An acquisition polarity standard for multicomponent seismic data

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ABSTRACT

This paper deals with the question of a polarity standard to apply generally to 3D multicomponent seismic data, or any subset thereof. The primary goal is to provide a field recording standard according to which the designations *normal polarity* and *reverse*(*d*) *polarity* may be used on any or all of the three or four components normally acquired in a multicomponent seismic survey. Since this includes three geophone components and a possibly a hydrophone or microphone component, this polarity standard should – and does – also apply in a consistent way to 2D or 3D land 3C, 3C VSP, vertical cable, and streamer seismic data.

Recommendations or guidelines are given on how to proceed, both in acquisition and preprocessing, to determine the polarity for any particular data component. The basis of this standard is the SEG polarity standard, which was first enunciated as a field-recording standard for vertical-component land data and marine hydrophone data. It is founded on a right-handed coordinate system, with z positive downward, x positive in the positive line direction in 2D, or some specified principal direction in 3D, usually that of the receiver-cable lines, and y positive in the direction 90° clockwise from x. The polarities of these axes determine the polarity of ground motion in any component direction.

The present recommendations are for a field-recording or acquisition standard (which is taken to include certain preprocessing steps) rather than a final-display polarity standard. A primary objective has been an internally consistent system of polarity specifications, encompassing all of the recorded components, in order to facilitate, among other things, consistent horizon correlation among multicomponent datasets and determination of correct reflectivity polarity. We also recommend a cyclic indexing convention for multicomponent seismic data, namely (W, X, Y, Z) such that, when used e.g. as subscripts, W would denote hydrophone (pressure), X inline geophone, Y crossline, and Z vertical. The (x, y, z) symbols denote the Cartesian distance coordinates of the right-handed system specified above.

INTRODUCTION

The issue of polarity is deceivingly simple, involving a number of separate considerations that very often are interrelated and compound each other, so that a binary question can soon compound into a complicated and confusing problem. The three fundamental questions that this paper addresses are: (1) How should we acquire multicomponent data in the field to ensure one or another acquisition polarity? (2) How should we preprocess seismic traces to ensure preservation of one or another (preprocessing) polarity? (3) Given a particular dataset prior to any phase-altering processing steps, how do we decide whether we have normal polarity or reverse polarity?

The concept of phase is not binary in nature, but continuously varying. So a polarity convention for data beyond the preprocessing stage, e.g., for final display, is an elusive concept, as processing modules can alter wavelet phase in complex ways (see e.g. Roden and Sepúlveda, 1999). Fulton et al. (1981) proposed in an SEG draft report a display-polarity standard that would be independent of field-recording standards, defined in terms of (acoustic) impedance contrasts. According to this proposed standard, a reflector having a downward increase in impedance should generate a reflection of positive polarity [a black central peak (to the right) on a zero-phase trace]. If adopted, their display-polarity standard would place upon the processor the onus of ensuring that an SEG-standard display had been generated. In this paper, we do not address the question of final-display polarity but, rather, the concept of an acquisition or preprocessing polarity, which has definite relevance and has served a valuable practical purpose in exploration seismology.

POLARITY STANDARDS

The SEG standard for impulse-signal polarity

In the absence of an agreement or convention, the decision as to what constitutes normal (i.e. positive) polarity on an output seismic section is an arbitrary one. There exists, however, a polarity standard, enunciated by the SEG, that is widely known, though not always so well understood. Many geophysicists are acquainted with the SEG polarity standard in the form stated by Sheriff (1991) in his authoritative SEG dictionary:

> "1. The SEG standard for causal seismic data specifies that the onset of a compression from an explosive source is represented by a negative number, that is, by a downward deflection when displayed graphically… This standard is historically based, so that refraction first arrivals break downward. A reflection indicating an increase in acoustic impedance or a positive reflection coefficient also begins with a downward deflection. 2. For a zero-phase wavelet, a positive reflection coefficient is represented by a central peak, normally plotted black on a variable area or variable density display…This convention is called **positive standard polarity** and the reverse convention is **negative standard polarity** or **reverse polarity**. Polarity standards are not specified for wavelets other than minimum-phase or zero-phase ones..."

Sheriff (1991) was evidently mindful of the conceptual difficulty in defining a final-display or processed polarity (see Fulton et al., 1981) in that he restricted his statement of the standard to minimum-phase and zero-phase wavelets. In what follows, it is convenient to assume that we record only minimum-phase wavelets, so that we can characterize waves or wavelets in terms of their first motions, following the rules of our polarity standard.

Somewhat less familiar is the original statement of this standard as formulated by Thigpen et al. (1975). The portion of that formulation that deals just with impulse-source systems says:

"A signal voltage going initially in the negative direction shall be produced by
(1) upward motion of the case of a seismic motion sensor, and
(2) pressure increase detected by a pressure-sensitive phone.

This negative-going initial signal voltage applied to the input of a recording system shall produce a
(1) negative-going output of the recording system,
(2) negative number on a digital tape, and
(3) wavelet minimum or trough (downward kick) on a seismogram."

There is a subtle but important difference between these two statements of the polarity standard. The original statement (Thigpen et al., 1975) is purely an instrumental one, relating the sense of the recording output (negative or positive) only to the sense of motion (up or down) of a geophone case or of the sense of pressure change (compressional or dilatational) at a hydrophone. The later statement (Sheriff, 1991), however, is both instrumental and geophysical, relating the sense of the recording output to (1) the sense of pressure change at an *unspecified* receiver, to (2) the sense of initial pressure change at the source, and/or to (3) the sign of the reflection coefficient represented. For the rare case of an implosive source, these two would give opposite definitions of normal polarity for a primary reflection arrival.

Extending the SEG standard to other components

Considered in the light of a 4C (four-component) survey, the original formulation (Thigpen et al., 1975) provided a standard only for the vertical-component geophone (cf. "upward motion" of the sensor case) and for the hydrophone (cf. "pressure-sensitive phone"). Sheriff's (1984, 1991) statements of this standard can only be applied *directly* to the hydrophone component. By using such terms as "compression" and "acoustic impedance", Sheriff's statement included hydrophone data – either upgoing or downgoing arrivals – but, for geophones, restricted the standard to the vertical (not horizontal) component and to upgoing (not downgoing) P-wave (not S-wave) onsets. Ironically, there seems to be a lack of general awareness of the standard in connection with hydrophones, and a lot of hydrophone data is apparently recorded with negative SEG polarity, that is with compressional onsets recorded as positive breaks.

