Onshore Multicomponent Seismic in Canada

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Abstract
Multicomponent seismic has experienced respectable growth in the last three years. Most of this growth has been on land and in Canada. The previous surge in the use of multicomponent seismic was using ocean bottom sensors for resolving gas cloud imaging issues primarily in the North Sea. The resurgence of multicomponent seismic on land is a result of acquisition advances, specifically the development of digital multicomponent sensors and processing developments including binning, statics, noise attenuation and prestack migration. However, the largest remaining obstacle is in the interpretation and, specifically, in the identification of a hugely successful application (such as the North Sea gas cloud example). We will review some of the latest developments in multicomponent technology broken down into acquisition, processing and interpretation.

Introduction
While the concept of multicomponent seismic has been around for many years, cost and quality concerns have limited its use in conventional exploration. Furthermore, we have not been able to clearly identify a clear-cut example of where we have absolutely needed the additional components.
On the acquisition side, recent technology advances, such as reductions in sensor size and weight, while maintaining or improving performance and reliability, are helping to address these problems. Silicon accelerometers have been available for over a decade, yet only recently has technology allowed these miniature accelerometers to be manufactured with a noise performance compatible with seismic requirements. Both Input/Output and Sercel have adopted this technology in the design of unique micro-machined digital accelerometers specifically targeted at the seismic acquisition industry.
Recent processing advances have included more sophisticated binning processes (ACP versus CCP and PSDM), better statics algorithms, application-specific noise attenuation and prestack time and depth migration. Prestack depth migration is a natural fit for multicomponent data since issues surrounding binning, registration and, of course, imaging are best handled in the depth domain.

From an interpretaters point of view, multicomponent data presents numerous headaches and uncertainties. Standard interpretation software does not lend itself well to multicomponent interpretation. Furthermore, the PS and, especially SS volumes are much noisier, lower frequency and typically bear little resemblance in character to the PP volumes. The registration process (event matching between events on the PP, PS and SS) is largely driven by the availability of dipole sonic logs. These dipole sonics are not as common as standard sonics and can often contain erroneous information. Therefore, the quality control and petrophysics required for PS and SS interpretation can be much more involved.

There is however, some room for optimism, since the potential benefits of multicompont data include the conventional P-wave data plus: more reliable rock property information, lithology descrimination, fluid identification, fracture and stress identification and characterization and improved imaging (eg. Below gas clouds, beneath salt and basalt and in low impedance PP reservoirs).

Acquisition - Digital Seismic Sensors
Both the I/O VectorSeis and the Sercel DSU digital sensors have two principal components, a micro-machined silicon accelerometer with a small inertial mass, suspended by miniature springs and a custom designed, mixed-signal ASIC control chip. Force re-balanced feedback operation provides a 24 bit digital output directly from the sensor unit obviating the need for A/D converters in the recording system. The acceleration-proportional output shows a flat transfer- and phase-response from very low frequencies up to 500Hz (Figures 1). Implementation of the digital sensor is in an orthogonal 3-component arrangement forming the core of both recording systems. Sensor design started as early as 1986 with the first prototype

field tests shortly thereafter following extensive laboratory testing. There are now two complete systems working in Canada that have recorded in excess of 70 surveys including 2D, 3D and 4D for both 2C and 9C.

For standard P-wave exploration, the analogue coil geophone has served the industry well for over 70 years. They are relatively inexpensive, rugged and reliable an they allow for flexible array designs. On the other hand, the natural resonance (for example, 10 Hz) limits the recorded signal fidelity at lower frequencies. Furthermore, the advent of 24 bit recording, improved processing options and cost constraints have lessened the concern if not the need for careful array design. For multicomponent applications the geophone's limitations become more noticeable. The vector fidelity and response of one vertical and two horizontally deployed coils is severely impacted unless the geophone is planted within a few degrees of perfectly level. Even then, vector fidelity is a concern, since the horizontal and vertical coils have significantly different response characteristics.

The operational advantages of recording multicomponent data with these new purpose built multicomponent sensors are substantial; They require fewer connections and less cable so, the overall weight of the equipment is reduced. The sensors do not have to be perfectly levelled in the field, since this can be corrected for in processing. The ability of the sensor to work at non-vertical orientations increases the acquisition rate and improves coupling since the sensor is not adjusted for levelling purposes. The recording systems allow for the segregation of individual compnents into individual files thus reducing processing time and uncertainty. The final result is more accurate and affordable multicompnent acquisition.

