Multicomponent Technology: Reducing Risk and Creating Opportunity

Roche, S.L., Gibson J., Mattocks, B., Ronen, S. and Watt, H.J., Veritas DGC, Houston, Texas, USA.

Copyright 2005, SBGf - Sociedade Brasileira de Geofísica

This paper was prepared for presentation at the 9th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, 11-14 September 2005.

Contents of this paper were reviewed by the Technical Committee of the 9th International Congress of the Brazilian Geophysical Society. Ideas and concepts of the text are authors' responsibility and do not necessarily represent any position of the SBGf, its officers or members. Electronic reproduction or storage of any part of this paper for commercial purposes without the written consent of the Brazilian Geophysical Society is prohibited.

ABSTRACT

Three-dimensional (3D) compressional-wave (P-wave) seismic methods routinely provide faithful structural images of the earth's subsurface but often lack the ability to provide complete and distinct information about rock properties. Shear-wave (S-wave) data, in concert with P-wave data (multicomponent), can provide additional information to reduce risk and create new opportunities[1]. Significant advances in the acquisition, processing and interpretation of multicomponent data have served to make this technology more viable but acceptance remains limited. More widespread acceptance of multicomponent methods is critically dependent on continuing demonstrations of value from field projects and on the development of interpretation tools and work processes conducive to evaluating multimode data.

This paper provides an overview of multicomponent technology and focuses on the techniques and advances that are improving viability and includes theory and practical examples of how multicomponent technology is improving the ability of the industry to find and produce more oil and gas.

WHY MULTICOMPONENT TECHNOLOGY?

Although the use of multicomponent seismic methods can be traced to earthquake seismology experiments in the 1800s[2], it wasn't until the 1970s that their application to petroleum exploration became more common, albeit with activity levels well below those of conventional compressional-wave (P-wave) seismic methods.

In the 1990s, improved subsurface imaging in the presence of gas clouds in the offshore provided a "killer application" that rejuvenated interest in multicomponent seismic methods[3]. The multicomponent acquisition technique employed in the offshore utilizes a conventional P-wave source with converted S-waves generated at reflecting horizons. Converted-wave methodology, referred to as 3C, is assumed in the discussion that follows. PP and PS data refer to P-wave and S-wave data, respectively, generated by a P-wave source.

Apart from gas cloud imaging, P-wave data generally provide good structural images of the subsurface. However, there is a real need in oil and gas exploration and development to go beyond structural images and understand issues such as pore fluids and their movement, rock types, porosity, permeability, stratigraphy and fracture geometry/intensity. P-wave information is often ambiguous or incomplete in addressing these and other issues. P- and S-waves respond differently to fluid and solid combinations in the subsurface and the joint use of both wave types provide more complete information about rock properties. Engelmark[4] writes: "The ability of multicomponent data to provide unique or improved solutions to virtually all imaging and characterization problems makes it the seismic tool of choice for the future".

Conceptually, one might view the additional information derived from multicomponent data as forming a "halo" around the information provided by conventional P-wave data (Figure 1). In an area where the P-wave data essentially provide a complete structural picture, the S-wave information can corroborate the P-wave structural picture (point A on A-B). For a gas cloud problem, the S-wave structural information can provide an imaging solution and thus a large "halo" of new information results (point B).

Profile C-D in Figure 2 is concerned with the use of Vp/Vs ratios (ratio of P- and S-wave velocities) to discriminate between attributes such as lithology, pore-fluid type and porosity. If the S-wave information simply confirms rock property information derived from P-wave AVO (Amplitude Versus Offset) analysis, there would be a small halo (point D). On the other hand, sands and shales are often difficult to distinguish based on P-wave data information alone but Vp/Vs analysis using both P and S information can facilitate the discrimination process and thus a larger halo can result (point C).

REDUCING ECONOMIC RISK

Ideally, using both P-wave and S-wave data reduces economic risk by providing the explorationist with more complete subsurface information. Figure 2 outlines hypothetical project economics for two cases, one using only P-wave seismic data and the second using both P-wave and S-wave data. Possessing more complete information would result in fewer wells being drilled with greater reserves per well. Also, the wells would be drilled earlier, thus reducing the project cycle time. There would be less uncertainty in the second project as opposed to the first, where uncertainties are often not discovered until the drilling phase, thus creating delays and the need for reevaluation of the data. The dotted lines represent project cash flow and show more favorable cash flow for the project utilizing both P-wave and S-wave information. Even with an increase in the cost of acquiring the multicomponent seismic data, the second case results in better project economics.