Horizontal-component geophones and S-wave arrivals are not covered in these statements of the SEG polarity standard (Thigpen et al., 1975; Fulton et al., 1981; Sheriff, 1991). However, Pruett (1987), in an unpublished SEG subcommittee report, recommended that 3C geophone data be recorded using a right-handed coordinate system with the z-axis pointing down. He also suggested orienting the x-axis to increase "down the line", that is in the direction of source advancement. Viewed from above the geophone, the y-axis is rotated clockwise 90° from the x-axis. More recently, Brook et al. (1993) and Landrum et al. (1994), in a published SEG polarity standard for vibratory systems, make a similar recommendation. It is reasonable that a new general polarity standard encompassing multicomponent data be consistent with these pre-existing SEG standards and conventions.

Since the SEG polarity standards were elaborated as surface-seismic conventions, land and marine, they did not explicitly make provision for downgoing in addition to upgoing wave arrivals. This does not invalidate the original statement in terms of geophone-case motion and pressure change at a hydrophone (Thigpen et al., 1975) but it exposes a problem in Sheriff's statement made in terms of compressions and reflection coefficients. This stems from the fact that upgoing and downgoing compressional onsets are recorded with opposite signs on a vertical-component geophone (velocity data) but with the same sign by a hydrophone (pressure data).

To extend existing SEG polarity standards to the OBS case, such matters as these have to be carefully considered and given provision, even though the extension may be fairly straightforward for the most part. A first step in this extension would be the adoption of a three-dimensional coordinate system in order to establish positive and negative senses of motion. In their SEG report on multicomponent vibrator acquisition standards, Brook et al. (1993) and Landrum et al. (1994) paraphrase the SEG subcommittee on 3C orientation (Pruett, 1987) by recommending the following coordinate system:

> z: positive downward;
> x: positive in the forward direction of the *source vehicle*;
> y: positive to the right, 90° clockwise from the forward direction.

By analogy, the forward direction of the source vehicle can be identified with the forward direction of a 2D seismic line or some specified principal direction in a 3D survey, normally that of the receiver-cable lines. Since this coordinate system is right-handed, is recommended by an SEG body, and is completely consistent with previous SEG standards, we incorporate it into the present scheme.

NOMENCLATURE AND NOTATION

The terms *inline* and *crossline* are commonly used for the two horizontal components when the geophones are laid out on a 2D line. In accordance with the SEG's recommendation, we denote these two sensor components, respectively, by the symbols X and Y, and the vertical as Z. X, Y and Z can be considered as aliases for the terms inline, crossline and vertical component. There is a conceptual difference between them, on the one hand, and x, y and z, the latter of which are mathematical symbols for position that can take on numerical values with units of length.

This usage can be extended to 3D if the inline and crossline survey directions are clearly defined. The terms radial and transverse (R and T), although they mean the same as X and Y in normal 2D work, are not, in general, the same in 3D, where, X (inline) and Y (crossline) should be reserved for the predefined horizontal directions of the survey layout. R (radial) should then indicate the direction of the line from a given shot to a given receiver, and T (transverse) the direction 90° clockwise from this. In 3D this shot-receiver azimuth will take on a whole range of values, depending on the choice of shot and receiver. Offset, in 3D, will become a two-component vector in the horizontal plane, expressible either via Cartesian (x, y) coordinates or source-centred polar coordinates, the horizontal subset of a source-centred cylindrical coordinate system, as proposed by Gaiser (1999).

Brook et al. (1993) and Landrum et al. (1994) recommend that "motion sensors for horizontally polarized vibrators record a positive-going sequence of numbers on tape when their cases are impulsed toward the direction of the positive axis they represent". We then define the displacement axes in the following way, consistent with their SEG polarity standard for multicomponent vibratory systems and such that [x, y, z] is a right-handed coordinate system:

X and *x*: the forward line direction; motion in this horizontal direction gives positive output from the inline phone (right-hand index finger pointing away from body while looking along the line from the start towards the end);

Y and *y*: the direction 90° clockwise from the forward line direction; motion in this horizontal direction gives positive output from the crossline phone (right-hand middle finger pointing to the right);

Z and *z*: the downward vertical direction; motion in this downward direction gives positive output from the vertical phone (right-hand thumb pointing down).

Other symbols are also in use, for example, in commonly used seismic software packages, to designate horizontal components, like H1 and H2, but we favour the use of the Cartesian symbols, primarily because they are well established and generally require little or no explanation. Besides, H is sometimes used to denote *hydrophone*. In fact, because of its several possible meanings, it is probably best to avoid the use of H as a symbol for anything at all connected with seismic acquisition. (H even does confusing double-duty in geomagnetic notation!) It is also true that X has been used at times to represent either the vertical component or the crossline component; however, these are minority usages and can easily be avoided. Other usages include: G for vertical geophone; I for inline geophone, and C for crossline geophone. Again, however, we think it is better to stick to universal conventions, like the Cartesian coordinate symbols, that enjoy widespread recognition over discipline boundaries.

Assuming that one were to agree with [X, Y, Z], there remains the question of what symbol to use for the hydrophone component. In my opinion, as stated above, H should be avoided. P has sometimes been used (for pressure) but that can be confused with P as in P wave, often used to denote the vertical (P-wave) component/section when S is being used for the inline (S-wave) component/section. My preference is to use W (for water) which also fits in cyclically as [W, X, Y, Z]. This would also agree logically with the numerical designation [0, 1, 2, 3] for these components, with the Cartesians retaining their established equivalence of [1, 2, 3] with [x, y, z]. Unfortunately, industry usage is commonly something other than this, e.g. [0, 1, 2, 3] for [W, Z, X, Y], although this is at least a right-handed permutation of [W, X, Y, Z].

