRS site. Figure 5 shows the Vp/Vs log extracted from the log data. In the shallow section, to about 350 m depth, the average Vp/Vs is approximately 2.3, reducing to about 2.1 for depths from 350 m to 1115 m (TD).

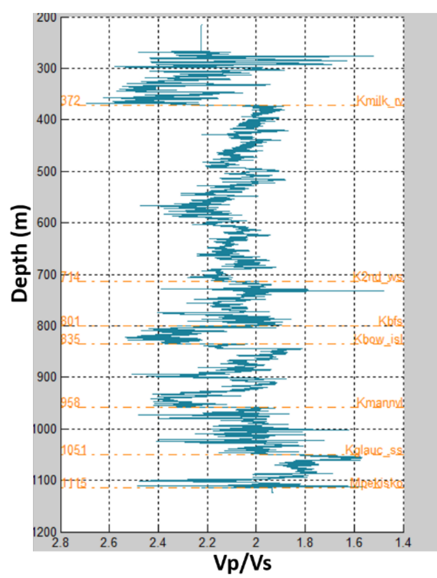

FIG. 5. Vp/Vs extracted from dipole sonic log from 01-07-18-15W4M

These Vp/Vs values were used to compute nominal PS fold at the target depths of 300 m and 500 m, using a ray-tracer built into CREWES survey design software PSDesign. Figures 6 and 7 show the PS fold for the 300 m (Vp/Vs = 2.3) and 500 m (Vp/Vs = 2.1) deep targets, respectively.

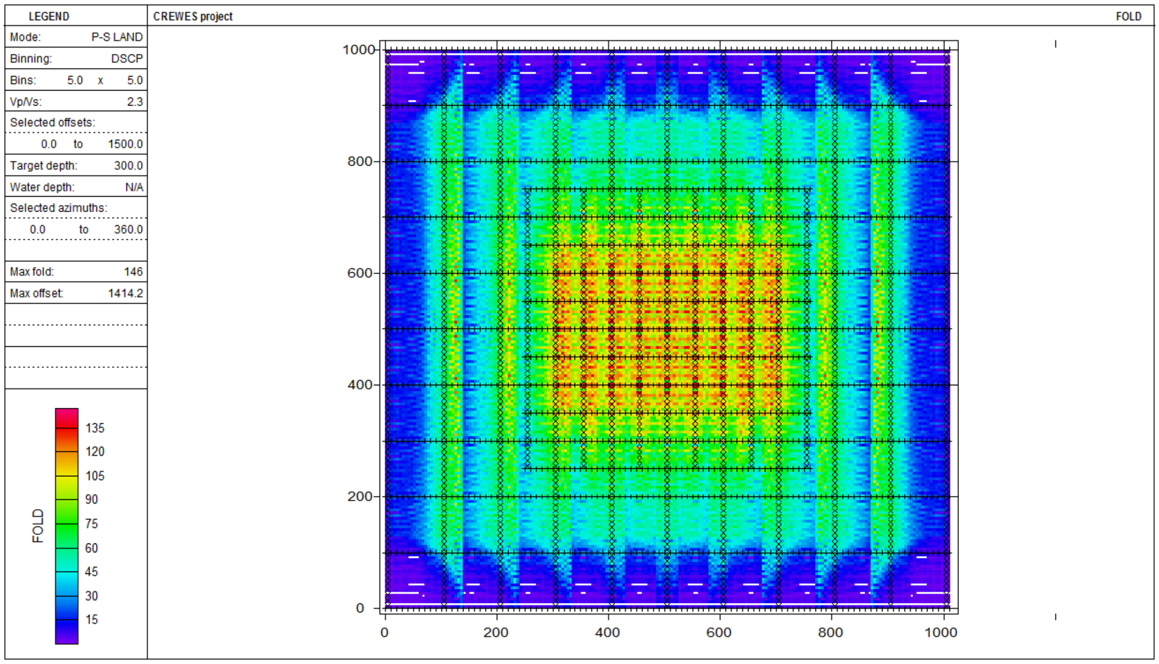

FIG. 6. Nominal pre-survey PS fold and a depth of 300 m for the FRS baseline survey.

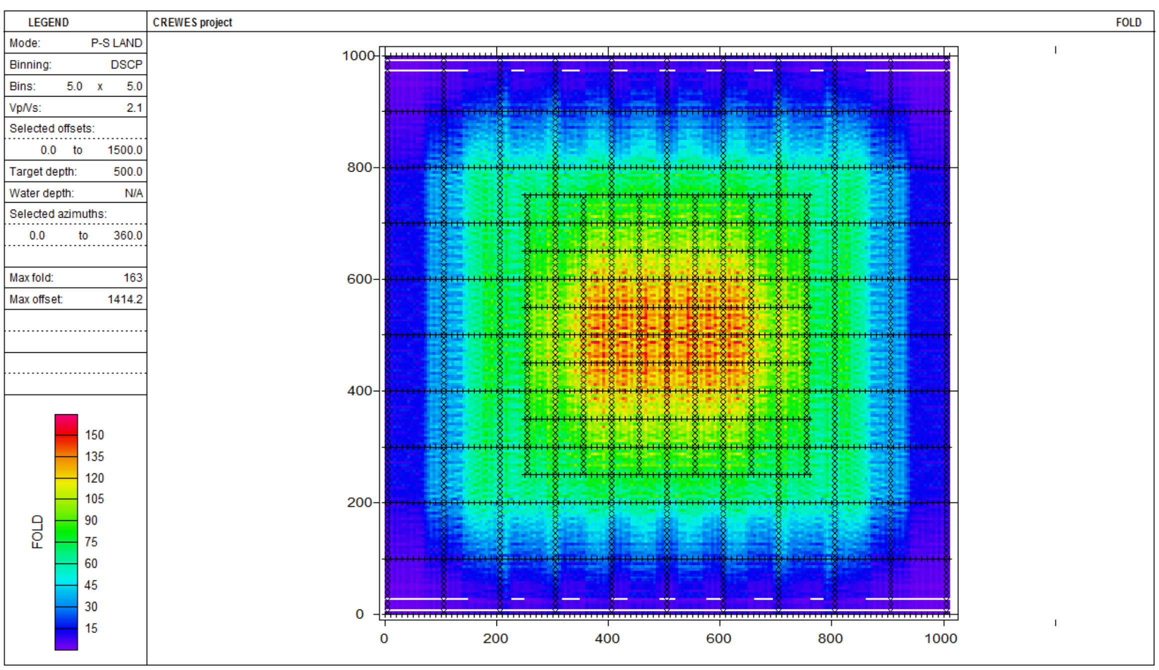

FIG. 6. Nominal pre-survey PS fold at a depth of 500 m for the FRS baseline survey.

No asymptotic PS design scenarios were considered as this approach is incorrect and misleading for large offset to depth rations. Maximum PS fold for the depth-specific binning for the two target depths are 146 and 163 respectively. The difference is caused by conversion-point scatter within the 5 m x 5 m bins.

FIELD DESIGN AND ANALYSIS

Geospatial surveying of the shots and receiver layout was undertaken by Cook Leach Surveys, under contract to CaMI. Within the FRS site there are two pipelines that required source setbacks. Figure 7 shows the actual field geometry used for data acquisition. The two southwest-northeast trending pipelines are clearly identifiable.