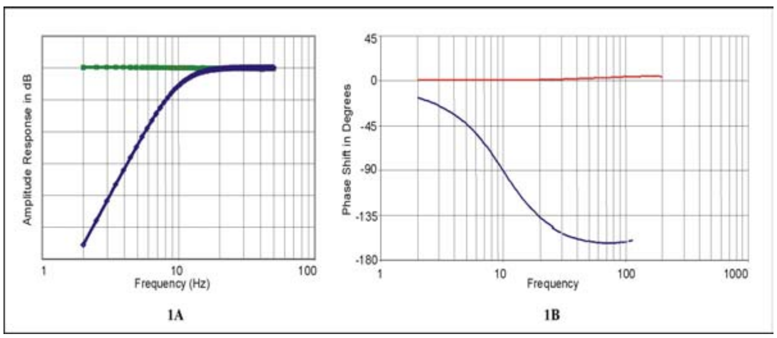

Figure 1: *Shaker table response for both a geophone and VectorSeis. The dark curve in 1a is the amplitude response for the geophone showing a drop-off of amplitude below the natural resonance frequency and the light curve showing the flat response for VectorSeis. Figure 1b shows the impulse response for the geophone (dark line) and the flat phase response for VectorSeis.*

Processing

Multicoponent processing and in particular, converted-wave processing, has not experienced any significant technological advancement within the last 15 years. Some of the biggest obstacles with regard to obtaining high-quality (S/N) and high frequency results are binning/velocity analysis, datuming, statics and noise attenuation. These four processing stages are critically intertwined and overall improvements in the final section will be a result of small improvements in each of these stages. Binning is a critical step and for converted-wave processing, it is tightly linked with velocity analysis. Datuming and statics also go hand in hand. For interpretation puposes, it is important that the two volumes be processed at the same datum and all statics referenced back to this common datum. Furthermore, shear statics are typically large, unrelated to the P-wave statics and it is not possible to derive them from standard refraction methods. Noise attenuation is no different for converted waves than it is for the pure-mode case, except that we typically have lower S/N on converted-wave data and even lower S/N on pure shear-wave data.

Datums, Binning and NMO

The conventional P-wave NMO equation assumes that all shot-receiver pairs for traces within a midpoint gather are at the same elevation. Data are typically processed to meet this assumption by the application of statics. While this method is applicable in areas of minimal topography, it progressively breaks down in areas where topographical variations exceed a few tens of meters, making accurate velocity analysis difficult. In order to account for elevation differences between the shot, receiver and common midpoint (CMP), the paths from shot to the CMP and from the CMP to receiver have to be considered separately (Figure 2).

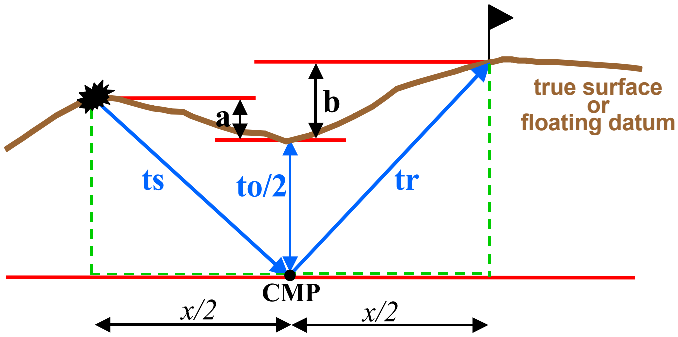

Figure 2. *Schematic illustration for the derivation of NMO with the double square root equation. 'ts' is the travel time from shot to CMP, 'tr' is the travel time from CMP to receiver, 'to' the two-way zero offset time, and 'x' the source-receiver offset.*

The conventional P-wave single square root NMO equation can then be modified to include the elevation differences as follows. If 'a' is the difference between shot and CMP elevation, and 'b' is the difference between receiver and CMP elevation, as illustrated in Figure 2, and v is the RMS velocity, the total travel time from the source to the receiver is described by the following double square root (DSR) equation, which is similar to that commonly used in prestack imaging:

$$t = \sqrt{\left(\frac{to}{2}+\frac{a}{v}\right)^2+\left(\frac{x}{2}\right)^2\left(\frac{1}{v^2}\right)} + \sqrt{\left(\frac{to}{2}+\frac{b}{v}\right)^2+\left(\frac{x}{2}\right)^2\left(\frac{1}{v^2}\right)}\ . \qquad (1)$$

In practice, because of the presence of the near-surface low-velocity or weathering layer, drift static corrections have to be computed first. These can be done in a surface-consistent way to a floating datum, and NMO with the DSR equation can follow. Velocity analysis is performed by scanning a cube of constant velocity stacks, or by other techniques. A temporally and laterally varying velocity function is interactively picked and applied to the gathers using Equation 1. Such a flow is also compatible with prestack time and depth migration surface-consistency requirements.

Problems caused by the assumption of a flat surface are more pronounced on C-wave data because of the larger travel time effects in the near surface due to lower shear-wave velocities. Hence, we have also modified the PS-NMO equation as with the P-wave case to take account of elevation changes between shot, receiver and the CCP. This form of the DSR equation is also convenient for handling the differences in velocity between the downgoing P-wave and upgoing S-wave ray paths. We use this modified equation to NMO correct the gathers prior to CCP binning. This enables velocity analysis and NMO correction to be performed from the true topographic surface or a floating datum.

