# Using 4-C to characterize lithologies and fluids in clastic reservoirs

FOLKE ENGELMARK, WesternGeco—Seismic Reservoir Services, Kuala Lumpur, Malaysia

Multicomponent seismic has been around for a long time without gaining widespread acceptance. The potential benefits of having both compressional (*P*-wave) and shear (*S*-wave) information have never been disputed, but the cost of acquiring and processing the large data volumes has been high and the quality of the *S*-wave data has sometimes not met expectations.

However, recent technological developments in the area of sources, sensors, telemetry, and data processing are making multicomponent data increasingly popular as a way to provide better quality data at lower cost.

Although shear information can be accessed through the AVO response of the *P*-waves, the pure shear (*SS*) mode or the converted shear wave (*PS*) mode provide direct and more accurate information about the shear properties of the subsurface. Getting this improved information about the elastic properties of the subsurface is indeed one of the main reasons for acquiring multicomponent data.

There are two major ways of acquiring multicomponent seismic data. Land multicomponent seismic is typically acquired using dedicated vertically and horizontally polarized traction sources to generate downgoing *P*- and *S*-wave modes. The seismic can then be recorded as three-component (3-C) or nine-component (9-C) data sets. The latter involves three consecutive 3-C recordings of direct and converted modes by activating each dedicated source mode in turn (i.e., vertical followed by in-line and cross-line horizontal components).

Marine multicomponent data, known as 4-C, is acquired using the traditional air-gun sources to generate a pressure wave (*PP*), but the receivers are on the seafloor to record the 3-D vector field. The fourth component is a hydrophone recording the pressure field just like ordinary seismic streamers.

By placing three-component geophones on the seafloor, converted shear waves, known as the *PS* mode, can also be recorded. A propagating wave front will, in addition to reflection and transmission, undergo a partial mode conversion of seismic energy whenever the waves impinge on a boundary at any angle different from normal incidence (NI). These converted modes are also transmitted, reflected, and mode converted again, but there is a substantial loss of energy at each conversion. Hence, except in situations involving large velocity contrasts such as salt and basalt contacts, which are very efficient mode converters, we typically find that only the first-order converted mode is strong enough to be successfully recorded. We are then looking for downgoing offset *P*-wave energy that is converted to *S*-wave energy at the lithologic boundaries and then directly transmitted to the recording sensors at the seafloor.

The fact that this first-order converted wave often provides marine data of excellent quality has been a pleasant surprise that has generated an entirely new marine seismic market in the last five years. Indeed, it has been so successful that we are now routinely extracting the *PS* mode from land multicomponent data also, because the dedicated shear mode often is of very poor quality. Shear waves are very heavily attenuated by the weathering layer, or in marine data by the unconsolidated sediments at the seafloor, and because half the propagating distance is covered by the more robust, longer-wavelength *P*-wave, the resulting *PS* image is often superior to direct shear (*SS*).

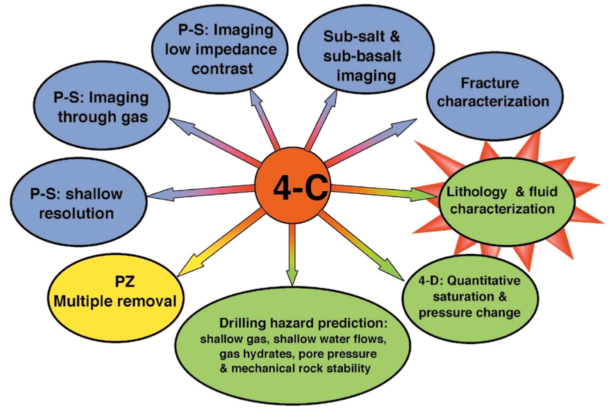


**Figure 1. The range of 4-C applications. In yellow is the one application based exclusively on *P*-wave data, and in blue are all the ones based on converted (*PS*) waves. In green are all the applications involving both the *PP* and the *PS* mode. Lithology and fluid characterization are highlighted as the specific topic of this paper.**

Given data of equal quality, it is preferable to work with dedicated shear rather than converted shear data, because the normal incidence shear reflectivity is the single most important piece of shear-wave information we can extract. However, the information content is very similar in *SS* and *PS* waves; it's just not so readily available in the *PS* mode.

The reason converted shear has become so popular is because it is currently our best means to acquire marine shear data—and with surprisingly good quality to boot.