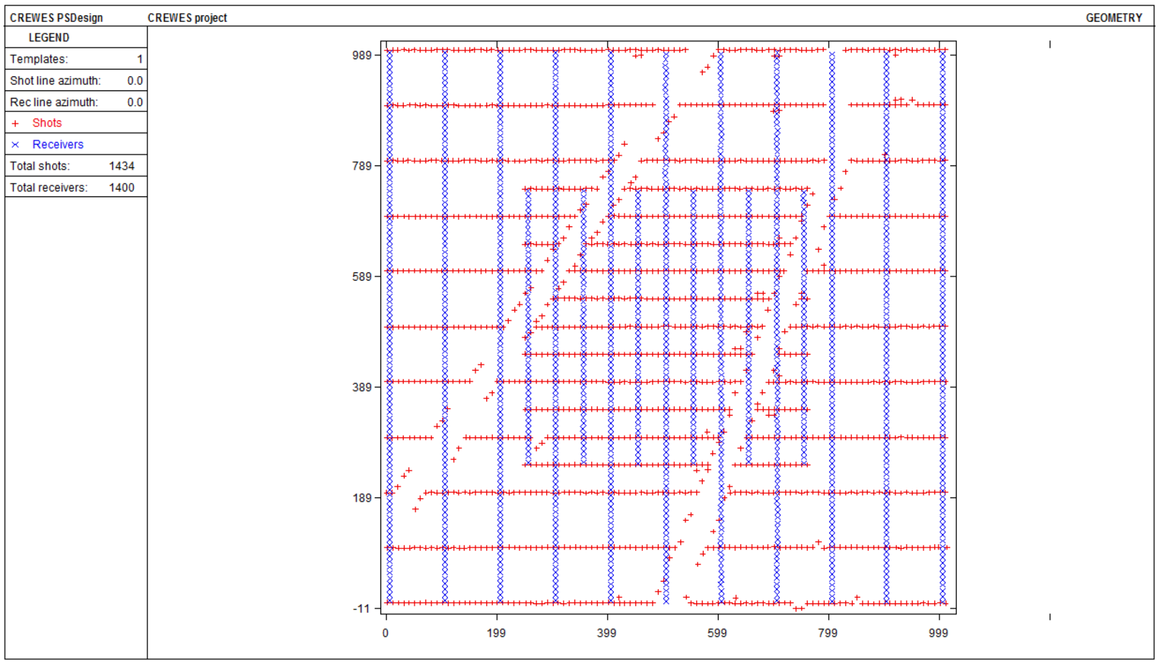

FIG. 7. Field geometry for the FRS baseline seismic program

The fold maps shown in Figures 4, 6, and 7 are nominal fold with all source-receiver offsets included. Realistic fold maps must include the likely offset-mute pattern in order to compute effective fold (i.e. traces that actually contribute to final stack). This was assessed from seismic data available to the project prior to the survey, as well as post-survey analysis during processing of the 3C3D data itself (Figure 8).

The PP offset-mute was established from a super-gather from the survey, shown in Figure 8. Offset mutes for the two shallow zones of interest are shown by the arrows in Figure 8, and are 430 m and 600 m respectively. Whilst these zones are of the most interest for the CMC project, excellent reflection signal quality is seen in later events, with useable source-receiver offsets of 1300 m (Figure 8). For general geophysical research, CREWES is interested in reflection data acquired over all depths.

Figures 9 and 10 illustrate the effective PP fold for maximum source-receiver offsets of 430 m and 600 m respectively. The fold patterns are similar but the maximum effective fold is obviously less than the nominal fold, shown in Figure 3. PP fold in the centre of the survey area is 63 and 111 for offset limits of 430 m and 600 m respectively. For PS fold analysis, the field data has not yet been processed to the extent that offset-mutes could be established. Based on earlier studies, PS fold was computed for an offsets up to 1.5 times the target depth.

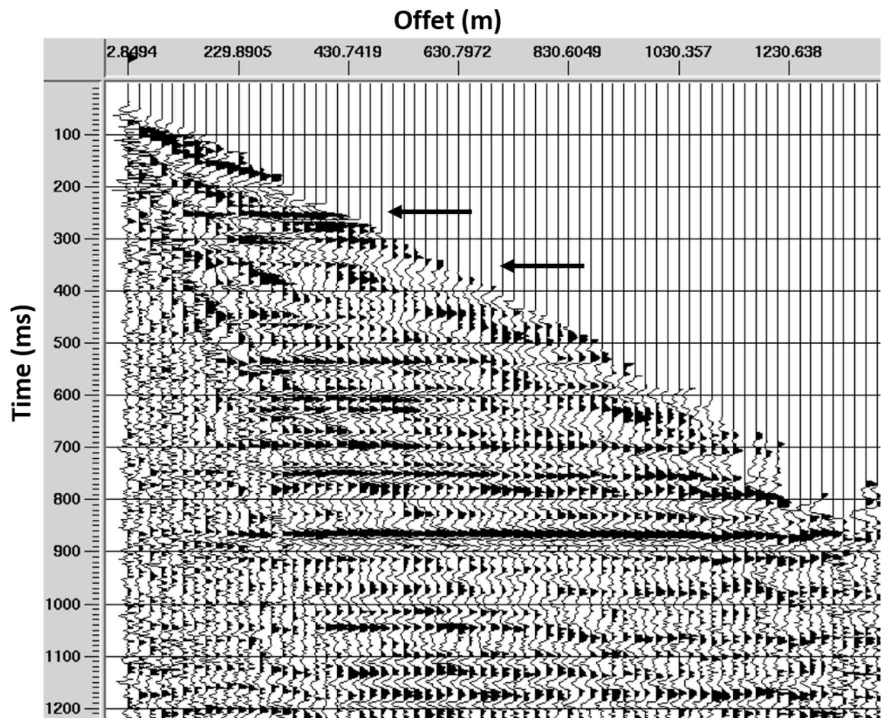

FIG. 8. PP super-gather showing the offset-mute pattern. Arrows are the 300 and 500 m target depths for the CaMI project.