Converted-Wave PSDM

In converted-wave (C-wave) processing, we usually try to relate events on the P-wave section to corresponding events on the C-wave section (registration). This can be problematic for two very different reasons. First, "corresponding events" on the C-wave section might not even exist. That is, rock property changes that cause P-wave reflections might be transparent to mode conversion or vice-versa. Second, shear waves propagate at different velocities from P-wave velocity, resulting in different arrival times for any corresponding events that do exist. To add to the second reason, a given amount of seismic anisotropy, expressed (for instance) in terms of Thomsen parameters, affects P-wave velocity and S-wave velocity differently. As a result, the stretching and squeezing needed to correlate a P-wave section with a C-wave section can depend on anisotropy in a complicated way.

So time processing, considered to be very natural for pure-mode data, is less natural for C-wave data. As a result, we need to ask ourselves whether the quality of the C-wave stack that we migrate has been compromised by time processing. We also need to ask ourselves whether a single process, such as prestack depth migration, can present a suitable alternative to time processing, in the sense of providing a satisfactory image free of static and velocity problems, in a reasonable amount of time.

Prestack depth migration also naturally solves the binning/velocity conundrum since the velocity and hence binning criteria that are necessary to flatten the gathers will be obtained through velocity model building techniques such as manual tomography.

Statics

Statics correction is a key step in converted-wave processing and is also one of most difficult tasks. Although the converted waves have been used for reservoir characterization and seismic imaging for many years, few converted-wave statics correction methods have been developed. Converted shear-wave (*P-SV*) statics have many features different from conventional PP data and require special considerations. One of them is the large magnitude of converted wave statics which can be two to ten times greater than the P-wave statics (Figure 3, right). This often produces cycle skips when attempting to use conventional residual statics algorithms to resolve them. Another feature is that the converted waves are generally much noisier than P-P data. This makes it less reliable to pick time delays in CCP (Common-Conversion-Point) gathers. P-wave statics are typically not related to S-wave statics in a simple and predictable manner (Figure 3, right). Consequently, most P-wave statics methods do not work well for converted wave data.

Major advancements have been made with repect to solving the receiver-side statics (shear) of the converted-mode experiment in the last few years. Since a converted-wave first break does not exist we have to use other methods for getting the very slow and often critical shear weathering statics. We use combinations of P-wave horizon-based pilots for correcting the receiver stacks (Grech, 2004), cross-correlation techniques in the receiver domain (Jin, et al., 2004) and converted-wave head-waves.

Assuming the shot statics are obtained from conventional P-wave processing and applied to the converted waves, only the receiver statics (shear) are then required. Jin and Ronen (2004) have shown that a modification to Cary and Eaton's (1991) method of obtaining an initial estimate of large, short-wavelength receiver statics by optimizing the trace-to-trace coherence of the Common Reveiver Stack (CRS) can be very effective. The solution of the inverse problem is the one that minimizes the trace-to-trace time difference within a trace window. This inversion can better handle the uncertainty of time delay picks in the presence of noise, because the crosscorrelation coefficients are used as weights in the optimization process to limit the influence of bad picks on the solution. Figure 3 (left) is a synthetic data example that demonstrates how this tchnique can resolve large statics. Figure 3a shows the CRS section contaminated by strong statics. We added random noise to make the data more realistic. Note that the reflectors are aliased due to large statics. For this kind of data, the use of the methods that need a pilot trace can be unpractical. Figure 3b shows the CRS sections after statics correction obtained by the weighted inversion. A 21-trace window is used in the inversion. The data are so noisy that few maximum crosscorrelation coefficients are larger than 0.5 and many picks are erroneous. Even in this situation we can see that the method correctly estimated most of the statics. Real data examples and additional techniques will be presented at the convention.