**4-C applications.** Figure 1 shows the various applications for 4-C seismic data. Yellow indicates the one application involving *P*-wave data only: *PZ multiple removal*, in which simultaneous recording of the pressure (P) and vertical velocity (Z) wavefields improves multiple attenuation by combining the two, known as PZ imaging. In addition, the vertical-component geophone often offers a wider bandwidth and, hence improved resolution. Other important factors improving the imaging are more accurately known receiver positions, higher fold, and the fact that 4-C allows better illumination through acquisition of all azimuths.

Blue indicates applications that involve the converted mode only. *PS resolution at shallow depths* exceeds resolution of *PP* data due to the shorter wavelength of the shear mode. The single most successful application of converted wave data so far has been *PS imaging through gas obscured areas. PS imaging of low-impedance contrast* reservoirs tends to be the most successful alternative to offset stack *P*-wave imaging where the AVO gradient is small (i.e., heavy oils in unconsolidated clastic sediments). *Subsalt and subbasalt imaging* is another very important application of converted waves because a large part of the transmitted energy through the high-velocity layers is in the form of converted shear. An analysis of shear-wave splitting using converted waves is

**Table 1. Elastic properties of a shale overlaying a sandstone reservoir with brine, oil, and gas**

| Lithology | *P*-velocity (ft/sec) | *S*-velocity (ft/sec) | Density g/cm$^3$ | Poisson's ratio | *P*-impedance | Shale/sand reflectivity |
|---|---|---|---|---|---|---|
| Shale | 9249 | 4730 | 2.359 | 0.323 | 21821 | — |
| 100 % brine in sandstone | 11155 | 6884 | 2.163 | 0.193 | 24131 | 0.050 |
| 90 % oil in sandstone | 10566 | 7045 | 2.065 | 0.116 | 21821 | 0.000 |
| 90 % gas in sandstone | 10613 | 7264 | 1.943 | 0.060 | 20633 | -0.028 |

**Table 2. Brine-saturated sandstone reservoir with porosity variation emulating the model with fluid variations***

| Lithology | *P*-velocity (ft/sec) | *S*-velocity (ft/sec) | Density g/cm$^3$ | Poisson's ratio | *P*-impedance | Shale/sand reflectivity |
|---|---|---|---|---|---|---|
| Shale | 9249 | 4730 | 2.359 | 0.323 | 21821 | — |
| 30.0 % porosity sandstone | 11155 | 6884 | 2.163 | 0.193 | 24131 | 0.050 |
| 33.6 % porosity sandstone | 10369 | 6265 | 2.105 | 0.213 | 21821 | 0.000 |
| 35.6 % porosity sandstone | 9954 | 5932 | 2.072 | 0.225 | 20633 | -0.028 |

**The 30% porosity model is identical to the shale-over-brine model in Table 1*

**Table 3. Variations in sealing shale overlying a homogeneous oil-saturated sandstone reservoir***

| Lithology | *P*-velocity (ft/sec) | *S*-velocity (ft/sec) | Density g/cm$^3$ | Poisson's ratio | *P*-impedance | Shale/sand reflectivity |
|---|---|---|---|---|---|---|
| Soft shale | 8528 | 4164 | 2.314 | 0.344 | 19732 | 0.050 |
| Medium shale | 9249 | 4730 | 2.359 | 0.323 | 21821 | 0.000 |
| Hard shale | 9686 | 5074 | 2.384 | 0.311 | 23090 | -0.028 |
| 90 % oil in sandstone | 10566 | 7045 | 2.065 | 0.116 | 21821 | — |

**The "medium-shale" model is identical to the shale-over-oil model in Table 1*

**Table 4. Variations in sealing shale overlying a homogeneous oil saturated sandstone reservoir***

| Lithology | *P*-velocity (ft/sec) | *S*-velocity (ft/sec) | Density g/cm$^3$ | Poisson's ratio | *P*-impedance | Shale/sand reflectivity |
|---|---|---|---|---|---|---|
| Soft shale | 8528 | 5090 | 2.314 | 0.223 | 19732 | 0.050 |
| Medium shale | 9249 | 4730 | 2.359 | 0.323 | 21821 | 0.000 |
| Hard shale | 9686 | 4550 | 2.384 | 0.358 | 23090 | -0.028 |
| 90 % oil in sandstone | 10566 | 7045 | 2.065 | 0.116 | 21821 | — |

**The shear velocities of the soft and hard shale have been modified to create the same AVO response as the model with variations in the reservoir fluids without affecting the already identical NI response. The "medium-shale" model is identical to the shale-over-oil model in Table 1.*

the most accurate way of *fracture characterization* in terms of their direction and spatial frequency.