VERTICAL GEOPHONE AND HYDROPHONE

Vertical geophone

In seafloor or OBS (ocean-bottom seismic) or OBC (ocean-bottom cable) multicomponent acquisition, apart from the fact that we have to consider downgoing as well as upgoing waves, the SEG polarity standard can virtually be taken as is and applied to the data of the vertical-component geophone (Z). To ensure that the data have been recorded on Z with normal (positive) polarity, it is only necessary to verify that the direct downgoing P wave, from a near-surface airgun array to a seabottom array of sensors, has been recorded on Z with positive first breaks, at least for smaller offsets. With this arrangement, upgoing P waves with compressional first motion reflected from positive reflectors will register with negative breaks. Normally, the recording instrumentation is set up so that this is the Z field polarity.

Figure 1 shows an OBC vertical-component common-receiver gather. The first breaks, due to direct downgoing P, are seen at zero offset at about 915 ms. This arrival has a positive break (if one ignores the low-amplitude high-frequency coherent precursors). Upgoing reflections are seen to start arriving at zero offset at about 985 ms. This gather is compared below with the corresponding hydrophone gather (Figure 2).

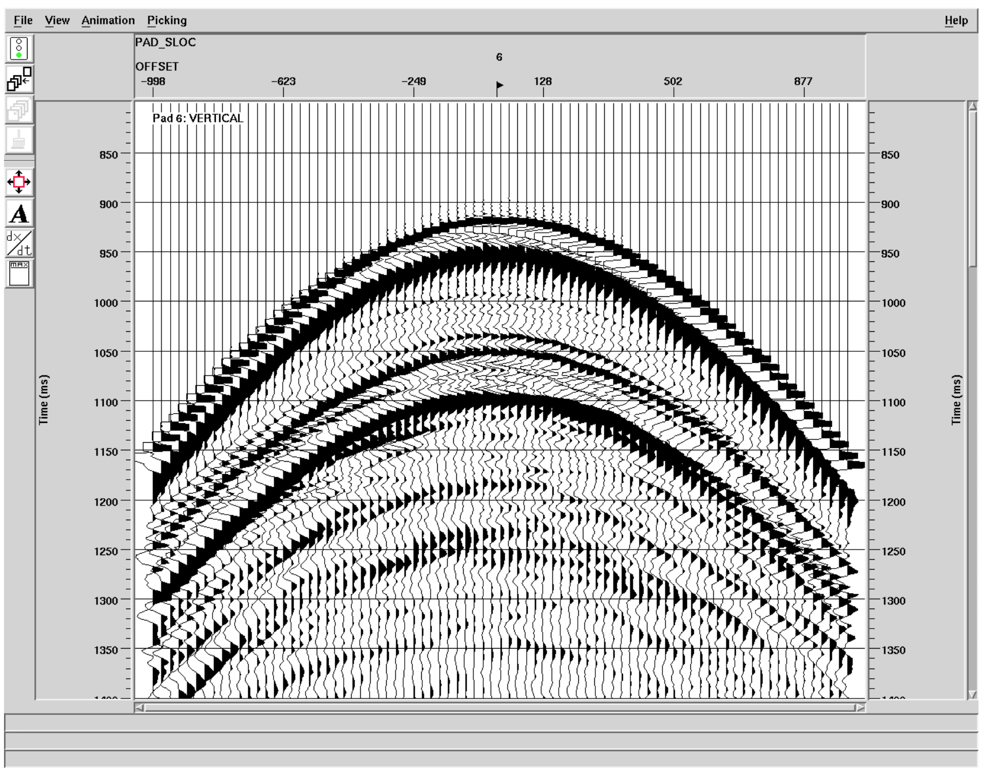

Figure. 1. Vertical-component (Z) common-receiver gather, with positive field polarity.

The polarity of the vertical-component first breaks should be examined to verify the overall polarity and to see whether any individual receivers might have been wired incorrectly or otherwise have the wrong polarity. If a particular vertical geophone happens to show negative polarity, all traces recorded on it have to be reversed prior to processing. In actual fact (though not recommended as practice!), the vertical geophones could be wired randomly with regard to polarity (but not changed during the course of a survey); then following the above procedure in the preprocessing would ensure consistent positive polarity.

There are other separate factors that can affect the appearance of a reflection arrival but which are not directly involved in the polarity considerations mentioned above. For example, a rock interface might have a downward increase of acoustic impedance, representing a positive reflection coefficient at normal incidence. But this reflection coefficient, which in general varies with angle of incidence, might change sign at some point. Thus, this reflection could appear to have negative polarity over a certain offset range. This is really an AVO (amplitude-versus-offset) issue rather than a polarity one. Here, we tacitly assume near-normal incidence in speaking about signs of reflection coefficients.

Hydrophone

Hydrophone (W) data can be regarded in much the same light as data from vertical geophones. Consistent with the SEG polarity convention (Thigpen et al., 1975; Sheriff, 1991), upgoing P waves with compressional first motion reflected from positive reflectors should register with negative breaks. Since hydrophones record pressure, regardless of direction of wave propagation, the foregoing requires that all compressions register as negative breaks. In particular, in OBS surveys, the direct downgoing P wave, with compressional first motion, should then be recorded with negative onsets (Figure 2).

