Tutorial

If terms like 'integration' and 'multi-disciplinary' are to have meaning, then the geoscience and engineering community needs to share a common language. Our suspicion is that many useful terms and technologies are not properly understood and so are either misapplied or simply not applied at all. This is why we are introducing the first of a series of occasional *First Break* Tutorials. The idea is to provide brief, authoritative but accessible discussions of commonly used – and some neglected – concepts, techniques and technologies that should, but may not be, part of everyone's working knowledge.

This is very much an open-ended series, and the Editorial Board of *First Break* would welcome any suggestions for future topics, better still, contributions which in the first instance should be addressed to Andrew McBarnet, publishing editor (E-mail: andrewmcbarnet@telus.net.)

Phase, polarity and the interpreter's wavelet

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Introduction

Despite the complexities of sound propagation in the earth, the model of the seismic reflection signal in the mind of the interpreter is a simple one. It is the convolutional model comprising a reflection coefficient series convolved with a time series representation of the seismic pulse in the zone of interest (Fig. 1). This pulse is often called the seismic wavelet.

So, before starting to assign significance to the troughs and peaks of seismic data the interpreter needs to establish the form of the 'wavelet' in the data. This is not always as easy as it may seem. What is more, to counter this simple concept there is, unfortunately, a geophysical terminology that tends to confuse rather than simplify. More often than not terms are used loosely and inaccurately.

A common question posed in discussions of seismic interpretations is 'what is the phase and polarity?' The question concerns the shape of the 'wavelet' and what, if any, is the sign (positive or negative) of the dominant part of the wavelet that relates to a particular contrast of acoustic impedance. As we shall see the question should be more specific and comprise a number of related questions:

- Is there a dominant loop to the wavelet, and if so what is it?
- Is there a time lag?

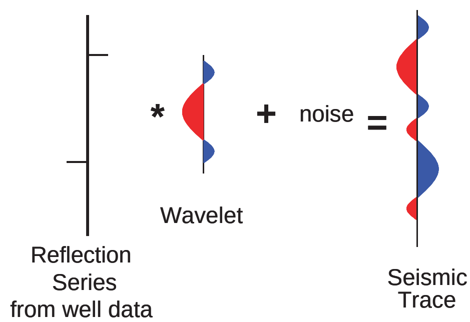

Figure 1 The convolutional model.

- If the wavelet is not symmetrical why has the data not been zero phased?

The motivation behind asking these questions is the need to know if and how the data can be used to reliably indicate hard and soft reflections, and what signature or response should be expected from different reflection types. Usually the enquirer will have in mind a relative amplitude model, for example that shale/brine sand reflections are hard and shale/gas sand reflections are soft. It may be slightly more sophisticated if there is also an AVO component to the model: for example if looking for shale/gas sand reflections that show increasing amplitude with offset (Fig. 2). In data processed for the purpose the form of the AVO response maybe diagnostic of lithology or fluid type. Understanding the wavelet shape is

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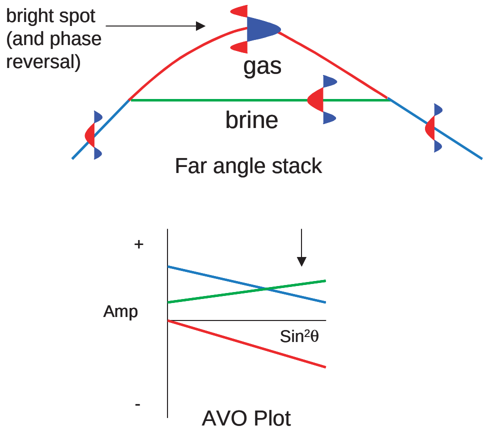

Figure 2 An example of rock physics models and expected reflectivity responses.