The use of both PP and PS seismic data for exploration and development ultimately reduces risk. The hypothetical impact on a given development project may be that a 16 well program is reduced to a 12 well program, booking the same amount of reserves although drilling fewer marginal wells.

FUNDAMENTALS

Multicomponent seismic data hold great promise for the exploration and development of oil & gas. A key principle for understanding and interpreting seismic images of the subsurface reflectivity is that seismic waves are basically sensitive to three bulk rock properties- compressibility, rigidity and density. Recording both wave modes allows better separation of these three properties, thus providing more accurate estimation of the desired reservoir characteristic such as lithology, porosity, fractures or fluid discrimination.

Information about the subsurface is carried by P-wave and S-wave propagation. The advantage in using both P- and S-waves is that the two wave modes possess different sensitivities to the bulk rock properties. S-wave propagation is sensitive only to rigidity and density, while compressional-wave propagation is sensitive to rigidity, density and compressibility. As a generalization, P-wave propagation changes both the shape and volume of a subsurface element while S-waves change the shape only[5]. One manifestation of these two modes of propagation is that P-waves tend to have a higher sensitivity to fluids in the pore space. Similarly, factors such as open fractures more strongly affect rock rigidity. Since S-waves are more sensitive to rigidity changes, they are more suited for fracture characterization. Interpreting both P- and S-wave reflectivity offers the ability to discriminate lithology, porosity, fractures and possibly fluid content.

KEY IMPROVEMENTS TO 3C TECHNOLOGY

A number of barriers historically inhibited the acceptance and growth of multicomponent technology. These include:

- lack of interpretation and analysis tools;
- high cost compared to perceived value;
- poor data quality;
- lack of specialized acquisition equipment; and
- immaturity of data processing techniques.

Further, expertise and experience with multicomponent methods have resided with a very few in the industry.

A number of advances in data acquisition, processing and interpretation have significantly improved the general usability and viability of multicomponent technology. Advances in multicomponent acquisition equipment[6-7] and processing algorithms have fueled an important improvement in the quality of converted-wave data.

Purpose-built multicomponent MEMS (Micro Electro Mechanical System) sensors have vastly improved attributes including:

- Single sensor (point receiver) recording
- Direct digital output
- Improved vector fidelity
- Broadband linear phase and amplitude response
- Low harmonic distortion
- Measurement of sensor tilt
- Reduced power consumption

Less complex recording systems produce fewer field errors and allow for more efficient deployment, which in turn, has helped to reduce costs of multicomponent data acquisition[8]. A number of service companies have multicomponent seismic capability with sufficient equipment inventory to conduct sizable projects.

Converted-wave data are inherently more difficult to process than P-wave data due primarily to the asymmetry of the travel path. Standard processing techniques for P-wave data are not directly applicable and both algorithms and processing flows require modification. Significant improvements in converted-wave processing algorithms and methods are now producing improved subsurface images and facilitating more effective integration of P- and S-wave data. Further work remains in developing and implementing true vector processing methods for the full elastic wave field to fully exploit the value of converted-wave data. Such methods must necessarily treat data processing and interpretation in a parallel rather than serial manner.

The success and sustainability of multicomponent methods is ultimately tied to value demonstrations and to development of interpretation tools and work processes which allow shear-wave information to be effectively utilized. Specialized elastic wave interpretation packages such as Hampson-Russell's ProMC are helping to promote the extraction of information from multicomponent data. A reality is, however, that typical interpretation workstations today are not designed to effectively and efficiently manage and evaluate multimode data. Continuing demonstrations of value from multicomponent data will undoubtedly catalyze further workstation development.

MULTICOMPONENT APPLICATIONS

The literature provides a broad range of converted-wave applications[9-10]. Additionally, Veritas DGC has actively pursued the development of applications over the past two years. Some of these are discussed in the examples which follow.

North Emerald 3C3D Test – Anadarko Basin Gas Play

The Anadarko Basin is a major gas production province with both mature fields and ongoing exploration efforts. Production is from Ordovician through Permian-age clastics and carbonates. In the North Emerald 3C3D study area, thin sands (less than 8m each) produce natural gas from the Mississippian Springer Formation at depths near 3.2 km. Production is from offshore sandbars trending NW – SE that were bisected by NNE – SSW trending erosional systems during periods of lowstand. The Springer interval is approximately 70m thick containing three reservoir units: the Cunningham, Britt and Boatwright sands. Production is primarily related to porosity development. Wells with greater than 2m of 8% -12% porosity tend to be commercial while porosities less than 8% are non-productive. Natural gas production is through pressure depletion.