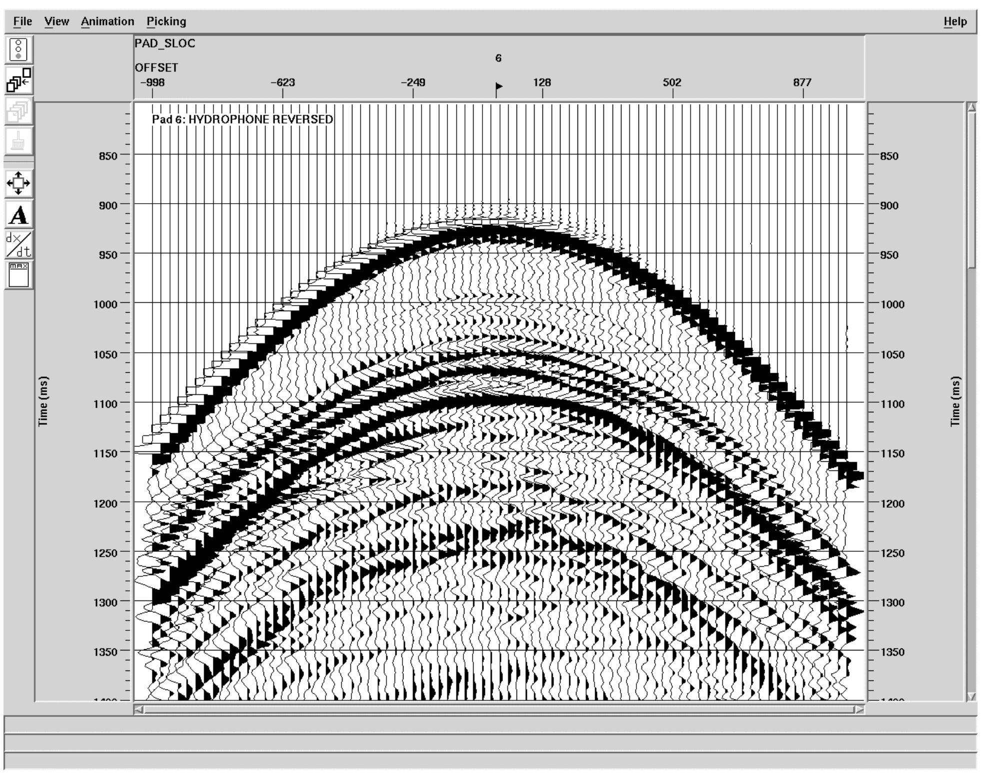

Figure. 2. Hydrophone (W) common-receiver gather, with positive field polarity.

Often, however, hydrophones are wired so that compressions (positive pressure changes) register as positive trace excursions (M. Norris, personal communication). This is contrary to the SEG polarity standard as stated explicitly for pressure-sensitive phones by Thigpen et al. (1975). Such hydrophone polarity should be reversed, preferably in the instrumentation, but failing that, in the preprocessing. The hydrophone common-receiver gather in Figure 2 was acquired with negative polarity but is shown with positive or normal W polarity.

In Figure 2 one can see that the first breaks, due to the direct downgoing P wave, occur at just about the same time as in Figure 1. The difference is that this arrival now has a negative first break, the opposite of the vertical component. In fact, this entire first-arrival wavelet, with a duration of about 60 ms, is highly negatively correlated with that of the vertical over this duration.

In contrast, the upgoing reflection energy, which is seen to start arriving at about 980 ms at zero offset, appears to be substantially in phase on the two gathers. It is hard to conceive of any further arrivals of coherent downgoing energy (i.e. through the water) between the end of the direct P wavelet, around 975 ms, and the onset of the first water-column multiple, around 2550 ms. So we can be fairly confident that the events below 975 ms in Figures 1 and 2 represent upgoing energy. The fact that these arrivals in the two figures are substantially in phase is then in agreement with the assumptions and statements made in the preceding paragraph.

Another way of showing the phase relationship between the vertical geophones and hydrophones is by so-called *binary gathers* (Figures 3 and 4). These are constructed from the Z and W gathers (Figures 1 and 2) by first obtaining the absolute-value section of each, dividing each original gather by its absolute-value section to obtain two binary sections (±1), one each for Z and W, then multiplying these two binary sections together. On the resulting binary gather, trace values are –1 (blue) where the hydrophone and vertical gathers (Figures 1 and 2) have the opposite sign and +1 (yellow) where they have the same sign. In other words, where downgoing energy is arriving the gather should show blue and where upgoing energy is arriving the gather should show yellow.

There are three basically different fields in Figure 3: (i) before the first breaks there is essentially a random mix of blue and yellow, down- and upgoing energy; (ii) the first breaks (downgoing) are overwhelmingly blue, and (iii) the rest (upgoing) is overwhelmingly yellow. The correlation is not perfect, partly due to the presence of noise, but probably mainly due to differences in the wavelets of the two gathers, in turn likely due to the factors mentioned in the next section

Figure 4 shows a larger portion of the same gather as Figure 3, with trace-lines removed. There one can see where the downgoing energy of the first-order water-column multiple hits around 2600 ms at zero offset, and where the second-order multiple arrives around 4300 ms. Between these two, and mixed in with many upgoing arrivals, there appears to be a steady stream of downgoing arrivals. These are mainly first-order water-column multiples of primary reflections that arrived before 2600 ms (and which started arriving around 980 ms).

Hydrophone gathers, like their vertical counterparts, should be checked for overall polarity and for any individual phones that might have been incorrectly wired or otherwise have the wrong polarity. Correct polarity can be accomplished in the preprocessing but it is preferable to acquire the data with the correct polarity already

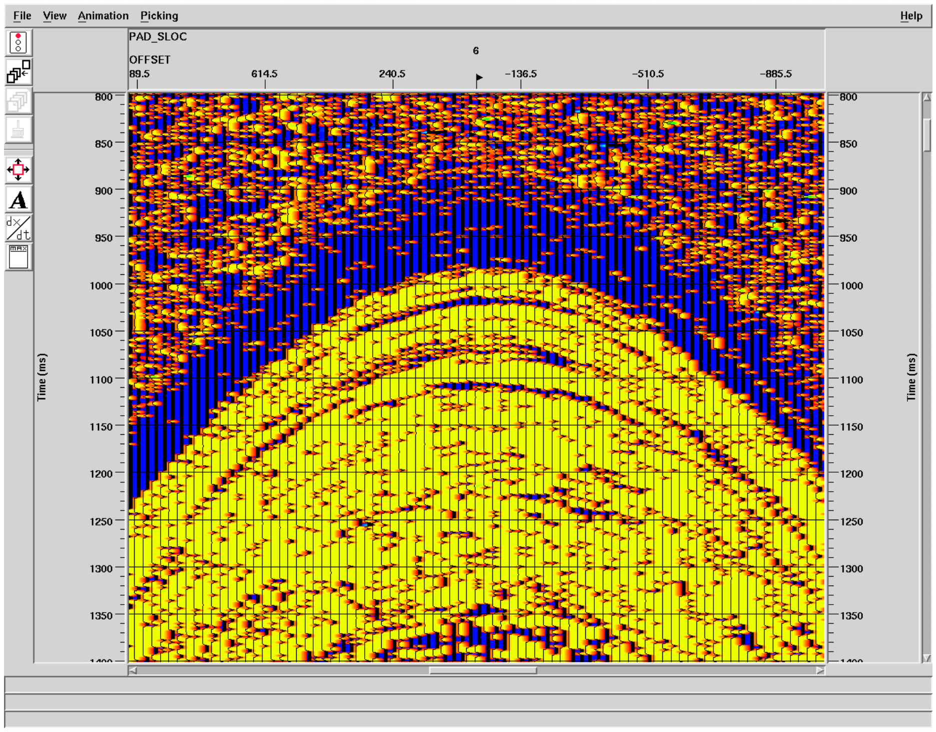

Figure. 3. Blow-up from Figure 4: binary gather showing blue where hydrophone and vertical have opposite sign and yellow where they have the same sign.