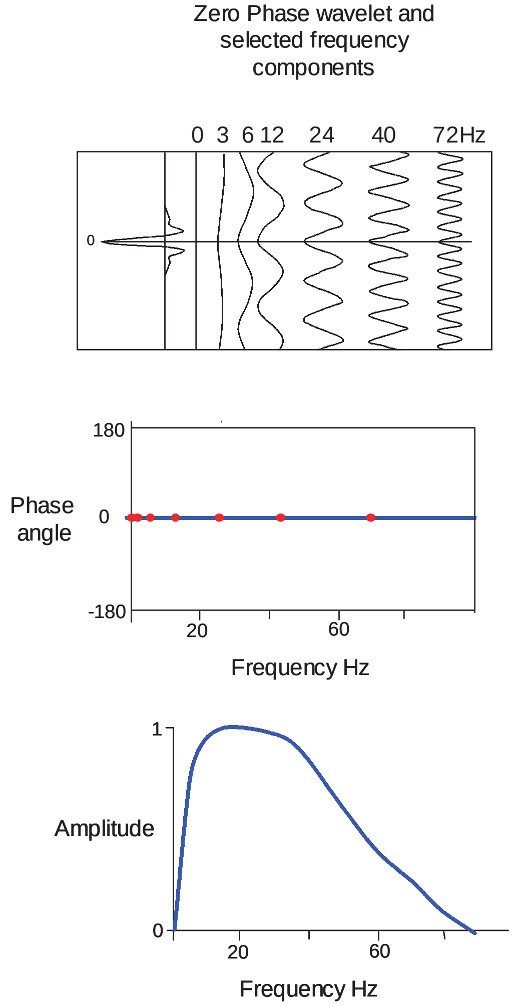

Figure 3 Illustrating the frequency components of a zero phase wavelet (at each frequency the peaks are aligned at zero time).

therefore a critical starting point in amplitude interpretation logic.

The question of phase and polarity is simple enough. Invariably, however, it causes considerable debate and it is not unknown for these discussions to result in ill feeling and possibly loss of credibility for some poor interpreter. Before addressing the practice of estimating the interpreter's wavelet the definitions of phase and polarity and their relevance to the seismic interpreter need to be addressed.

Phase

Phase describes the relative timing relationships of the various frequency components that make up the seismic wavelet. Two concepts of phase, minimum and zero phase, are regularly referred to by geophysicists, often wrongly. These are not the only descriptions of phase but they serve as convenient 'buzz' words. Common usage of minimum and zero phase as descriptors is based on the fact that sound sources such as explosives and air guns have minimum phase (or close to minimum phase) signatures, and zero phase wavelets are the most desirable for interpretation.

Figure 3 shows that a zero phase wavelet comprises frequency components that have peaks aligned at zero time. Zero phase wavelets are symmetrical with the dominant loop corresponding to the reflection from the acoustic boundary. Although it is quite common for any symmetrical wavelet to be referred to as zero phase, if the timing of the dominant loop is non-zero then strictly speaking it cannot be described as zero phase.

Minimum phase describes a phase characteristic of so-called 'causal' wavelets, that is, wavelets having a definite onset time. For any amplitude spectrum there is a number of possible causal wavelets and in practical terms usually a large number. The minimum phase wavelet is unique among this set of wavelets in building up its energy in the minimum time. The name comes from the frequency domain, where the minimum phase stays closer to zero than the phase of any other of the possible causal wavelets. That does not mean that the minimum phase is necessarily close to zero since rapid changes in the amplitude spectrum inevitably induce sharp changes in phase. Source signatures are of course causal but it requires very careful analysis, and very clean recordings, to decide whether a signature is a minimum phase wavelet. Seismic wavelets at usual target depths are never determined accurately enough for any rigorous test of whether they are minimum phase.