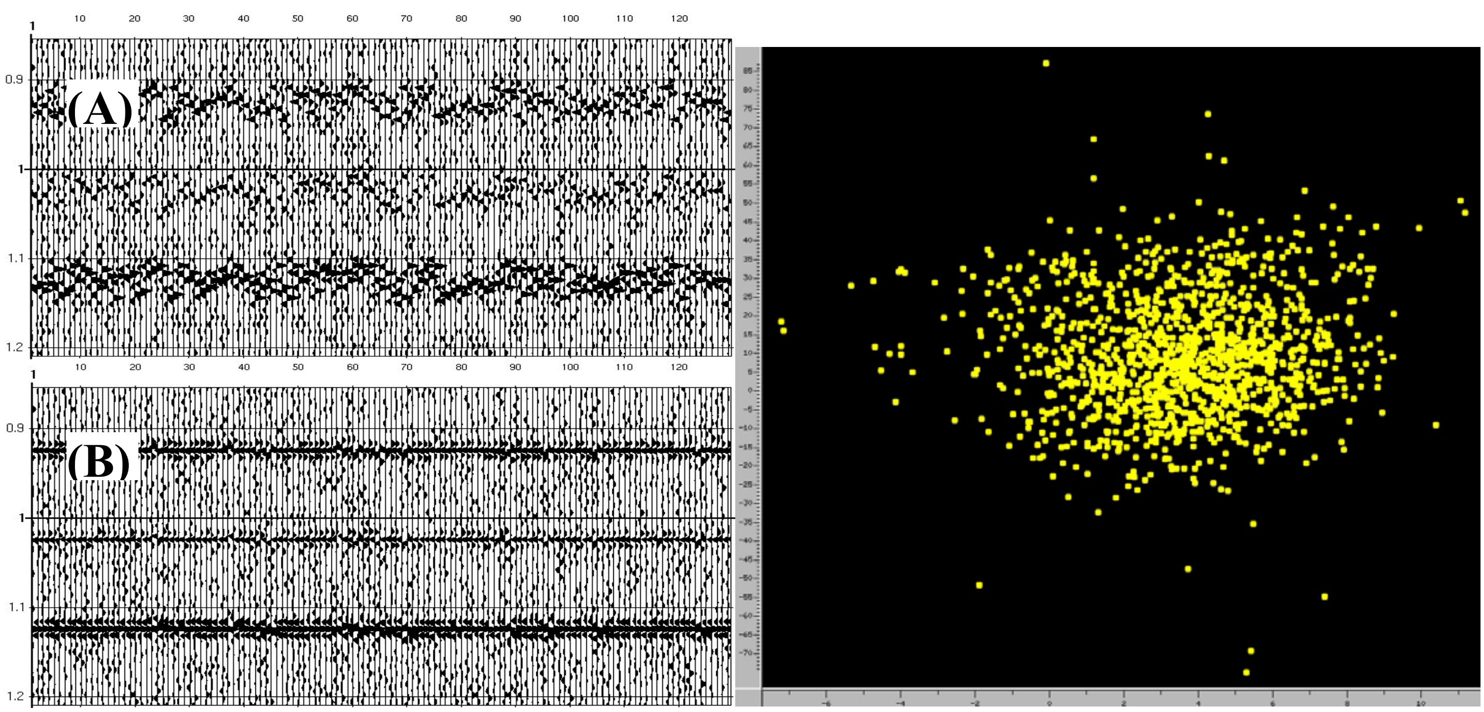

Figure 3: *Left (a): Synthetic CRS section. (b): CRS section after statics correction by the inversion. Right: Crossplot of shear statics on the vertical axis versus compressional statics on the right. Note how the shear statics are an order of*

magnitude greater than the compressional statics and the lack of any trend through the points that would suggest a relationship between shear and compressional statics.

Multicomponent Interpretation

The largest obstacle in the further development and ultimate acceptance of multicomponent seismic is the interpretter. From an interpretaters point of view, multicomponent data presents numerous headaches and uncertainties. Standard interpretation software does not lend itself well to multicomponent interpretation. Furthermore, the PS and especially SS volumes are much noisier, lower frequency and typically bear little resemblance in character to the PP volumes. The registration process (event matching between events on the PP, PS and SS volumes) is largely driven by the availability of dipole sonic logs. These dipole sonics are not as common as standard sonics and can often contain erroneous information. Therefore, the quality control and petrophysics required for PS and SS interpretation can be much more involved. The additional data can be viewed as a hindrence and not helpful for narrowing down uncertainties about reservoir properties. The analysis of this extra information will of course take more time.

New, multicomponent-specific interpreatation software such as Hampson-Russell's PoMC are making the interpretation of multicomponent seismic a reality. The new package provides the means of incorporating dipole sonic and conventional sonic logs into the interpretation workflow. Horizon picking and event registration are easy to do on multiple sections simultaneously. Furthermore attribute generation, such as Vp/Vs maps, instantaneous frequency, amplitude ratios, etc is possible. Once the registration is done, further analysis, such as PS-AVO can be persued. We will show examples of the interpretation workflow and results.

Conclusions

While we realize that there may still be a long way to go before multicomponent seismic is widely accepted, it is apparent that recent advances in acquisition, processing and interpretation are helping. Modern digital multicomponent sensors are providing accurate and affordable solutions for acquisition. Processing advances such as improved statics algorithms, more accurate binning and velocity analysis and prestack depth migration are helping to improve the S/N, frequency content and overall quality of the data. Finally, recent advances in multicomponent interpretation and analysis are setting the stage for significant breakthroughs in multicomponent exploration.