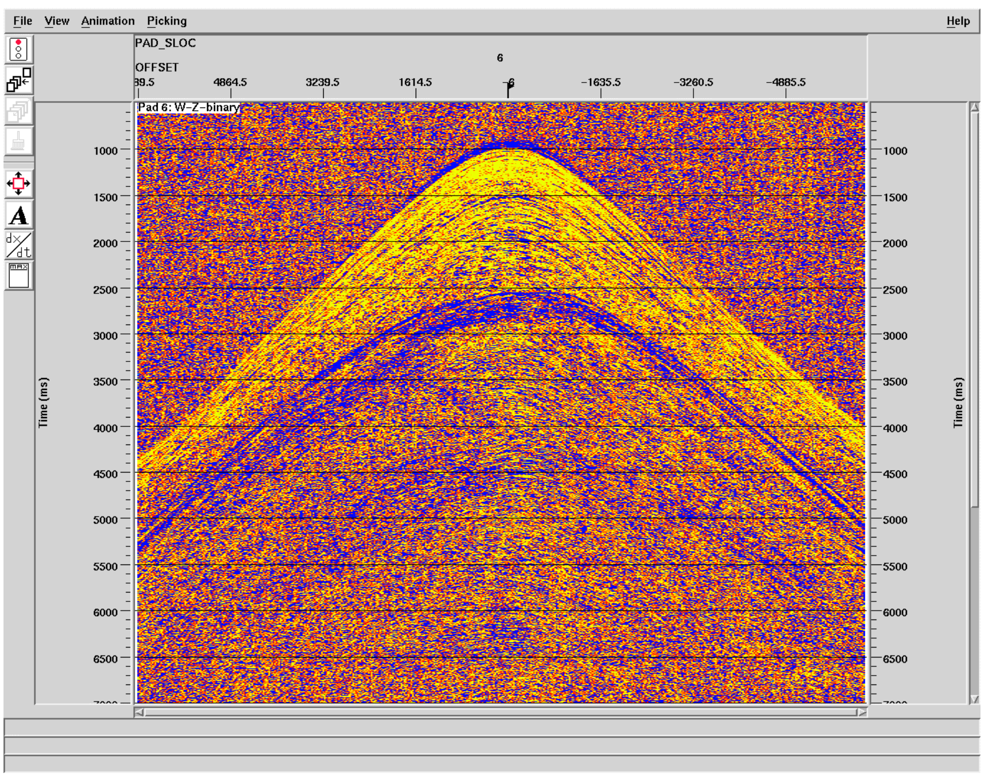

Figure. 4. Binary gather showing –1 (blue) where hydrophone and vertical have opposite sign and +1 (yellow) where they have the same sign.

on the field tapes so that one might confidently proceed with fixed, standard preprocessing routines. The question of hydrophone polarity is further examined below.

Vertical-geophone records versus hydrophone records

There is a temptation to think that the seismic sections produced from seafloor hydrophones (W) and vertical geophones (Z) ought to be quite similar. However, there are some essential differences between the two types of sensor that will always entail some differences in what they record and how they image. One essential difference, already mentioned, is that hydrophones record pressure, a scalar, while vertical geophones record only the vertical component of particle motion. They therefore record downgoing P arrivals with opposite signs and upgoing P arrivals with the same sign (Figure 3).

The term *motion* is used loosely here to imply any or all of displacement, velocity or acceleration. The three bear a phase relationship to each other of 0º, 90º and 180º, respectively. Still, when a wavelet pulse or onset arrives at a receiver station, all three break the same way from zero. So we don't have to be too precise in using the term *motion* with respect to first-break polarities.

A second essential difference lies in which of the incident, reflected and refracted phases register on the sensors. In the case of an upgoing P wave (Figure 5) incident from below on a seafloor multicomponent receiver, and assuming perfect coupling of the receiver case (often a poor assumption for geophones), a vertical geophone will record the sum of the vertical components of the three waves in the seabed, shown in green in Figure 5, that is, the incident and reflected P waves, and the reflected S wave. Given continuity of vertical displacement, this will be equal to the vertical component of motion of the transmitted P wave propagating up through the water. A hydrophone, on the other hand, will record not the vertical component but the scalar magnitude of this transmitted P wave in the water, shown in blue (Figure 5); actually, its omnidirectional pressure.

Recall that S-wave particle motion is perpendicular to propagation direction (in an isotropic medium), so its vertical component increases as the propagation direction becomes less vertical. Also, depending on the velocities and densities of the two media, seawater and seafloor, there could be phase reversals on reflection or transmission, so the signs of the various vertical components could be positive or negative.

In the case of a downgoing P wave (Figure 6) incident from above at the station, the vertical geophone will record the vertical component of the resultant of the seafloor (green) phases, in this case the transmitted P and S waves. The hydrophone will record the scalar sum of the (pressure) amplitudes of the water (blue) phases (Figure 6), here the incident and reflected P waves.

A third and very important difference, though one that potentially could be overcome, is the fact that, in general, the two types of phone have different instrumental responses, which will lead to different embedded wavelets in Z and W.