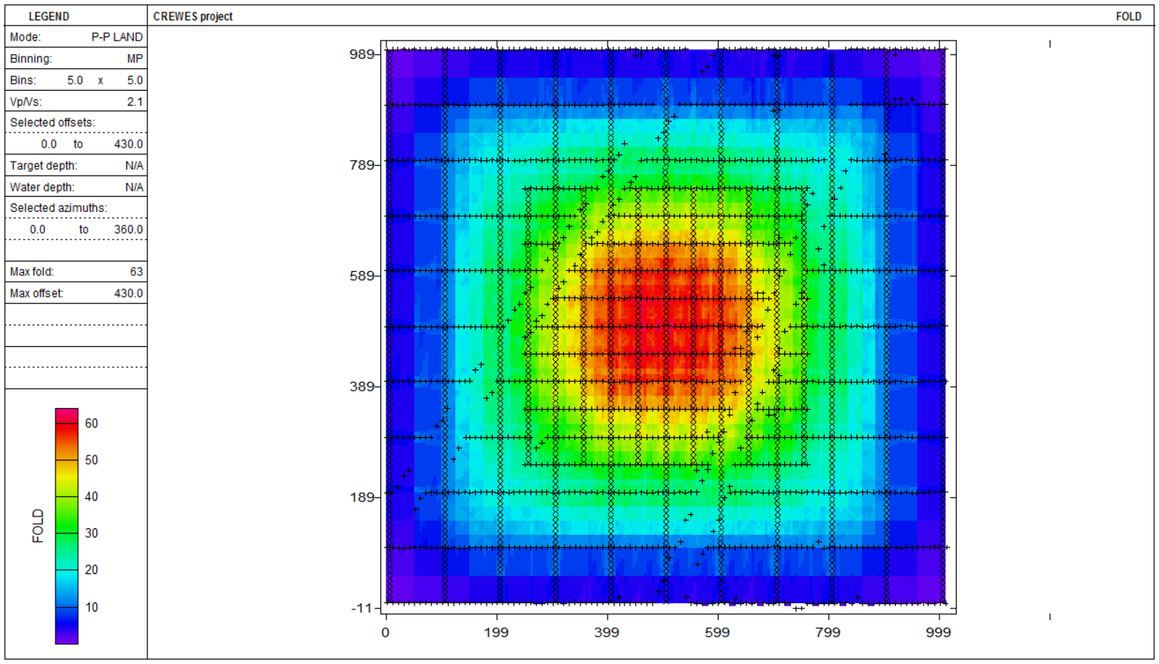

FIG. 9. Field PP fold for the FRS baseline survey, offsets limited to 430 m.

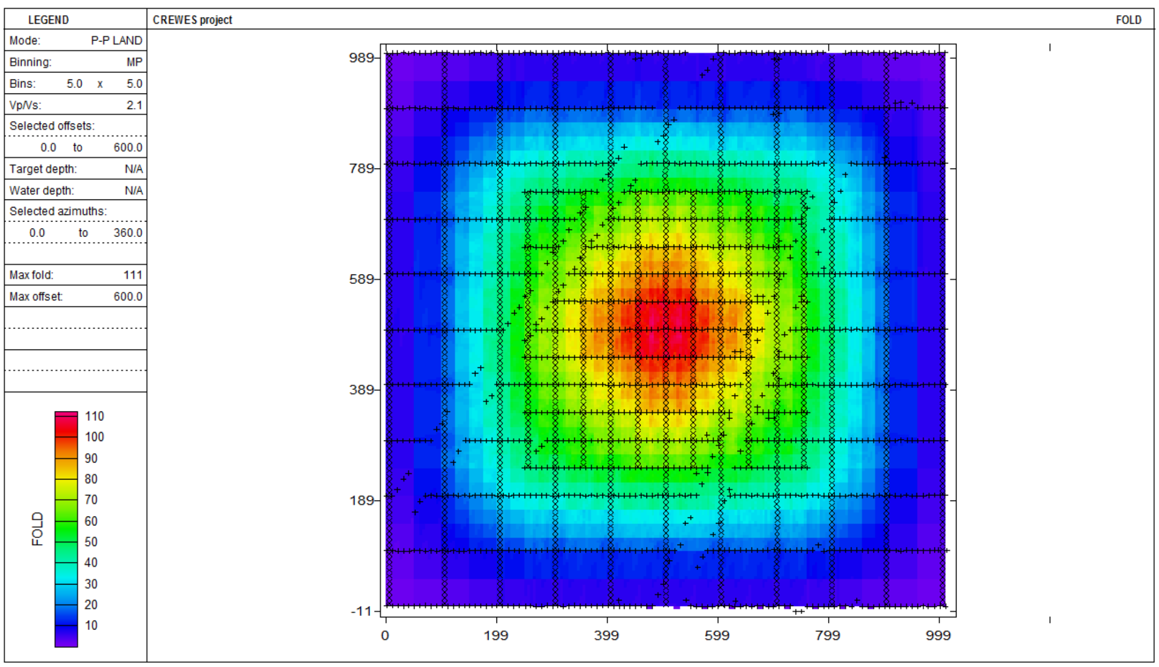

FIG. 10. Field PP fold for the FRS baseline survey, offsets limited to 600 m.

Figures 11 and 12 illustrate the effective PS fold for maximum source-receiver offsets of 450 m and 750 m, respectively, corresponding to imaging depths of 300 m and 500 m. Maximum fold is 79 and 143 respectively. For interest, we also modelled the PS fold for a target depth of 1000 m, using all available offsets (Figure 13).

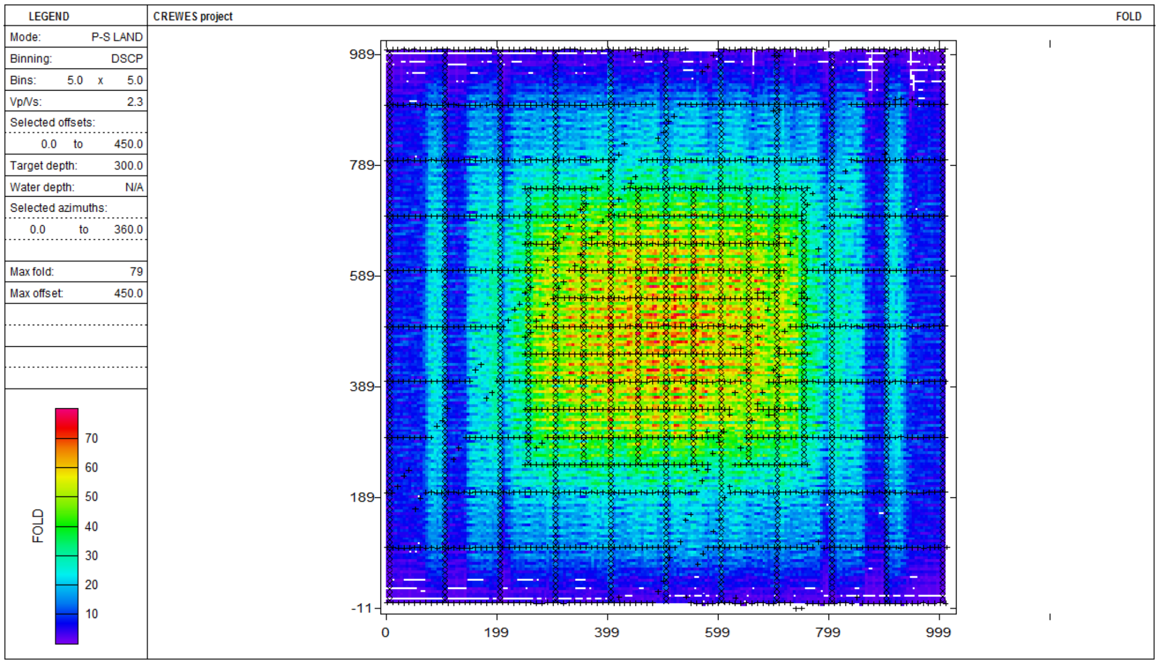

FIG. 11. Field PS fold for the FRS baseline survey, offsets limited to 450 m, target depth 300 m.