The authors observed changes in both P-wave (PP) and converted-wave (PS) reflectivity associated with gas production. Their hypothesis was that porosity development in these lithified Paleozoic sediments primarily changes the rigidity with little effect on compressibility. Both PP and PS reflectivity "see" the change in rigidity, but the PP reflectivity is damped by the large compressibility term.

The authors used a neural network waveform classifier to quantitatively determine whether using the PP and PS data together could provide a better empirical estimate of gas production than using PP data only. For 17 wells in the 3C3D image area with Springer penetrations and tests, a simple log trace was created representing cumulative gas produced. Using cumulative gas as the target, a neural network was trained and the most significant seismic attributes were identified. For validation, each well was removed from the process and tested based on the relationships determined by the remaining population.

Figure 3 shows the empirical results for predicting cumulative gas production. Results using both PP and PS data correctly identified the three wells with higher cumulative gas produced. Crossplots of estimated gas versus actual gas production show that using PP and PS data together produced a more accurate linear fit than when using the conventional P-wave data alone.

The authors conclude that changes in both PP and PS reflectivity associated with gas production fit their hypothesis that porosity development in these lithified, sands primarily changes the rigidity with little effect on compressibility. The development of porosity allows for commercial quantities of gas to be produced[11] .

USA Carbonate 3C3D Test – Fractured Gas Reservoir

Replacing a subset of receiver groups in a P-wave 3D survey with three-component single-sensors provides a method of examining both the feasibility of PS-wave recording, and its capacity to determine the orientation of horizontal stress through azimuthal anisotropy. This carbonate example of such a test displays strong mode-converted reflections at the depths of interest, and demonstrates all the expected characteristics of shear-waves in azimuthally anisotropic media.

Detecting the presence of azimuth velocity anisotropy is important because measurements of "fast" and "slow" S-wave polarizations can be related to open fractures and crack-like pore structures in the subsurface. The potential benefits of PS-wave data for fracture characterization, the methods of analysis, and examples of its application are well-documented in the literature[12-14] . Nonetheless, the viability of PS-wave acquisition in any specific geological environment or geographical location is often in doubt. An embedded multicomponent test, where conventional geophone groups are either replaced by or co-located with single-sensor 3C MEMS receivers, is a cost-effective method of evaluating 3C technology.

The azimuth stacks of this embedded test display all the expected characteristics of azimuthally anisotropic PS-waves (Figure 4). The radial component shows azimuthal variation in arrival times of the various reflections, with the fastest arrivals occurring approximately east-west, and the slowest arrivals north-south. The transverse component – which would be free of reflections in isotropic media – shows polarity reversals separated by azimuths without reflections, at both N80°E and N170°E. The "phase flip" semblance display permits the orientation of the symmetry planes to be determined graphically; however, a 90-degree ambiguity remains. This is resolved through the azimuthally varying travel-time of the radial component, in which travel-time minima coincide with the fast-shear axis (or isotropy plane) and travel-time maxima coincide with the slow-shear axis (or symmetry-axis plane). In this case, the fast shear axis is N80°E, which represents the maximum horizontal stress orientation[15] .

A typical output display for fracture characterization utilizes vectors to indicate the local direction of fracture orientation and colors to provide a measure of fracture intensity. Such a display would typically describe orientation and intensity for a given target interval. Figure 5 reflects a measure of cumulative anisotropy from the surface rather than local anisotropy for a given target interval.

Long Lake 3C3D – Heavy Oil Play

A third example of multicomponent applications is from the shallow heavy oil sands of Alberta, Canada. Production is from bitumen-saturated, Cretaceous-age sands within a fluvial valley-fill depositional system. The productive formation, the McMurray, is 80m thick at a depth of 220m in the 3C3D survey area. The method of extraction involves drilling pairs of horizontal wellbores, vertically separated by 5m, injecting steam into the upper wellbore and producing the heated bitumen via the lower wellbore. A main source of economic risk is shale plugs and layers interfering with the injection/extraction process by imposing impermeable barriers to fluid flow.