It follows from this discussion that to ask an interpreter whether his wavelet is minimum phase is actually a misconceived question. In practice minimum phase wavelets can have a variety of shapes including symmetrical and asymmetrical and everything in between. Putting it another way, to say that a wavelet is minimum phase says nothing of real sig-

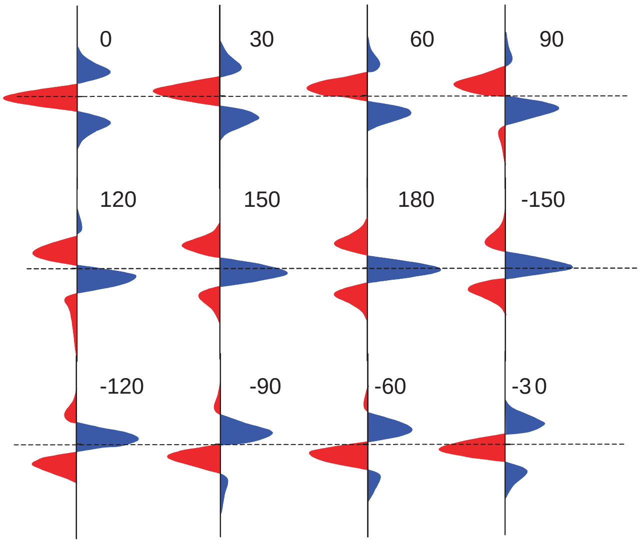

Figure 4 Phase rotation of a zero phase wavelet.

nificance to an interpreter. The response to this assertion should be 'so what?'

A much more useful aid in describing and discussing wavelets is phase rotation as this describes a critical feature of wavelets, namely their symmetry. Figure 4 illustrates the concept with respect to a zero phase wavelet. As the phase rotates, the relative amplitudes of the peaks and troughs of the wavelet change. A negative phase rotation or phase lag delays the main peak; a positive phase rotation or phase lead advances it in time. Because phase is cyclic, a phase lead of 150 degrees, for example, is equivalent to a phase lag of 210 degrees. At ± 90 degrees the wavelet is anti-symmetric: the two loops have the same amplitude. Sometimes asymmetric wavelets will be described (perhaps erroneously) as 90 degree wavelets.

Polarity

Of all the concepts that serve to confuse the interpreter the worst culprit is polarity. In practical terms for symmetrical wavelets with a dominant loop 'polarity' describes whether it is the red or blue or the trough or the peak that represents a particular reflection type (hard or soft). Hard reflections are caused by increases in acoustic impedance downwards across a boundary.

Again whilst this is a simple and pragmatic concept, established definitions of polarity (normal and reverse) serve to confuse the issue. The seismic processor will assert that the final data delivered to the workstation is 'normal or reverse' polarity. Exactly what this means depends on which convention (European or US) is being adhered to. European convention normal polarity is 'negative number on tape = compression = trough' (Fig. 5). Of course 'reverse' polarity is

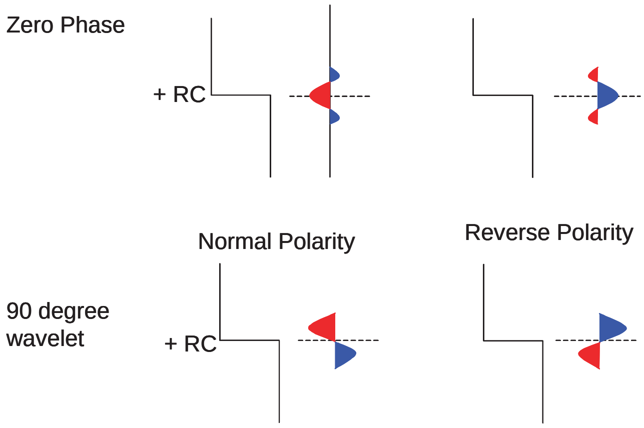

Figure 5 European polarity convention (modified after Badley 1985).

the opposite. Confusingly, US convention normal polarity is European reverse polarity. So quite clear really.

For the purposes of interpretation discussions, polarity conventions have been long disregarded by some and held onto dearly by others. Whilst it is good to know what has gone on in the processing (for example whether the deconvolution has significantly altered the wavelet shape, as with spiking deconvolution, or whether the data has been 'flipped', that is, has been multiplied by –1) it is not possible without performing a quantitative well tie (see section on 'estimating the wavelet' below) to confidently assume that knowing the polarity convention necessarily implies that the shape of the wavelet is also known.