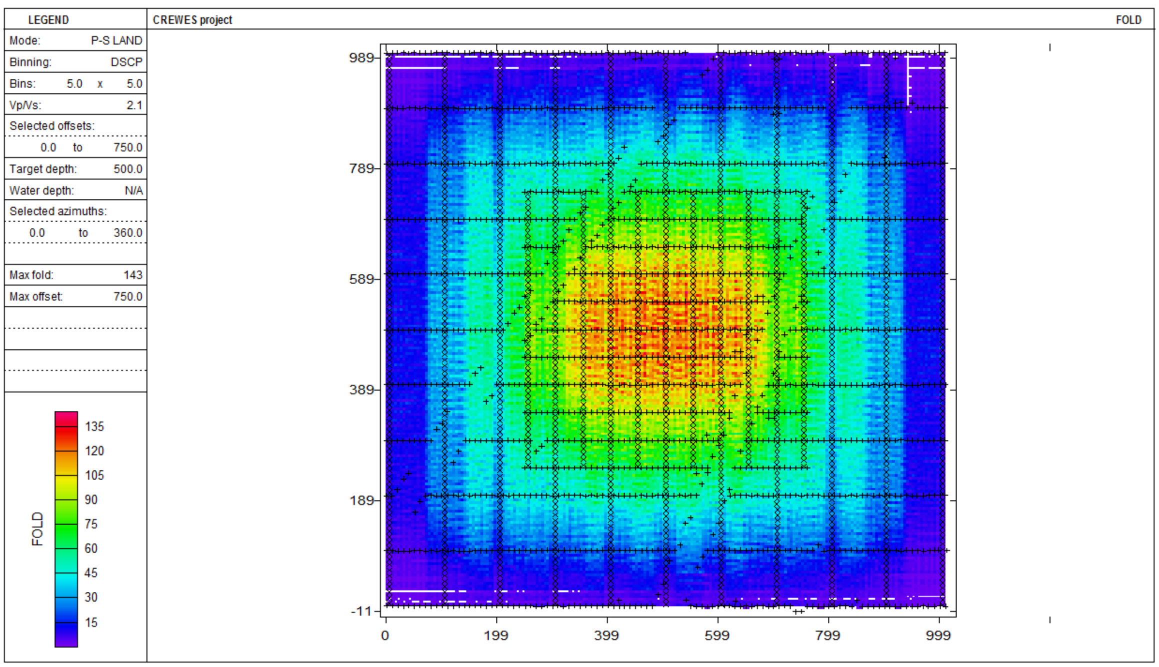

FIG. 12. Field PS fold for the FRS baseline survey, offsets limited to 750 m, target depth 500 m.

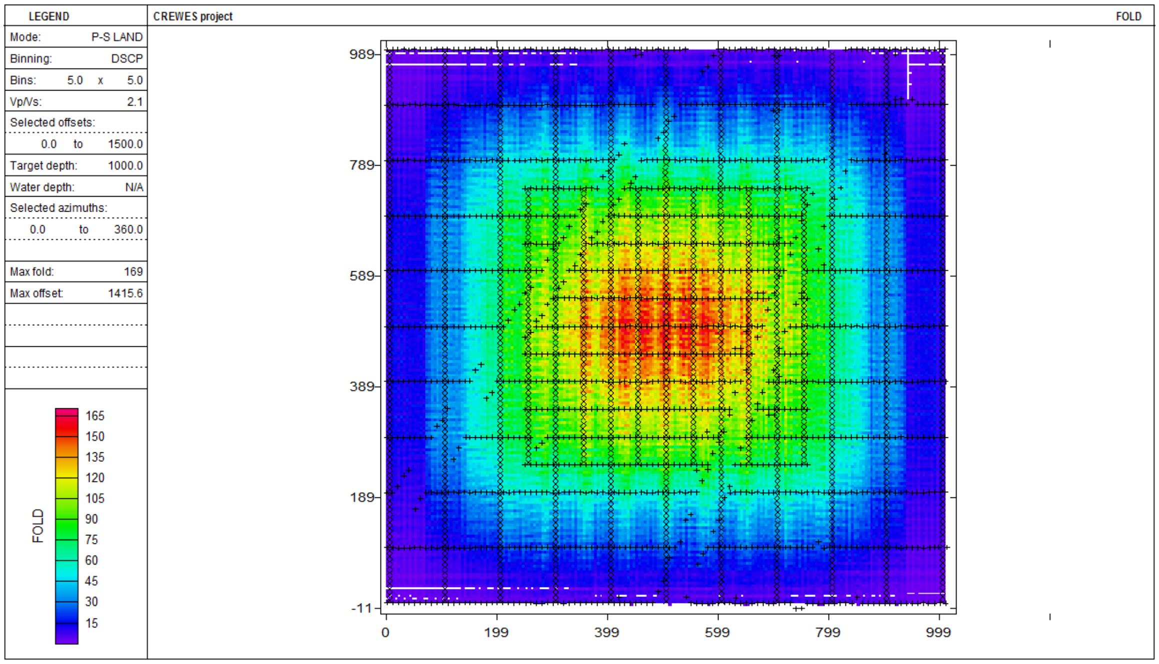

FIG. 13. Field PS fold for the FRS baseline survey, all offsets, target depth 1000 m

Maximum fold, at the centre of the survey, in this case is 170 and the high-fold bins tend to cluster more towards the centre of the survey.

One of the attributes developed for PSDesign is quality of the source-receiver offset and azimuth distributions within each bin. A quality factor of unity means there is at least one trace in every offset bin or azimuth sector. There is also a quality factor for the product.

As examples, Figures 14 through 16 illustrate the quality factors for the offset and azimuth attributes for PS data for offsets up to 750 m and a target depth of 500 m. Offset panels were 37.5 m and azimuthal sectors were 20 degrees.