3C3D data were acquired using digital MEMS sensors and integrated with the available well control. Seismic inversions of both the PP and PS data were input into the Hampson-Russell EMERGE algorithm to produce an estimate of shale volume. A cross section through the shale volume is shown in Figure 6. Four wells are integrated into the profile showing the measured sand/shale volumes from log control. Core data were also extracted at these four well locations to produce an interpreted core cross section (Figure 6). There is excellent agreement between the seismic shale volume estimate, using PP and PS data, and the corresponding well information [16].

Improving P-wave Data Quality

3C data can also be important in improving the quality of the P-wave image. For onshore applications, a source-generated surface wave known as 'ground roll' can be particularly bothersome. Historically, large arrays of single-component geophones were used in 2D seismic acquisition to attenuate surface waves but these can produce an attendant loss of image resolution. In 3D acquisition, fewer geophones are deployed at each receiver location for economic reasons leaving the task of surface wave attenuation to processing algorithms. Unfortunately, these algorithms are highly dependant on spatial sampling and velocity discrimination between the undesirable "noise" and desired reflected signal.

By recording the 3D particle motion using 3C sensors, polarization filters can be employed to attenuate ground roll and other surface waves. For example, ground roll can be attacked by detecting and exploiting its characteristic elliptical particle motion, in contrast with the linear particle motion of reflection signal. The detection and subsequent removal places no demand on potential costly increases in spatial sampling since polarization filtering is a single-sensor operation.

An example of improved P-wave data quality using single-sensor MEMS seismic data and polarization filters is shown in Figure 7. Two 2D seismic profiles are shown. Section A is recorded using conventional geophone sensors deployed as 12 element linear arrays at 50m intervals. Section B utilized a single 3C MEMS sensor at 25m intervals with polarization filtering applied to improve resolution by attenuating surface waves. These 2D profiles traverse a shallow thrust. The faults and steeply dipping base of the thrust are better imaged using the single-sensor 3C MEMS sensors[17].

EVALUATION THROUGH EMBEDDED TESTS

Case histories are certainly helpful in understanding applicability of multicomponent methods but the potential user wants to know whether the technology can be successfully applied in their geographical area of interest. State-of-the-art multicomponent acquisition systems allow for seamless integration of standard P-wave and multicomponent recording. It is straightforward to embed a multicomponent test within a planned P-wave survey to assess the technology.

2-D or 3-D embedded test locations are preferably selected to tie existing well control so that subsurface information is available for calibration.

Objectives of such testing might include:

- a comparison of P-wave data quality using conventional P-wave geophone arrays and multicomponent sensors;
- an evaluation of multicomponent data quality;
- a determination of required spatial sampling for future project work; and
- assessment of the value of multicomponent data for solving an exploration or production problem.

SUMMARY

Multicomponent data provide an array of potential applications ranging from corroborating P-wave results to providing solutions where P-wave data alone are inadequate. New information available from these data can be critical in better understanding and effectively exploiting oil and gas reservoirs.

Significant advances in multicomponent data acquisition, processing and interpretation have enhanced the attractiveness of multicomponent methods. Acquisition costs are more competitive, data quality has improved ,the value of multicomponent data is being demonstrated and embedded tests and full multicomponent surveys are beginning to highlight the full value these technologies provide. Usage of multicomponent technology is expected to continue to grow as new tools and products are developed and the workstation environment is suitably adapted to more effectively accommodate multimode data.

Acknowledgments

The authors thank Veritas DGC, Veritas Land Library Services, NEXEN and an anonymous corporation for permission to publish this work. We also thank our many co-workers whose hard work made these examples possible.

References

1. B. Hardage, 1996, "Combining P-wave and S-wave Seismic Data to Improve Prospect Evaluation", Report of Investigations No. 237, Bureau of Economic Geology, pp. 1-47

2. R. Garotta, 2000, "Shear Waves from Acquisition to Interpretation", SEG Distinguished Instructor Short Course, No. 3

3. J.R.Granli, B. Arntsen, A. Sollid and E.Hilde, 1999, "Imaging through gas-filled sediments using marine shear-wave data", Geophysics, Vol. 64, No. 3, pp 668-677

4. F. Engelmark, 2001, "Using 4-C to characterize lthologies and fluids in clastic reservoirs", The Leading Edge, Vol. 20, No. 9, pp. 1053-1055