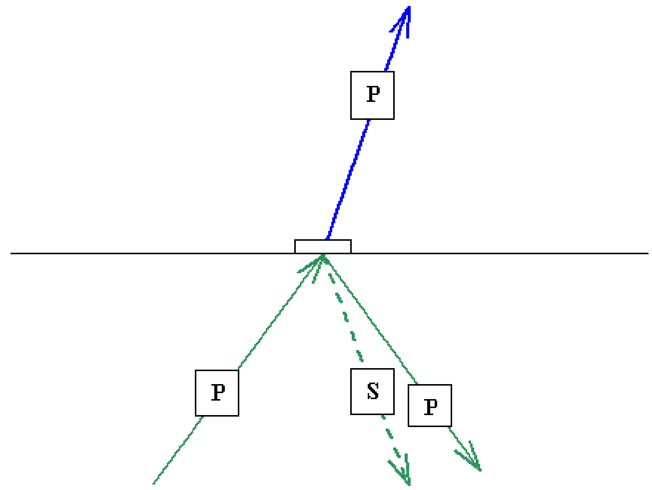

Figure. 5. P wave incident at seafloor from below. A hydrophone records the blue phase; a vertical geophone records the sum of vertical components of the green phases.

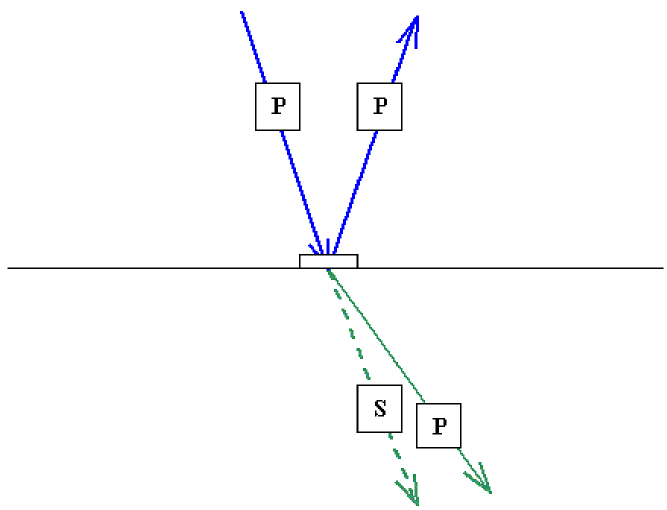

Figure. 6. P wave incident at seafloor from above. A hydrophone records the scalar sum of pressures of the blue phases; a vertical geophone records the sum of vertical components of the green phases.

There is increased usage of hydrophone cables deployed in wells on land. Once again, we are challenged to understand the polarity relationship between land hydrophone cables and geophones. Consistent with the above definitions, Gulati et al. (2000) consider the case of a vertical hydrophone cable on land compared to a 3C geophone buried nearby. They find the same polarity on upcoming first arrivals on both hydrophone and geophone events.

HORIZONTAL GEOPHONES

Initial polarity considerations

For the inline geophone (X), polarity considerations are complicated by three factors. First, assuming approximately horizontal layering, traces recorded at positive offset have the opposite polarity to that of traces recorded at negative offset. Second, there is not a 100% consistent relationship between the signs of R_{PP} and R_{PS} (the P-P and P-S reflection coefficients) for a given lithologic interface. Third, although there are some partial recommendations from the SEG (Thigpen et al., 1975; Pruett, 1987; Brook et al., 1993; Landrum et al., 1994), a full-blown universally accepted polarity standard for 3D and 4C data does not yet exist to tell us what constitutes normal field polarity for the horizontal components. This is discussed further below. It turns out that the first and third of these can easily be dealt with, whereas the second presents more of a fundamental difficulty.

The change of polarity for positive versus negative offsets is well known and is a necessary step in preprocessing the inline component. It is often expressed as 'reversing the polarity of the trailing spread (negative-offset traces)'. However, the question should really be asked: "To get *normal* polarity, should we reverse the polarity of the trailing spread or the leading spread?" In order to answer this, one has to consider: (1) the signs of first breaks of reflection arrivals on X; (2) the meaning of 'trailing spread', and (3) the sign convention for offset in OBS work.

First it is necessary to establish what is meant by positive and negative phase, or positive and negative R_{PP} and R_{PS}. We are here following Aki and Richards (1980), whose convention (illustrated in their Figure 5.5) states that the wave phase, or the displacement amplitude (and therefore the velocity amplitude) associated with a rightward propagating plane P or S wave is positive when the horizontal component of its first motion is directed toward the right. Reflection and transmission coefficients, being amplitude ratios, then have their signs determined by this convention. One should be careful to distinguish between the sign or polarity of the *wave phase* or *amplitude* and that of its *recorded first break,* or *trace onset*. For example a P wave with compressional first motion will have positive phase and amplitude, but will have a positive or negative onset on a vertical geophone (velocity) trace depending on whether it was incident from above or from below; and it will have a negative onset on a hydrophone (pressure) trace (if recorded as recommended herein) regardless of whether it was incident from above or from below.

In order to consider the relationship between the signs of R_{PP} and R_{PS}, we have computed reflection and transmission coefficients (in particular, R_{PP} and R_{PS}) as functions of angle of incidence at the interface between two elastic media, one of which may be liquid. The results show that when R_{PP} is positive, R_{PS} is *normally* – but not always – negative; and vice versa. Assuming for the moment that this relationship of opposite signs of R_{PP} and R_{PS} holds most of the time (Figure 7), we can specify *normal* or *positive polarity* for inline data in such a way that a particular interface will appear on the processed inline (P-S) section with the same polarity as on the hydrophone and vertical (P-P) sections – *most of the time*. The goodness of this assumption is examined more closely below.