Green indicates applications that require simultaneous analysis of both *PP* (yellow) and *PS* (blue) modes. Yellow and blue make green, right? *Lithology and fluid characterization* are highlighted because they are the topic of this paper. Specifically, we will look at how combined analysis of *PP*- and *PS*-waves will disambiguate the characterization of lithologies and fluids. Next is *4-D quantitative saturation and pressure change,* made possible by the fact that the *PP* mode is sensitive to changes both in effective pressure and saturation, whereas the *PS* mode is almost exclusively sensitive to pressure. *Drilling hazard prediction* is another important application in which multicomponent seismic can significantly reduce the lithology-fluid-pressure ambiguity because the *PP* mode is sensitive to changes in rock fabric and pore fluids, whereas the *PS* mode is mainly sensitive to variations in the rock fabric. This allows for improved and more accurate evaluation of shallow gas, shallow water flows, gas hydrates, excessive pore pressure, and mechanical rock stability with reduced ambiguity.

**4-C lithology and fluid characterization.** Seismic *P*-wave data are notoriously ambiguous in the sense that variations in fluid, porosity, and seal properties can all result in the same NI reflectivity at the seal/reservoir boundary (Figures 2, 3, and 4).

Figure 2 shows a sandstone reservoir with 30% porosity buried at 7000 ft. The fluids are brine, an API 40 weight oil, and gas with a specific weight of 0.75 relative to air. The sandstone is encased in shale. The properties of the reservoir and seal are listed in Table 1.

Figure 3 shows how the same variations in sandstone *P*-impedance, and hence normal incidence reflectivity, as a function of pore fluid, can be achieved by varying the porosity of the brine-saturated reservoir based on the input parameters in Table 2.

It is also conceivable to have a situation in which reservoir porosity and fluid fill remain constant and the observed variation in reflectivity originates in variations in the overlying seal (Figure 4). The corresponding elastic parameters are listed in Table 3. *Soft*, *medium*, and *hard shale* refer to their degree of consolidation and hence their relative acoustic impedance magnitude.

In Figure 5, the *PP* reflectivity is shown for NI and at 30° angle of incidence together with the *PS* reflectivity at maximum amplitude, which occurs at about 30° for the three cases under consideration. The identical NI reflectivities are highlighted for all three models. The *PP* AVO component shows high sensitivity to fluid variations, and this is of course the basis for using AVO as a fluid indicator. However, the *PS* mode adds additional information that further decreases ambiguity. It is the lithologic changes in reservoir porosity and shale hardness that are clearly indicated by the strong variation in the converted-wave reflectivity; the changes in pore fluids cause very little change in *PS* reflectivity. Notice also that the "oil" model and the "medium-shale" model are identical in all elastic parameters and hence also highlighted in green for all modes. The "brine model" and the "low-porosity" model are also identical in all respects and are seen highlighted in magenta.

Why not just use AVO then to separate fluid changes from lithologic changes? That's exactly what we have been doing for the last 20 years with varying success. The problem is that AVO analysis often involves substantial uncertainty. This is illustrated by changing only the shear velocities of

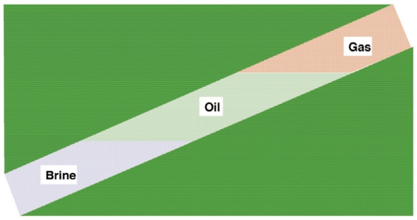


**Figure 2. A sandstone reservoir with 30% porosity saturated with brine, oil, and gas encased in shale.**

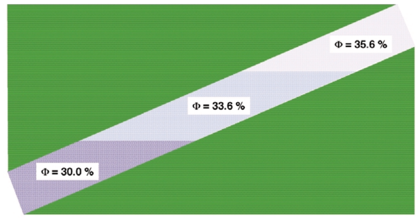


**Figure 3. A brine-saturated sandstone reservoir with variations in porosity such that the acoustic impedances matches those of the fluid model in Figure 2. The 30% porosity model is identical to the shale-over-brine model in Figure 2.**

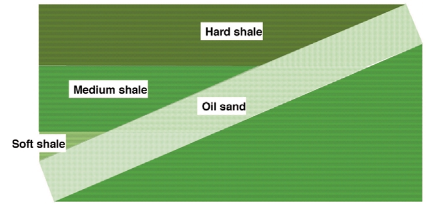


**Figure 4. Variations in the overlying shale resulting in the same NI reflection coefficients as in Figures 2 and 3. The "medium-shale"model is identical to the shale-over-oil model in Figure 2.**