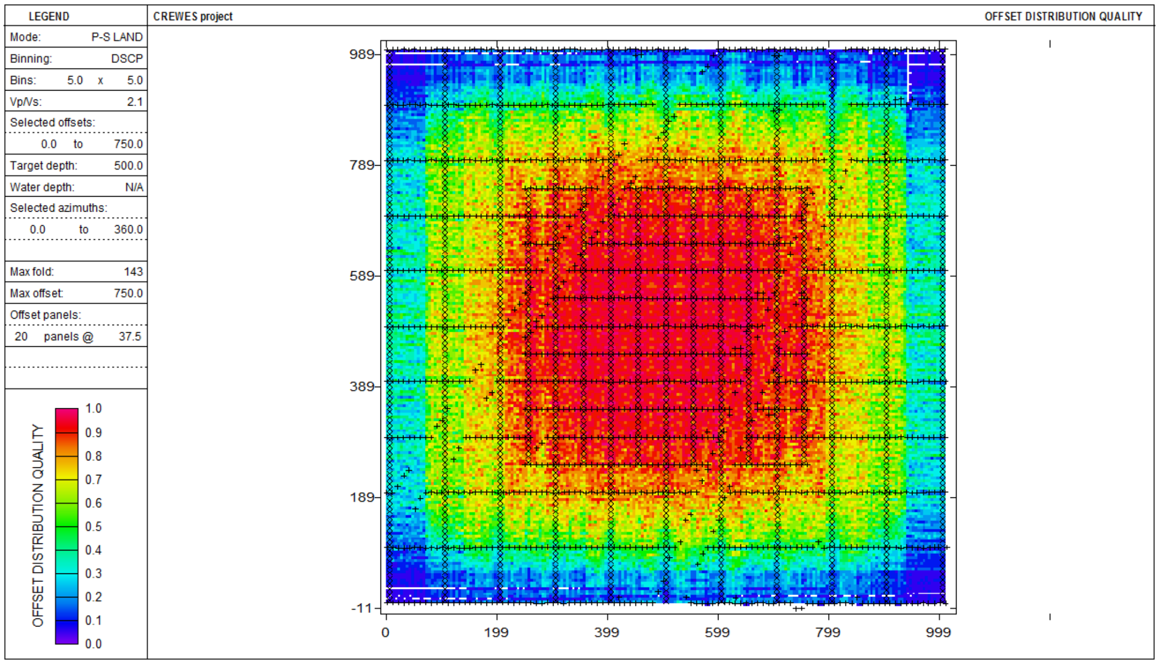

FIG. 14. Offset distribution quality for PS binning, for the FRS baseline survey, offsets limited to 750 m, target depth 500 m. Offset panels 37.5 m.

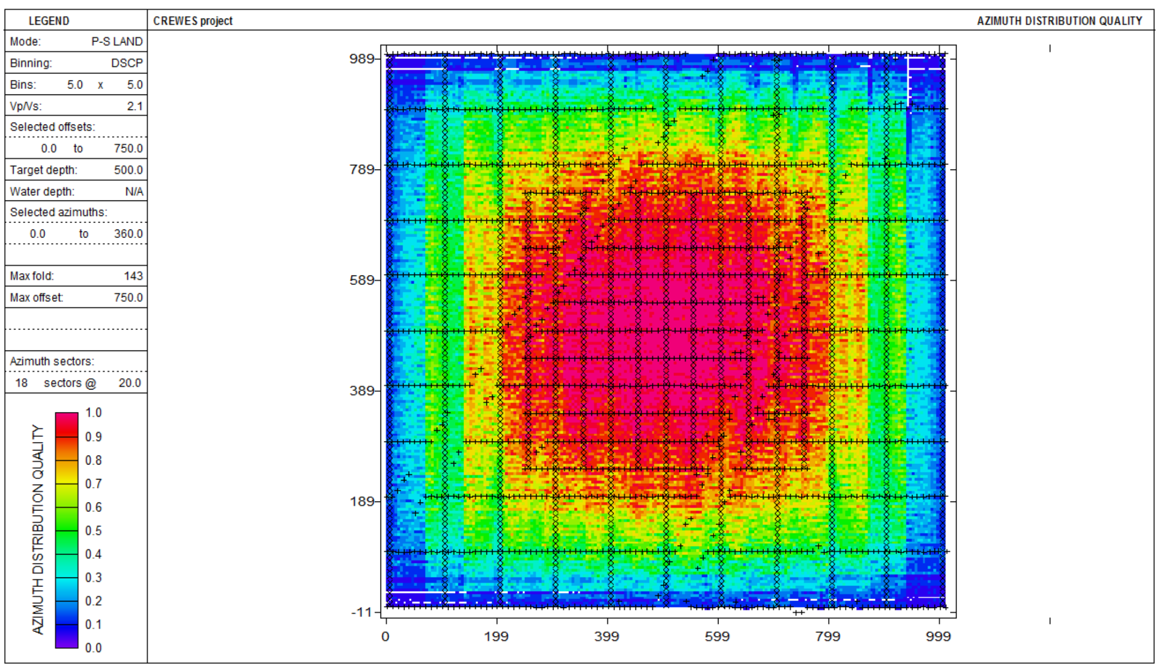

FIG. 15. Azimuth distribution quality for PS binning, for the FRS baseline survey, offsets limited to 750 m, target depth 500 m. Azimuth panels 20 degrees.

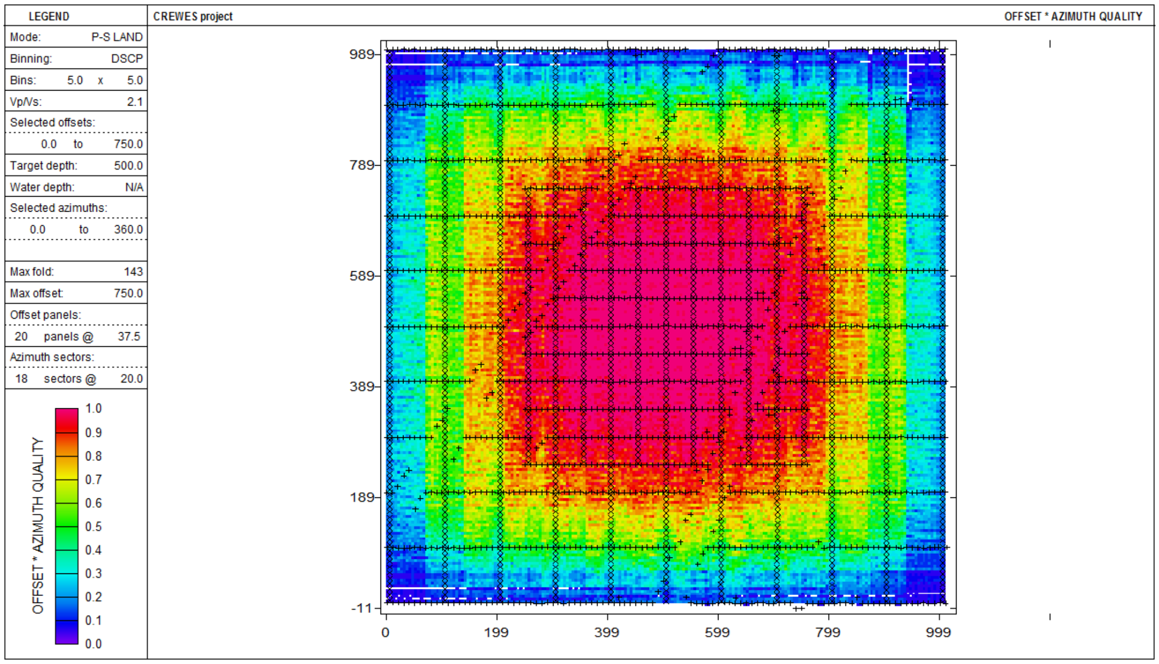

FIG. 16. Offset * azimuth distribution quality for PS binning, for the FRS baseline survey, offsets limited to 750 m, target depth 500 m; offset panels 37.5 m, azimuth panels 20 degrees.

One reason to increase the receiver density within the central part of the survey area, is because of the asymmetric ray paths for PS data. The conversion point is always on the receiver side of the midpoint, so the distance from the conversion point to receiver will always be less than the distance from the source to conversion point. This is shown graphically in Figures 17 and 18. These figures show ray paths projected for a CCP bin near the centre of the survey.