Common, and erroneous, assumptions are that a minimum phase wavelet is either always dominated by the leading loop (a trough in the case of European normal polarity) or that it is always asymmetric. In fact results from well ties where the wavelet has been derived from the data (see discussion below)), show that, after supposedly minimum phase processing, wavelets at the target of interest are not infrequently close to symmetrical and dominated by the following loop. This loop would be the peak in the case of European normal polarity convention. The response of seismic recording systems virtually ensures that the initial loop is not the dominant loop of a seismic wavelet (Fig. 6).

Estimating the wavelet

So how do we estimate the wavelet in seismic data? One approach is to attempt to model the propagation of sound waves through the earth to the target of interest. The signature of the air gun array, for example, is measured and estimates of earth filter effects are applied to the pulse to match the bandwidth evident on the seismic. The 'wavelet' in this context is directly related to a model of sound propagation which can be monitored, in marine surveys, from source to seabed and through the recording instruments, but becomes

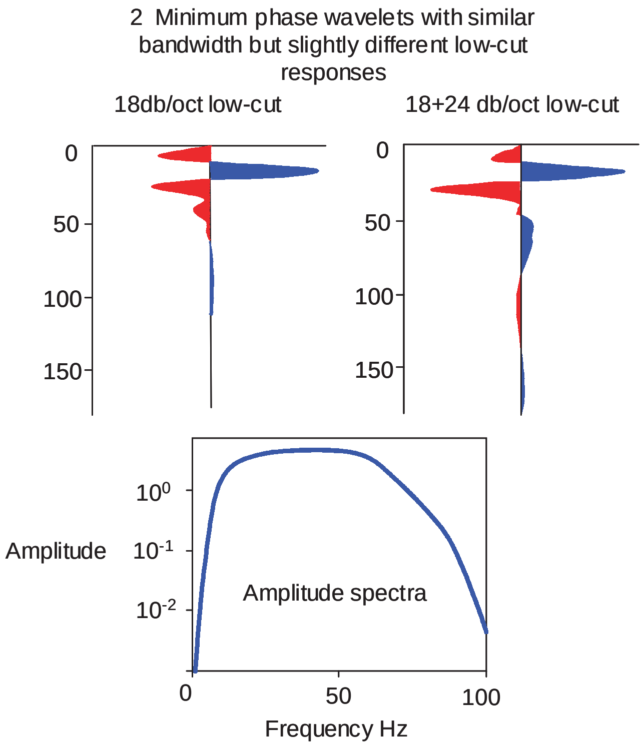

Figure 6 The effect of different instrument responses on the shape of a minimum phase wavelet (for example 18 db/oct might be typical of a seismic recording system whereas 24 db/oct could be the response of the hydrophones and associated sea surface ghosts).

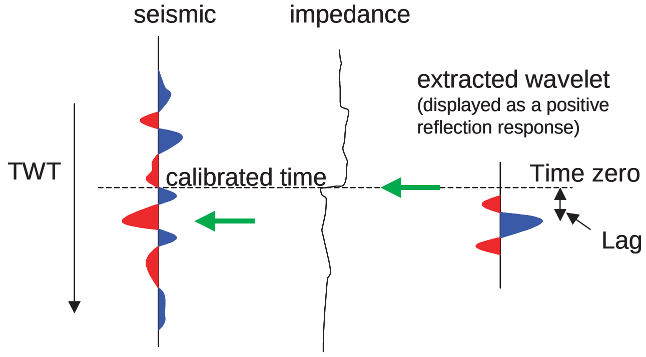

Figure 7 An illustration of practical polarity, showing the key components of wavelet shape and timing. The wavelet shown here is characteristic of many 'normal polarity' marine wavelets.

much more uncertain over the transmission path from seabed to target. In many instances earth filtering effects are complex and it is difficult (some might say impossible) to adequately model them. This applies not only to wavelet shape but also to the timing of the wavelet. In addition to earth filter effects different processing steps can also change wavelet shape and timing.