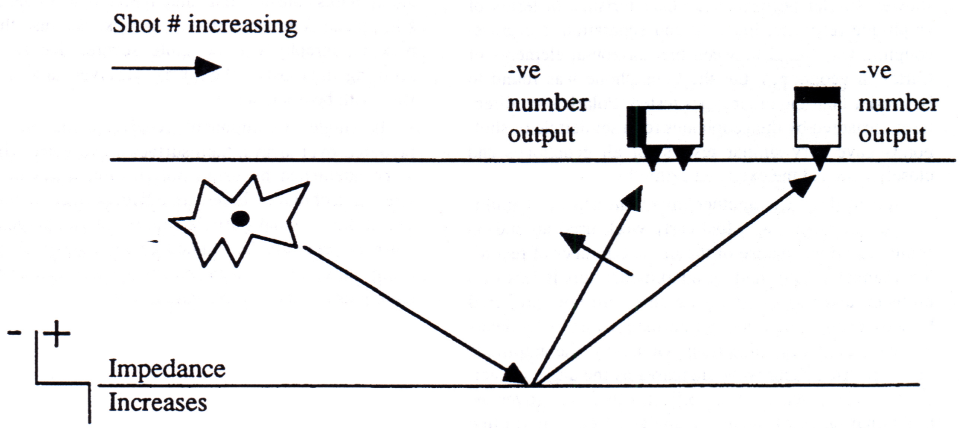

Figure 7. The 'normal' situation in which both acoustic and shear impedances increase downward across the boundary

Inline geophone

Although it would be best if all data were acquired with normal field polarity, it will also be desirable to establish a procedure that will give normal polarity in those cases when the field polarity is 'reversed'. Thus, an upward propagating S wave, after conversion from P at an interface with a *positive P-P reflection coefficient*, preferably should give a negative break on the inline trace. In the 4C OBS case, when the P-wave is on its way down through the water (the first part of this P-S phase) it would hit the inline geophone with a positive onset, opposite to that of the subsequent upgoing S (converted) wave. So we should arrange for this direct first break to be positive by reversing the polarity on those inline traces that have negative first breaks.

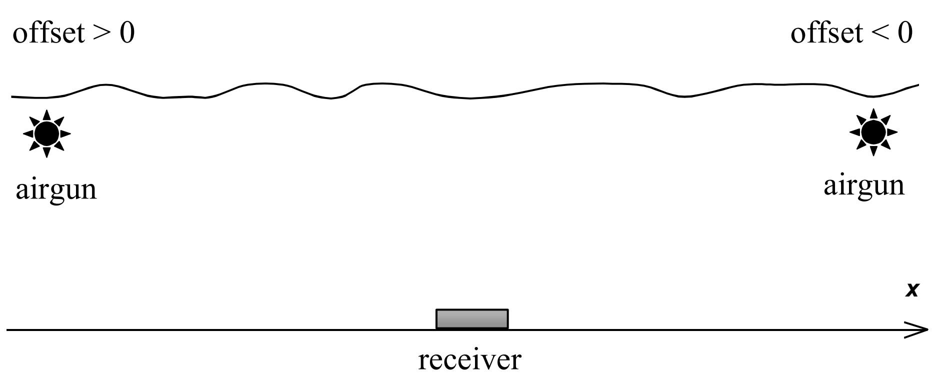

Figure 8. OBS common-receiver gather with offset decreasing from left to right.

If offset is defined in the conventional land-seismic way, as the distance vector from shot to receiver, then polarity should be reversed on inline traces at negative offsets. However, in OBS acquisition, there is typically a very high shot fold and very low receiver fold (compared to land seismic). It is therefore common practice to examine common-receiver gathers rather than common-shot gathers and, consequently, more natural to define offset as the distance vector from receiver to shot. Unfortunately, this flips the signs of all offsets and would mean that one should reverse the polarity of the *leading* spread (positive-offset traces). This latter practice should therefore be avoided, and we recommend defining offset consistently as the distance vector from shot to receiver. This vector may be expressed as two signed Cartesian coordinates or as a magnitude and source-centred azimuth.

The relationship between R_{PP} and R_{PS}

Assuming that R_{PP} and R_{PS} are of opposite sign, we can follow the above recipe for arranging normal polarity for the inline component. But how good an assumption is this? When do we have exceptional cases; that is, when do R_{PP} and R_{PS} have the same sign? We have computed R_{PP} and R_{PS} for about 200 different interface models, some more geologically realistic than others, to be sure, and have found several 'exceptional' cases.

In collating output from various combinations of the six interface parameters (the two P velocities, S velocities, and densities) it appears that exceptions can occur when there are parameter reversals across the interface, that is, when the three rock parameters do not all change in the same direction across the interface. For example, if both velocities increase but density decreases across an interface, etc. Conversely, the normal relationship between R_{PS} and R_{PP} appears to hold when there are no such parameter reversals.

Lithologically realistic exceptions can readily be imagined, for example, if one of the media has some unusual parameter ratios. Salt, for example, has an unusually high velocity-to-density ratio; and a gas sand can have quite low values of both density and the V_P/V_S ratio. In the three examples that follow (Table 1), a downward travelling P wave is incident at angle i_P on an interface for which α, β and ρ represent V_P, V_S and density; 1 and 2 refer to upper and lower layer; and R and T are coefficients of reflection and transmission, all respectively.

Examples 2 and 3 (Table 1) are geologically reasonable but give the opposite of the 'normal' sign of R_{PP}/R_{PS}. Despite the existence of these exceptions, the majority of geologically realistic cases are probably 'normal', that is, $R_{PP}/R_{PS} < 0$. In any particular case, however, one should consider the possibility that $R_{PP}/R_{PS} > 0$ by considering actual rock-unit parameters gathered from field observations (well-log, seismic, etc.). Knowledge of any parameter 'reversals' will forewarn one to expect reversals of polarity in correlating events from Z (P-P) to X (P-S) sections, even after care has been taken to produce only normal-polarity sections.

Crossline geophone

Geologically, the concept of normal or reverse polarity for crossline data has little

Table 1. Examples of reflection (*R*) and transmission (*T*) coefficients versus angle of incidence (*i*) (deg) for three different interface models of P-wave velocity (α) and S-wave velocity (β) (m/s) and density (ρ) (kg/m^3)

Example 1: the 'normal' situation.

$\alpha_1 = 2000$ $\quad\beta_1 = 800$ $\quad\rho_1 = 1900$

$\alpha_2 = 3500$ $\quad\beta_2 = 1800$ $\quad\rho_2 = 2400$

i_P	R_{PP}	R_{PS}	T_{PP}	T_{PS}
0.0	0.377	0.000	0.623	0.000
5.0	0.374	–0.079	0.624	–0.054
10.0	0.364	–0.153	0.628	–0.108
20.0	0.334	–0.268	0.654	–0.212
30.0	0.354	–0.264	0.776	–0.292

Example 2: clastic over salt.