Note that as the target depth and maximum source-receiver offsets increase, the shot pattern has a much larger surface footprint than does the receiver pattern and show active receivers that are clustered around the CCP bin. This is due to the asymmetry of the PS ray paths.

It is also interesting to visualize the distribution of conversion points within a CCP bin. Since the binning is depth variant, conversion (reflection) points will never be bin-centred using P-wave binning practices because the conversion point separation at the reflector is never equal to the CMP separation. The conversion point scatter in bins near the central part of the survey area is illustrated in Figure 19, and some attributes of a particular bin are shown in Figure 20.

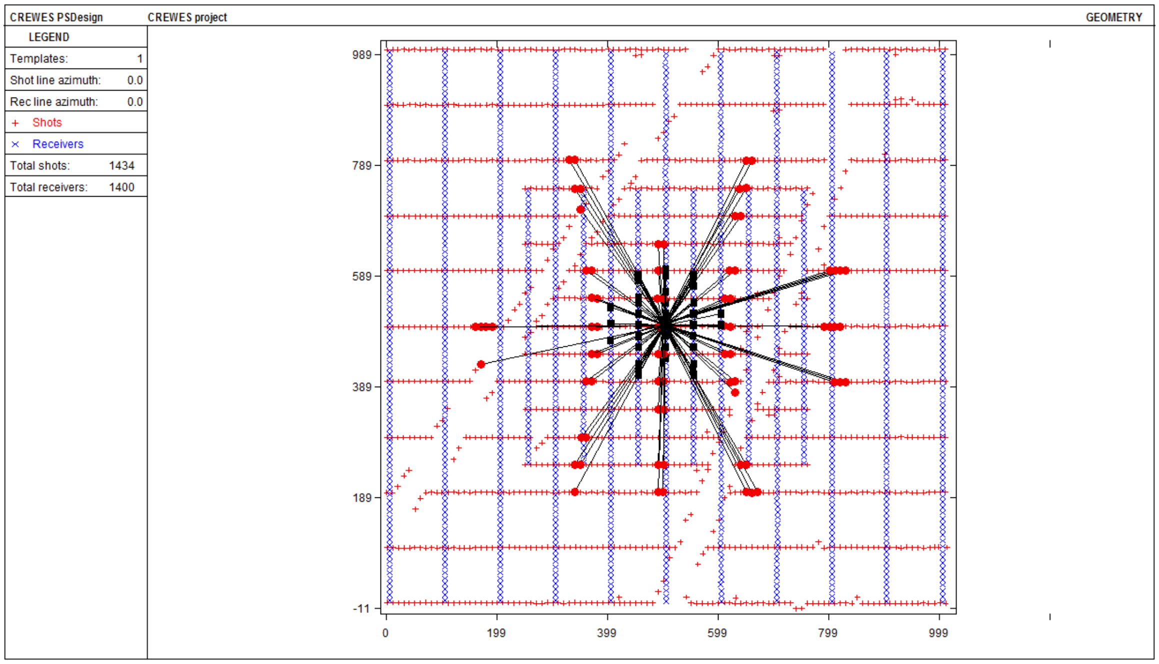

FIG. 17. PS ray paths for a CCP bin near the centre of the survey. Offsets limited to 450 m; target depth 300 m. Red dots are shots and black rectangles are receivers.

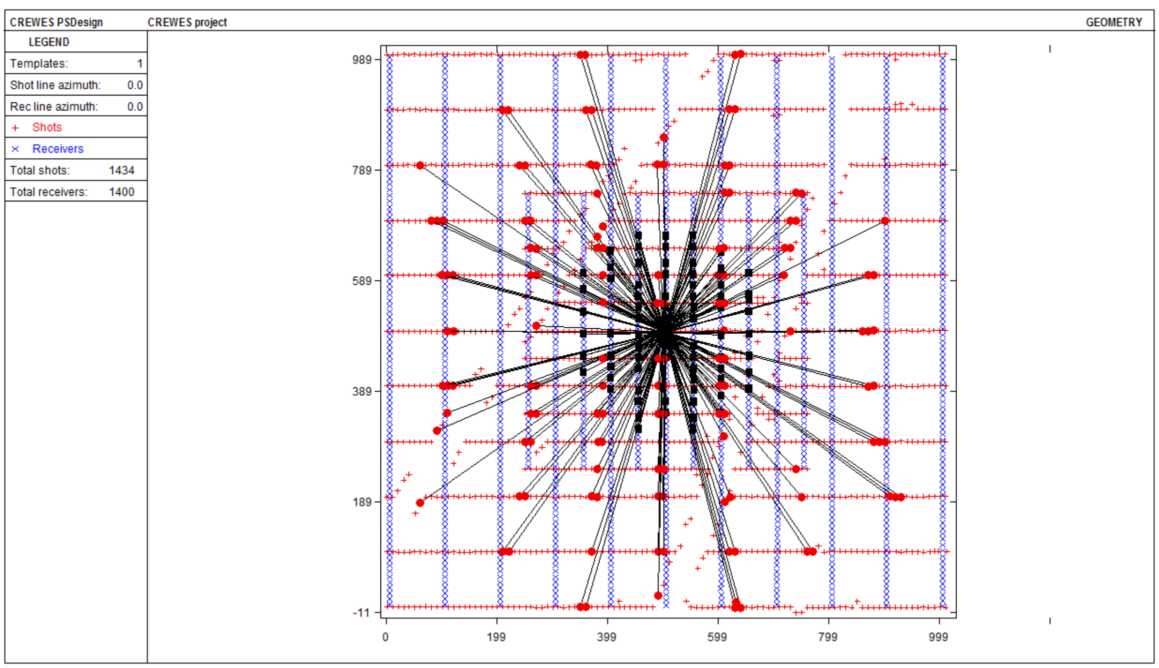

FIG. 18. PS ray paths for a CCP bin near the centre of the survey. Offsets limited to 750 m; target depth 500 m. Red dots are shots and black rectangles are receivers.