5. B. Goodway, 2001, "AVO and Lame Constants for Rock Parameterization and Fluid Detection", CSEG Recorder, Vol. 26, No. 6, pp. 39-60

6. D. Mougenot, 2004, "Land seismic: needs and answers", First Break, Vol. 22, pp 59-63

7. P. Maxwell, J. Tessman and B. Reichert, 2001, "Design through to production of a MEMS digital accelerometer for seismic acquisition", First Break, Vol. 19, pp 141-144

8. J. Gibson, H.Watt and S. Roche, 2003, "Multicomponent Seismic Data Acquisition…The Economics Revisited", CSEG Recorder, Vol.28, No. 8, pp. 16-21

9. R.R.Stewart, J.E.Gaiser, R.J. Brown and D.C.Lawton, 2003, "Converted-wave seismic exploration: Applications", Geophysics, Vol. 68, No. 1, pp. 40-57

10. R. Tatham, 2002, “Applications Demonstrate Multicomponent Seismic’s Value in Solving Variety of Problems”, The American Oil & Gas Reporter, pp. 101-110

11. S. Roche, M. Wagaman and H. Watt, 2005, “Anadarko Basin survey shows value of multicomponent acquisition”, First Break, Vol. 23, pp. 43-51

12. J.E.Gaiser and R.R.Van Dok, 2002, “PS-wave benefits for fractured-reservoir management”, Ann. Nat. Mtg., Can. Soc. Expl. Geophys., Abstracts.

13. X.-Y.Li, 1998, “Fracture detection using P-P and P-S waves in multicomponent sea-floor data” 68th Ann. Internat. Mtg: Soc. of Expl. Geophys., 2056-2059.

14. R.Van Dok, J.Gaiser, and J.Markert, 2001, “Green River basin 3D/3C case study for fracture characterization: Common-azimuth processing of PS-wave data”, 71st Ann. Internat. Mtg: Soc. of Expl. Geophys., 768-771.

15. D. Todorovic-Marinic, B. Mattocks, R.Bale, D.Gray, J.Dewar, 2005, “More Powerful Fracture Detection: Integrating P-wave, Converted-wave, FMI and Everything”,submitted to the EAGE 67th Conference and Exhibition, Madrid, Spain.

16. F.David Gray, Paul F. Anderson, and Jay A. Gunderson, 2005, “Prediction of Shale Plugs between Wells in the Heavy Oil Sands at Long Lake using Seismic Attributes”, submitted to the June 2005 AAPG Conference, Calgary, Alberta, Canada.

17. S. Ronen, C. Ansorger, W. Nowry, R. Kendall, S. Jin, J. Gibson, M. Wagaman, 2005, “Seismic Data in Rough Terrain: How about Multicomponent?”,submitted to the CSEG Conference and Exhibition.

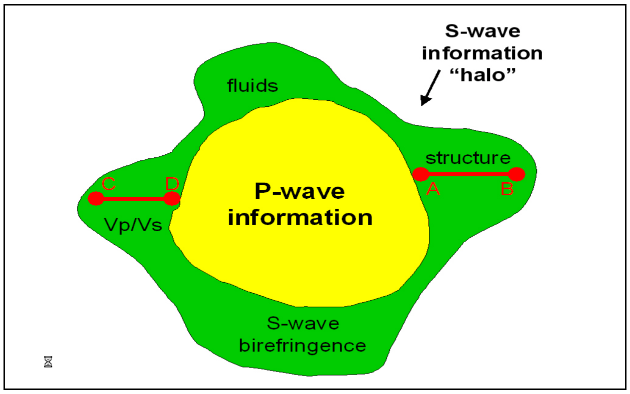


Figure 1. “Halo” of additional information provided by multicomponent data.

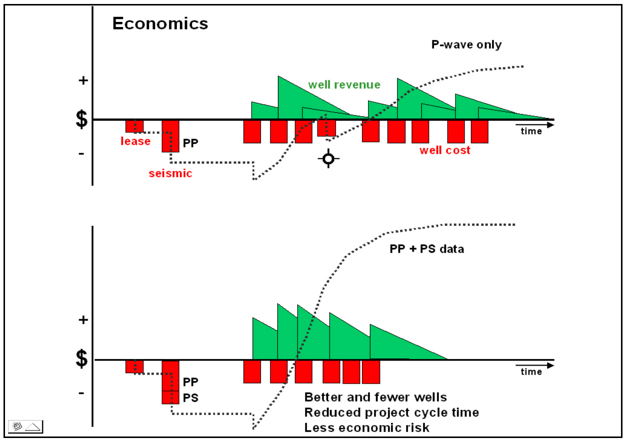


Figure 2. Hypothetical project economics using only P-wave seismic information (upper graph) versus P-wave plus S-wave information (lower graph). Dotted lines show project cash flow.