$\alpha_1 = 3600$ $\quad\beta_1 = 2400$ $\quad\rho_1 = 2600$

$\alpha_2 = 4500$ $\quad\beta_2 = 2500$ $\quad\rho_2 = 2100$

i_P	R_{PP}	R_{PS}	T_{PP}	T_{PS}
0.0	0.005	0.000	0.995	0.000
5.0	0.007	0.017	0.996	–0.004
10.0	0.013	0.034	0.999	–0.007
20.0	0.038	0.065	1.012	–0.015
30.0	0.086	0.089	1.041	–0.025

Example 3: shale over gas sand.

$\alpha_1 = 2150$ $\quad\beta_1 = 860$ $\quad\rho_1 = 2200$

$\alpha_2 = 1750$ $\quad\beta_2 = 1250$ $\quad\rho_2 = 1950$

i_P	R_{PP}	R_{PS}	T_{PP}	T_{PS}
0.0	–0.162	0.000	1.162	0.000
5.0	–0.164	–0.025	1.160	–0.035
10.0	–0.171	–0.050	1.155	–0.069
20.0	–0.200	–0.092	1.133	–0.135
30.0	–0.247	–0.119	1.094	–0.194

meaning for 2D seismic over horizontally layered sections and isotropic media. Still, a good initial rule is to treat crossline-geophone data in a manner corresponding to the way it is done for inline-geophone data. Assuming exactly correct acquisition geometry (geophone orientations, shot positions, receiver positions) and geology that is isotropic and laterally homogeneous (or with dip only in the survey direction), there should be no energy at all on the crossline component. In practice, this is never the case because we have one or more of: (1) imperfect acquisition geometry; (2) inhomogeneous media, particularly reflecting interfaces that show at least some dip in directions other than the survey direction, or (3) anisotropy in at least part of the section.

In the rare case where 2D data have been acquired with shooting lines significantly offset from receiver lines in the crossline direction, or where virtually the entire sedimentary section has a large dip component in this direction, the principle would be the same as for the inline component. We would want negative onsets for reflectors for which R_{PP} is positive, that is, reflectors for which R_{PS} is normally negative, in accord with the SEG convention. In these special situations, all effective crossline offsets should have the same sign, meaning that all or none of the polarities should be flipped according to whether the crossline offset (*y*-component of offset) is positive or negative. The extension to 3D is straightforward: we reverse polarities on Y traces for which the *y*-component of offset is negative.

In cases where some significant arrivals may be due to anisotropy, we follow the same acquisition polarity standard. The recommended directions of the positive *x* and *y* axes should follow the SEG field-polarity standards described above. The processed crossline and inline sections should then be rotated to new axes corresponding to the fast and slow S-wave directions. Ideally, we would then see the same reflectors represented on the 'fast shear-wave' and 'slow shear-wave' sections. However, if the anisotropy is azimuthal, the fast and slow shear waves will have opposite polarity. This can readily be confirmed by graphically decomposing the polarization of a vertically travelling SV wave first into fast and slow directions, then into fast and slow arrivals on each of the X and Y geophones. Analogous to Figures 1 and 2 of Thomsen (1988) for an SH source, the "mismatched" receiver, in the present P-SV case the crossline one, records the slow shear arrival with opposite polarity to that of the "matched" (here the inline) receiver. At this point, flipping the crossline trace polarities will achieve 'normal crossline polarity'. This could be confirmed by checking the polarities of equivalent reflectors on X and Y, being careful to keep the dynamic time delay between fast and slow arrivals in mind.

The danger in comparing the X and Y sections before rotation is that, without knowing the anisotropic geometry, we can't be sure of the relative amplitudes of the fast and slow shear waves on the two sections. This could hamper comparison and correlation of the fast and slow shear waves between X and Y for certain geometries. Conclusions on polarity thus made could then be invalid.

CONCLUSIONS

A multicomponent field-polarity standard consistent with Thigpen et al. (1975), Pruett (1987), Landrum et al. (1994), Stewart and Lawton (1998) should recommend that: (1) a dilatation gives positive output from the hydrophone, (2) motion in the forward line direction, or the positive inline or *x*-direction, gives positive output from the inline geophone; (3) motion 90° clockwise to the *x* direction [i.e. the positive crossline or *y* direction] gives positive output from the crossline geophone; and (4) downward motion [i.e. the positive vertical or *z* direction] gives positive output from the vertical geophone.. This could be called the *multicomponent field-polarity* or *acquisition standard.* It requires correct definition of the directions of x, y and z, including their senses, as stated above. These lower-case symbols stand for the physical quantity *distance* in the respective Cartesian axial directions, whereas the upper-case characters, W, X, Y and Z, are simply used as aliases for the four different sensors.

Since this proposed convention is stated in such a way as to be consistent with existing standards for single-component land and marine work (Thigpen et al., 1975) and 2D-3C land surveys (Brook et al., 1993; Landrum et al., 1994), it includes these acquisition modes as special cases.

To ensure a particular polarity on any one of the 4C OBS sections (with some reservation for the crossline), we should make use of the known relationship for that component between the polarity of the first breaks (i.e. the sign of the onset of the direct downgoing P wave) and the polarity (sign of the onset) of reflections from interfaces having positive R_{PP} or negative R_{PS}. This should be done by looking at the first breaks of the direct downgoing P near zero offset on common-receiver gathers. One should stay near zero offset to avoid other first arrivals than the direct P, mainly refractions through the seabottom. In OBS work, confining oneself to common-receiver gathers is usually a good idea because source-signature repeatability is generally higher than receiver repeatability. The latter is affected not only by purely instrumental variations but also by variations in seabottom placement and coupling, which can be considerable.

To ensure positive or normal polarity for the vertical (Z) component in OBS, one should ensure that the direct downgoing P have positive onsets. For normal polarity on the W component, the direct P should then have negative onsets. For many systems, this will mean flipping W polarity either instrumentally or in preprocessing. For normal polarity on the X component, the direct P should have positive onsets. This normally means flipping X polarity for negative offsets. The crossline component should be treated in the same way as the inline component. In those cases where polarity has a meaning with regard to the crossline component – due for example to anisotropy, inhomogeneity, or asymmetric geometry – there are special considerations.

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