A pragmatic approach consistent with the interpreters desire to correlate geology to seismic is to use the convolutional model, together with least squares matching techniques and statistical measures of fit and accuracy to match the seismic to the well data (White 1980; White *et al.* 1998). In this context the 'wavelet' is the filter that makes sense of the seismic in terms of the reflectivity. Thus where a well is available the interpreter has a chance to estimate the wavelet (both in terms of shape and timing) directly from the seismic and also to ascertain the level of confidence that should be placed in the wavelet.

When there isn't a well the problem of determining wavelet shape and timing becomes more problematic. In principle the answer is to look at the reflection response of 'unique' reflectors of 'known' impedance contrast, such as the hard sea bed or the top reflections of seismically 'thick' igneous intrusions or thick sequences of carbonates overlain by basinal shales. In practice there is usually a great deal of ambiguity arising from:

(a) the change of wavelet shape with depth (in response to attenuation and the effects of inter-bed reflections);

(b) tuning effects.

One approach in estimating phase (but not necessarily polarity) that is sometimes effective is to measure the amplitude of an event (i.e. a reflection from a single reflector) as the phase is rotated by increments. This relies on the fact that the phase spectra of wavelets in processed seismic data are normally fairly smooth across the seismic bandwidth and can be reasonably well approximated by a time shift and constant phase rotation. During the phase rotation procedure the point at which the wavelet is closest to zero phase is where the amplitude is highest. If the relative impedance contrast of the event is known then polarity can be assigned.

Wavelet features and the interpretability of seismic

The interpretability of seismic data depends on three aspects of the wavelet, namely

- The degree to which the wavelet is symmetrical;
- The timing of the wavelet;
- The relative amplitudes of the main loop to the side lobes.

Symmetrical wavelets are most desirable as the energy dominantly resides in a particular loop of the wavelet. Reflections can be interpreted clearly as hard or soft and the effects of interfering reflections can be most readily appreciated. Asymmetric wavelets (such as 90 degree phase rotated wavelets) are exactly the kind of wavelet that you don't want in the data. In these instances conversion of the data to zero phase is required.

The simplest way to get a zero phase wavelet is to rotate the phase of the data back to (near) zero phase. Good well ties make it possible to correct the phase more precisely but in general precise phase compensation would not make a significant improvement on phase rotation. Procedures that claim to transform from minimum phase to zero phase seismic data may not be effective because of the problems of measuring and validating minimum phase. Consequently the interpreter should be very wary of zero phasing procedures (usually applied by seismic processors) that are based on the seismic alone.

Timing of the wavelet (i.e. the timing of the main lobe relative to zero time) is a critical factor in interpretation. Figure 7 illustrates the importance of knowing the timing of the wavelet in order to accurately relate the reflecting interface to the correct amplitude in the seismic. This example also shows why simply posting tops on seismic sections may not be an adequate way of tying wells to seismic. Although a seabed reflection may give some clue to the timing of the wavelet, accurate timing in particular can be found only from well ties. In the interests of brevity we shall leave a discussion of well ties to a later paper.

The other descriptor of wavelet shape is the side-lobe to main-lobe ratio. This is controlled by the bandwidth of the wavelet and the rates of spectral decay at low and high frequency. In some cases it is possible to enhance the ratio through wavelet processing.

Conclusions

What we are proposing here is a radical realignment of how interpreters describe and think about the seismic wavelet. We recommend that the use of 'minimum phase' and the reliance on polarity conventions be discontinued. Minimum phase is irrelevant in seismic interpretation and polarity conventions do not provide enough information about the wavelet shape and timing. Instead interpreters would be better served by reliable answers to the questions posed in the introduction. The interpreter needs to know:

- Is the wavelet symmetric and if so what is the polarity (i.e. the sign of the amplitude and/or colour representation) of the main lobe or dominant loop?
- If not, why not (are there problems in zero phasing)?
- Is there a time shift between the wavelet's time zero and the centre of its main lobe?

Of course polarity (in terms of the nature of the main lobe of the wavelet) is fundamental. The important question is: does the main lobe represent a reflection from an increase or decrease in acoustic impedance?

References

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