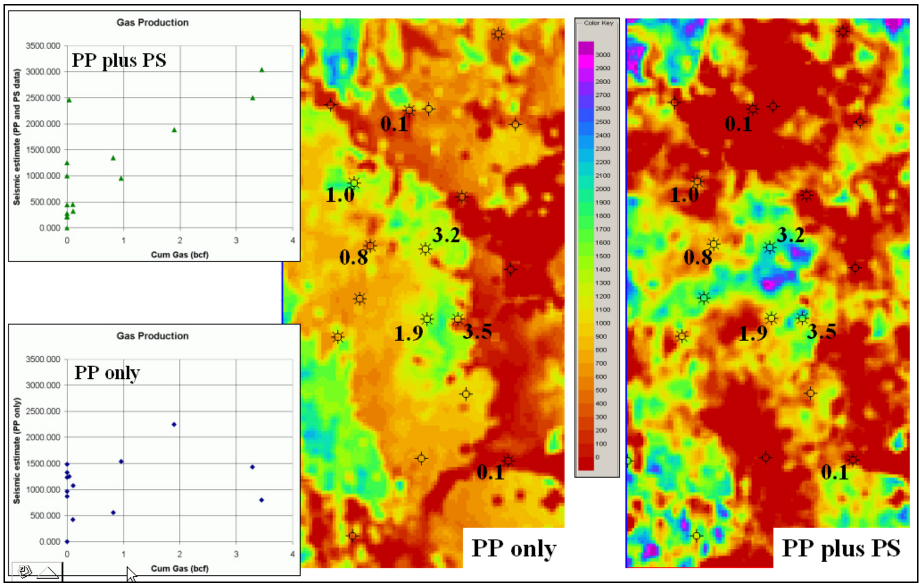


Figure 3. Predicted gas production based on seismic data attributes. Two estimates were calculated, one using the PP data only (left map panel), the second using both PP and PS data (right map panel). Red colors indicate low estimates of gas production, blue and purple colors indicate high estimates. Crossplots of estimated versus actual gas production show a better fit is obtained when using both the PP and PS data. Gas production (bcf) is noted for key wells[11].

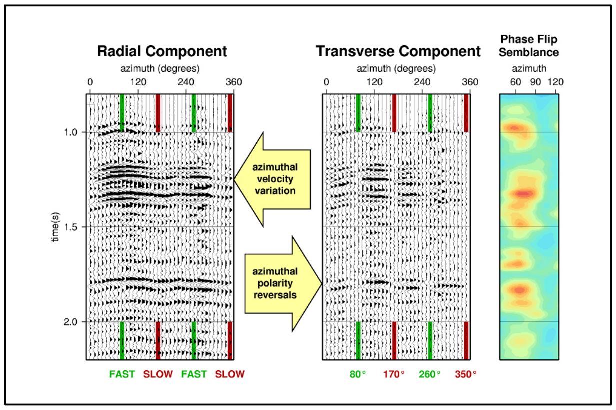


Figure 4. Azimuth stacks of radial and transverse component. Radial data shows "fast" and "slow" S-wave arrivals along the symmetry axes delineated by the nulls in the transverse component panel. These data indicate the "fast" S-wave polarization azimuth is N80°E, interpreted to be the orientation of maximum horizontal stress in the study area[15].