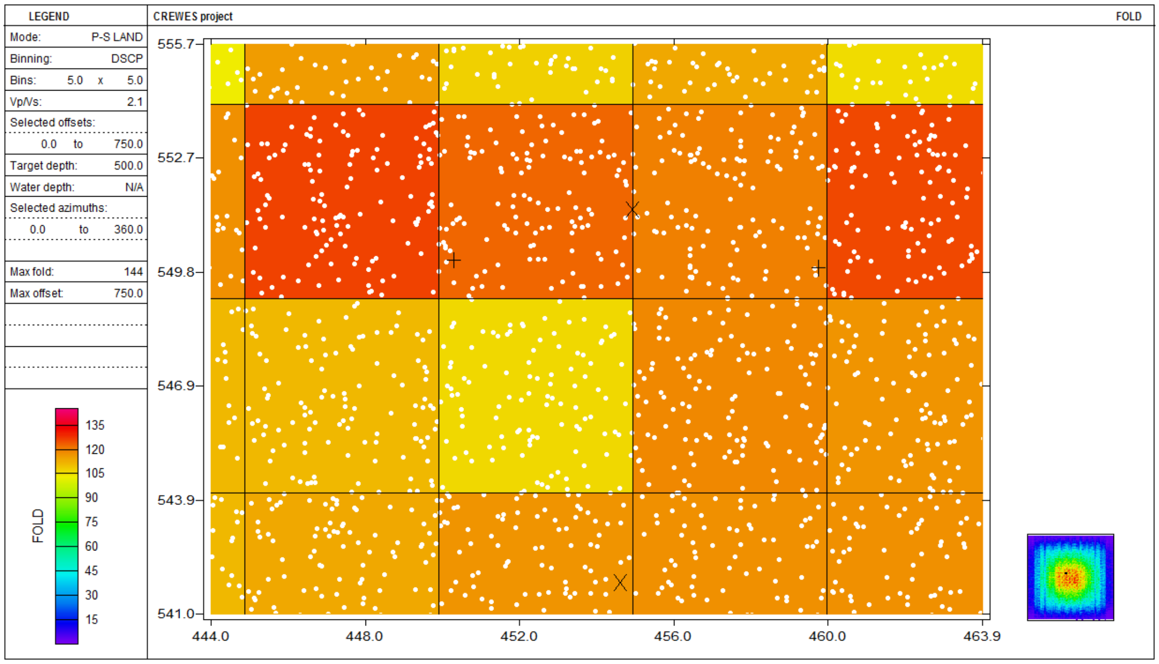

FIG. 19. Detail of conversion point distribution in bins near the centre of the survey. White dots are conversion points. Offsets are limited to 750 m; target depth 500 m.

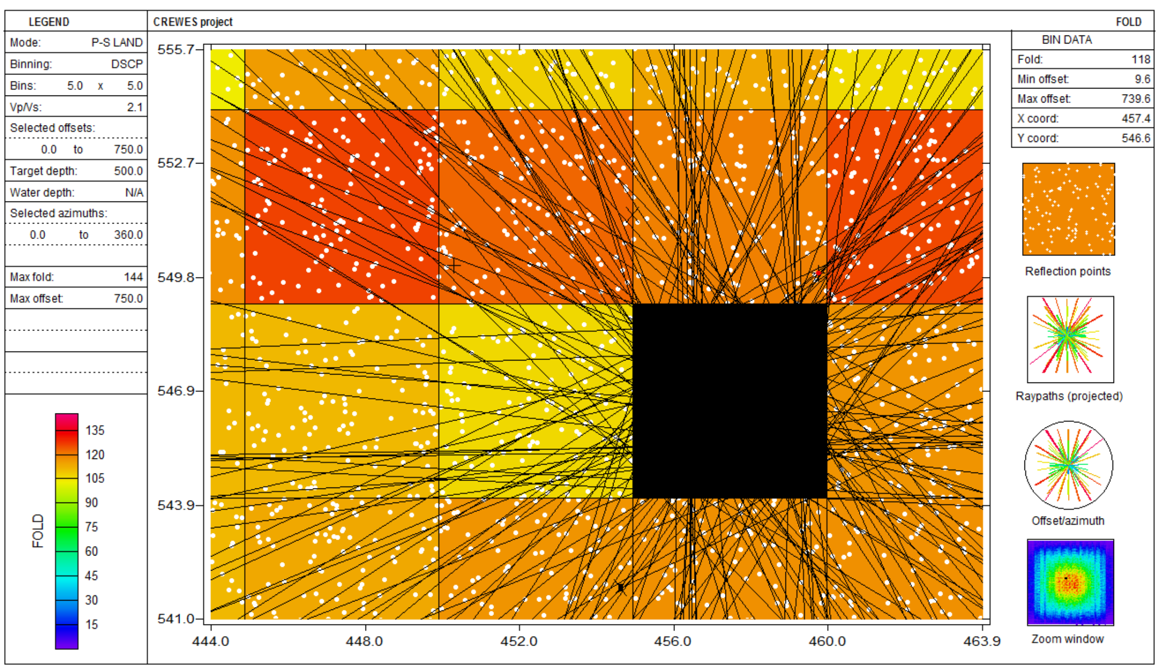

FIG. 20. Additional attributes of conversion point distribution in the bin highlighted in black near the centre of the survey. White dots are conversion points. Offsets are limited to 750 m; target depth 500 m.

DISCUSSION AND CONCLUSIONS

Processing of the PP data has been completed and the data have been included in the geostatic model discussed by Dongas and Lawton (2014). Some initial interpretation of the data and ties to nearby wells is also described by Isaac and Lawton (2014b). The PP data quality is excellent, with reflections good reflections from 200 ms to 1500 ms. Some in-line data and its interpretation are described by Isaac and Lawton (2014b). A chair display of the PP volume is shown in Figure 21.

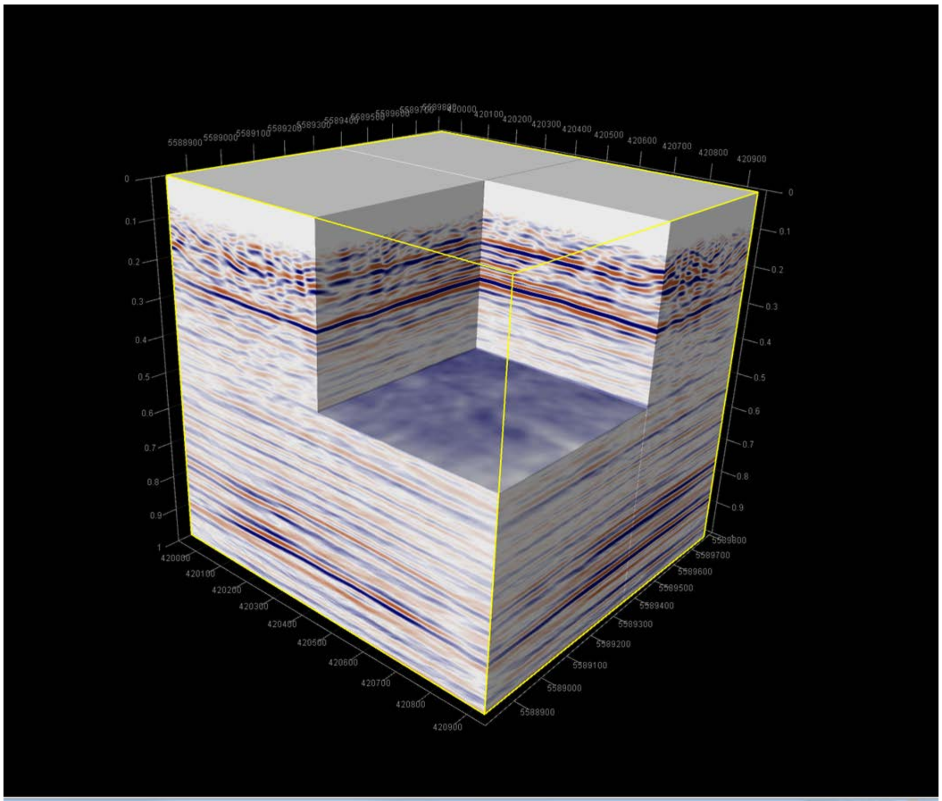

FIG. 21. Chair display of the migrated PP volume.