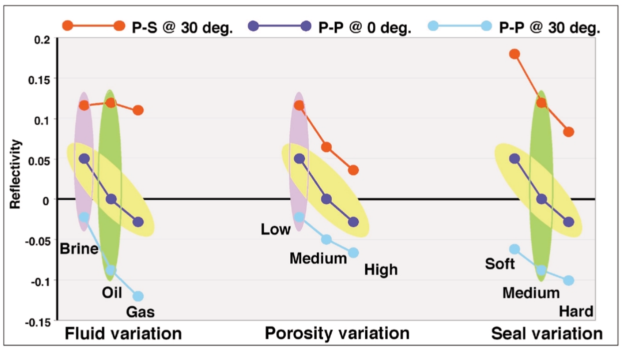


**Figure 5. Seal/reservoir reflectivity for the three models presented in Figures 2, 3, and 4, based on variations in pore fluid, porosity, and seal properties. The NI *PP* responses (dark blue) highlighted in yellow are designed to be identical. The fluid variation "oil model" and the seal variation "medium-shale model" are identical in all elastic parameters, hence highlighted in green for all three modes. Highlighted in magenta are the "brine model" and the "low-porosity" model, which are also identical in all respects.**

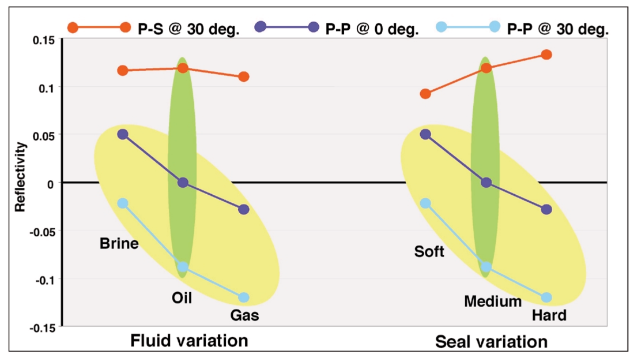


**Figure 6. Modification of the shear velocities in the soft and hard shale properties for the seal variation model, such that both the *PP* NI and AVO responses, in dark and light blue respectively, are identical to the model with fluid variations; both are highlighted in yellow. The *PS* mode in red clearly differentiates between the changes in pore fluids and variations in seal properties. Identical models are highlighted in green.**

the soft and hard shales in the previous seal variation model, as indicated in Table 4.

The result (Figure 6) is that the *PP* NI and AVO responses are now identical in the "fluid variation" and "seal variation" models (both highlighted in yellow). Notice that the *PS* response readily detects the differences in the shale, whereas the fluid changes are hardly registered at all. The oil and medium-shale models are, once again, identical in all elastic parameters (hence shown with all modes highlighted in green).

These shales are obviously very unusual, with the harder one having a higher Poisson's ratio than the softer shale. If the soft shale is thought of as a shale with a very low saturation of gas generated from intrinsic maturing organic content, it would have an unusually low Poisson's ratio. The hard shale, on the other hand, could be very rich in clay minerals and/or immature organic content, which would give it a high Poisson's ratio. The important issue is not whether there are any shales with these properties but rather the fact that whenever there are doubts about the origin of observed variations in reflectivity, the combined information in *PP* and *PS* data will resolve the ambiguity.

**4-C the seismic tool for all reasons.** In reality, we encounter situations in which observed variations in *PP* reflectivity may originate in any combination of changes in pore fluids and changes in the fabric of the constituent rocks. However, the important 4-C benefit always remains the same—namely that the *PP* mode will register changes in pore fluid and rock fabric with equal acumen, whereas the *PS* mode will almost exclusively register changes in rock fabric. It is then the combined information from the two modes that can be inverted to a unique set of elastic parameters with an accuracy limited only by the uncertainties in the magnitude of the reflectivity measurements.

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, and we will soon see permanent installation of multicomponent sensors on the seabed before the onset of production. The combined strength arising from the integration of a common subsurface model, flow simulator, and repeated 4-C seismic time-lapse surveys will be the ultimate reservoir management tool. It will allow the asset team to optimize the trajectories of production and injection wells based on pore pressure, rock strength, and fracture intensity in the overburden extracted from the seismic data. The hydrocarbon production and the ultimate recoverable volumes will be optimized by the enhanced reservoir characterization and monitoring resulting from the improved repeatability provided by permanently implanted 4-C sensors, together with the recognized ability of 4-C to provide nonambiguous solutions to observed changes in the 4-C seismic response. E

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*Corresponding author: folke.engelmark@slb.com*