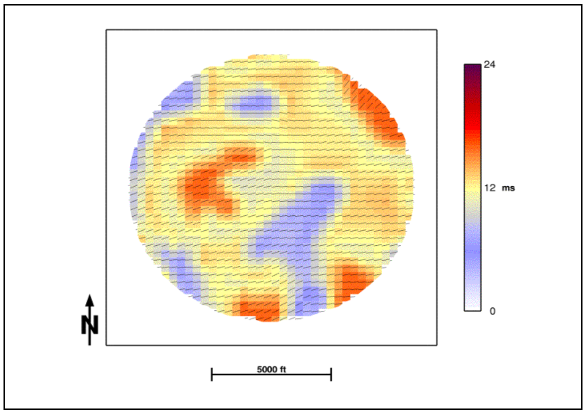
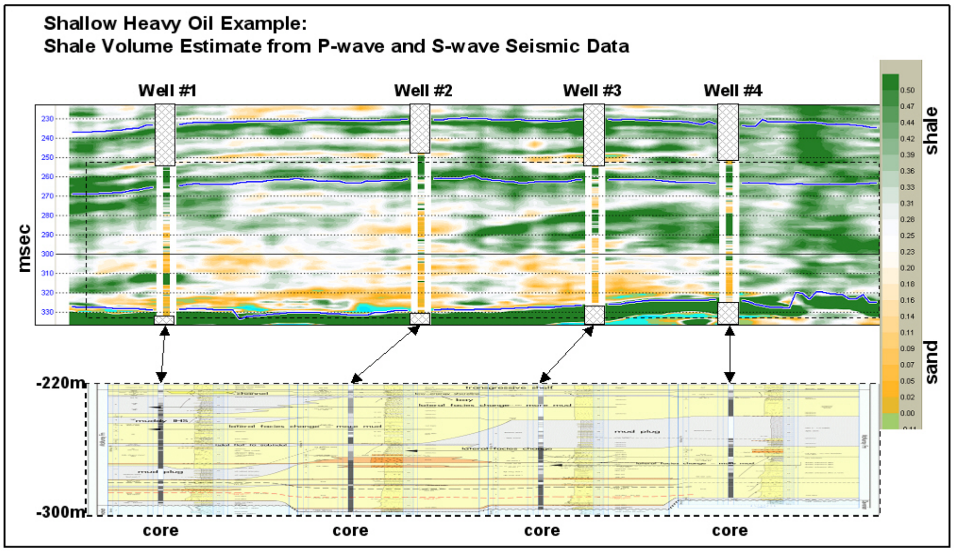


Figure 5. Fracture orientation and intensity. Fast shear-wave polarization (vectors) and slow shear-wave delay times (colors) for an event near 1.2 seconds (two-way time) on the seismic data. This information characterizes fracture orient ation (vectors) and intensity (color). [Note: The delay times in this example represent cumulative anisotropy from surface].

Figure 6. Shale volume estimate from P-wave (PP) and converted S-wave (PS) data compared with well control. Orange represents higher sand volume while green represents greater shale content[16]. Core cross section is shown.



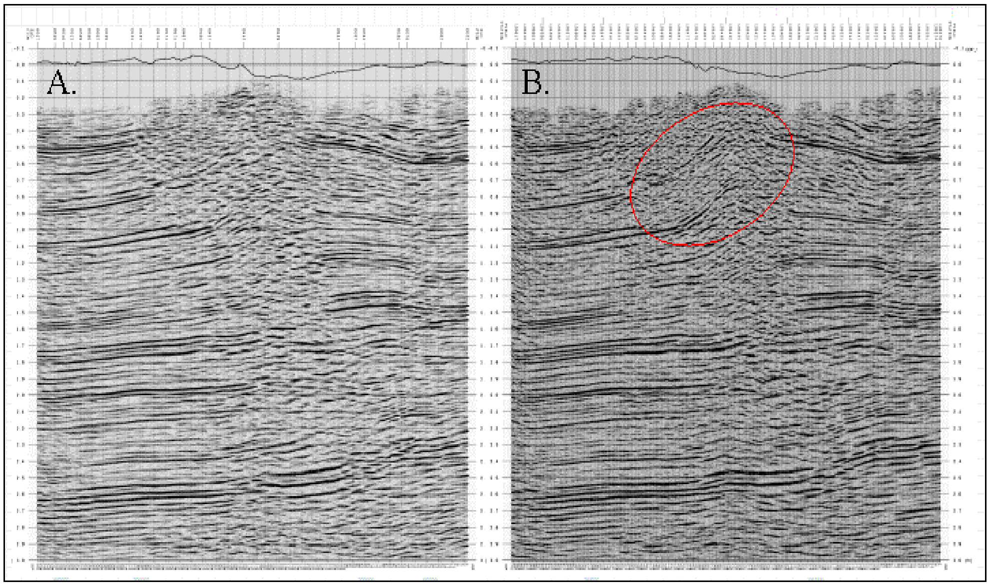


Figure 7. Comparison between conventional geophone array data at 50m group interval (A) and single-sensor MEMS data at 25m group interval (B) with polarization filter applied to attenuate surface waves (ground roll).