Figure 22 shows a time slice at 880 ms from the migrated PP volume. This slice shows locations of subtle structural changes in the data, interpreted to be caused by subsidence in reflectors due to dissolution of salts in the deeper Paleozoic formations. One of the objectives of the project is to assess vertical stress transfer into the shallow layers, which may cause facturing to occur in these layers. This integration of geomechanics with seismic analysis and interpretation is a new research direction that both CMCRI and CREWES are pursuing.

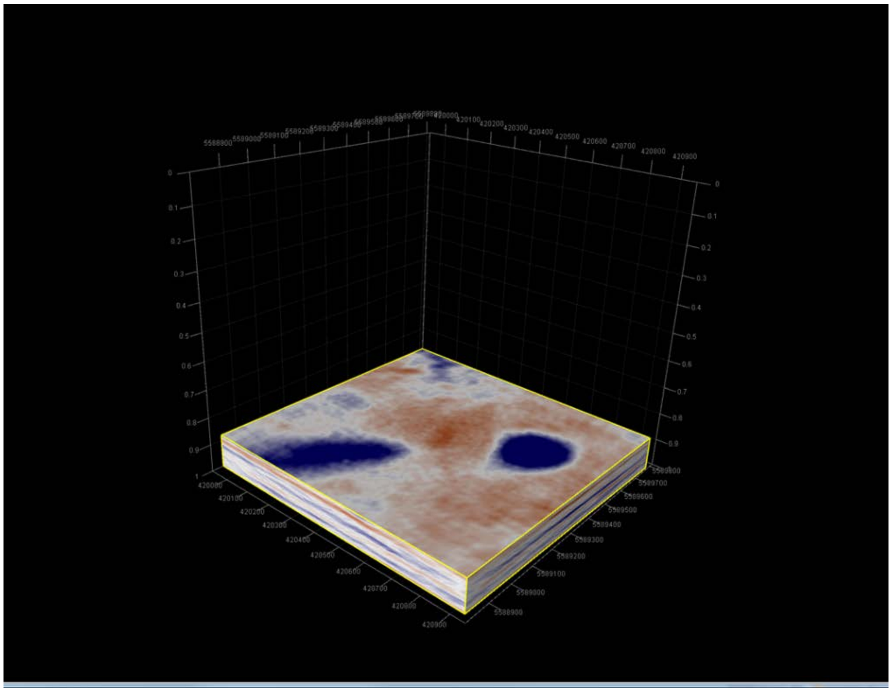

FIG. 22. Time slice at 880 ms of the migrated PP volume.

Processing and analysis of the PS data has just begun and will be completed by the end of 2014. An intial stack of the PS volume has been completed, including a very basic flow with predictive deconvolution and receiver (S-wave) statics. Figure 23 shows an in-line from the PP and PS volumes with appropriate time scales for Vp/Vs = 2. There is a reasonable correlation between the shallow to intermediate depth events.

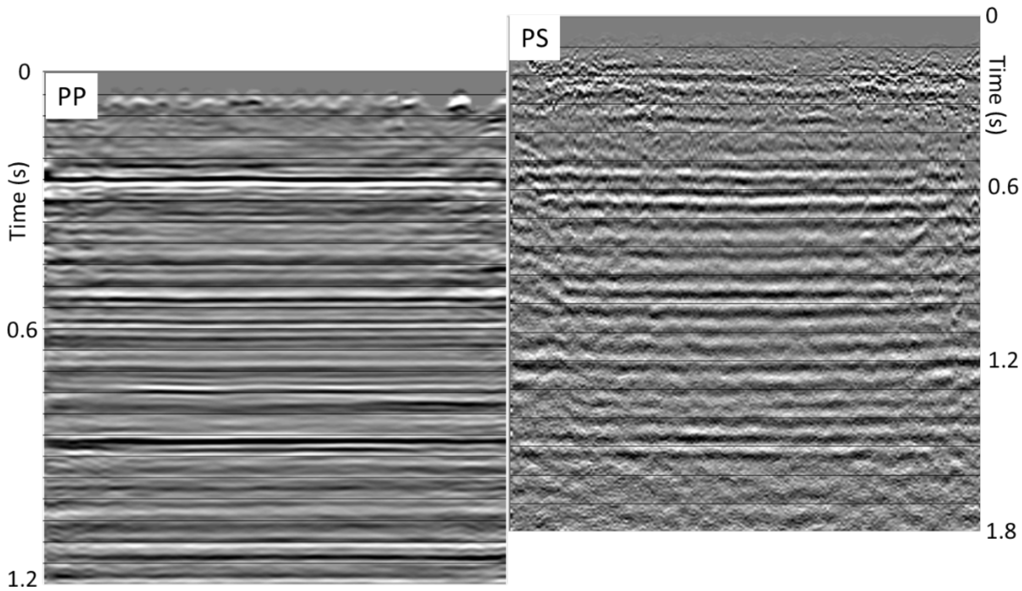

FIG. 23. Example in-line displays from the final PP volume and the initial PS volume from the FRS baseline multicomponent survey.

ACKNOWLEDGEMENTS

We thank CMC Research Institutes, Inc. for access to the seismic data and CREWES sponsors for contributing to this seismic research. We also gratefully acknowledge support from NSERC (Natural Science and Engineering Research Council of Canada) through the grant CRDPJ 379744-08.

The seismic program was recorded by Tesla Exploration under contract to CMCRI and we acknowledge them for their support of this acquisition program. Surveying was undertaken by Cook Leach Surveys.

REFERENCES

Cordsen, A., Galbraith, M., and Peirce, J., 2000, Planning land 3-D seismic surveys, Soc. Expl. Geophys., Tulsa, Oklahoma.

Andreas Cordsen and Don C. Lawton, 1996, Designing 3-component 3D seismic surveys, SEG Expanded Abstract, 81-83.

Dongas, Jessica M., and Lawton, Don C., 2014, Development of a geostatic model for a geoscience field research station in Alberta, CREWES report, this volume.

David W.S. Eaton and Don C. Lawton, 1992, P-SV stacking charts and binning periodicity, Geophysics, 57, 745-748.

Isaac, J. Helen and Lawton, Don C., 2014a, Preparing for experimental CO2 injection: geology of the site, CREWES report, this volume.

Isaac, J. Helen and Lawton, Don C., 2014b, Preparing for experimental CO2 injection: seismic data analysis, CREWES report, this volume.

Don C. Lawton and Brian H. Hoffe, 2000, Some binning issues for 4C-3D OBC survey, SEG Expanded Abstract, 2477.

Mark Meier, 2009, Converted-wave survey design, SEG Expanded Abstract, 4254-4257.

Stone, D.G., 1994, Designing Seismic Surveys in Two and Three Dimensions, SEG, Tulsa, Oklahoma.

Vermeer, G. J. O., 2002, 3-D seismic survey design, Soc. Expl. Geophys., Tulsa, Oklahoma

Jianli Yang and Don C. Lawton, 2002, Mapping the P-S conversion point in transversely isotropic (VTI) media, SEG Expanded Abstract, 1006-1009

Liliana M. Zuleta and Don C. Lawton, 2011, P-S Survey design, SEG Expanded Abstract, 127-131.