Towards a polarity standard for multicomponent seafloor seismic data

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ABSTRACT

This paper deals with the question of a polarity standard for multicomponent seismic data. The primary goal is to provide a standard according to which the designations *normal polarity* and *reverse*(*d*) *polarity* may be used in association with the seismic sections from any or all of the four components normally acquired in a multicomponent seafloor survey. Since this includes a hydrophone component and three geophone components, land 3C and streamer seismic should then also be comprised as special cases.

Recommendations or guidelines are given on how to proceed, both in acquisition and preprocessing, in order to arrive at a given 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 single-component seismic data. In effect, the present recommendations are for a field-recording and preprocessing standard, 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 enable consistent horizon correlation among these datasets.

INTRODUCTION

The issue of polarity is one that involves a number of separate considerations that very often are interrelated and compound each other. Polarity, being binary in nature, is a simple concept on the surface – but deceivingly so; for it can quickly become complicated and confusing. The three fundamental questions that this paper addresses are: (1) Given a particular dataset, how do we decide whether we have normal polarity or reverse polarity? (2) How should we preprocess seismic traces to ensure one or another polarity? (3) How should we acquire the data in the field to ensure one or another polarity? These questions are perhaps posed in reverse order considering the chain of events involved in the generation of the final seismic display. However, in analyzing how we should handle polarity through this chain, it makes sense to start with the desired final output and deal with these questions in the above order.

The whole question of polarity is an elusive one as wavelet phase is not a binary concept, and processing modules can alter wavelet phases in much more complex ways (see e.g. Roden and Sepúlveda, 1999). But the concept of instrument-recording polarity, considered prior to wavelet-altering processing, has definite relevance and

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has served a valuable practical purpose in exploration seismology. The concept of a polarity standard is considered in this light throughout this paper.

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):

> "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..."

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."

This original formulation provided a standard for hydrophones – explicitly –and for vertical-component geophones only, since it specified "upward motion" of the sensor case. Sheriff's (1984, 1991) subsequent statements of this standard, by using the terms "compression" and "acoustic impedance", restricted the standard to P-wave onsets. At the same time, this usage of "compression" implicitly included hydrophone data in the polarity standard, without mentioning it explicitly. Also, Sheriff (1991) showed a clear awareness of the conceptual difficulty in defining a final-display or processed polarity by restricting the standard to minimum-phase and zero-phase wavelets; though Sheriff (1984) makes no such mention. At the same time, if we record only minimum-phase wavelets, following the rules of our polarity standard, and if we retain this phase and the polarity through to final display, then we can meaningfully specify the polarity of this final display.

Although these statements of the SEG polarity standard do not explicitly cover horizontal-component geophones and S-wave arrivals, it is only reasonable, in view of its worldwide familiarity, that this standard form the basis for, and be consistent with, any new polarity standard proposed to comprise multicomponent seafloor data.

Extending the SEG standard to other components

The SEG standard, as enunciated above, can only be applied *directly* to one of the components of a 4C (four-component) seabottom seismic survey, namely the hydrophone. Ironically, there seems to be a lack of general awareness of the standard in connection with hydrophones and most such data is recorded with negative SEG polarity, that is with compressional onsets recorded as positive breaks. There are a number of reasons why the enunciated standard is not directly applicable to geophone data, but the most immediate one is that it does not take downgoing waves into account. It can only be applied to vertical-component geophone data if we restrict ourselves to upgoing wave arrivals. That is a simple condition but it must be clearly stated and understood if we are to avoid any possibility of ambiguity. Nor can it be applied to either of the horizontal geophone components without at least cursory consideration of its applicability. For example, on horizontal-component data we are normally trying to stack up shear-wave arrivals, which never constitute compressions (or dilatations either). In generalizing, we should instead speak of positive and negative phase of wave onsets, of which compressions and dilatations form a subset applicable in the case of P waves.

As implied above, the SEG standard, as a surface-seismic convention, did not consider the possibility of downgoing as well as upgoing wave arrivals. Had it done so, it would have had to take account of the fact that the onset of a downgoing compression is recorded with the opposite sign to that of an upgoing compression on a vertical-component geophone (velocity data). On the other hand, both upgoing and downgoing compressional onsets are recorded with the same sign by a hydrophone (pressure data).

Furthermore, the SEG standard (at least for impulsive sources) assumes that the compressional onset comes from an explosive source. Strictly then, one should really consider whether or not an airgun array is always equivalent to an explosive source, always emitting an initial compression. Here it is assumed that the wavelet from an airgun array does, in fact, always entail an initial compression, though detailed consideration of this question is beyond our present scope.

In order to extend the SEG polarity standard to these other components, such matters as these have to be carefully considered and given provision in the new extended standard, even though the extension may turn out to be fairly straightforward for the most part.

A first step in this extension would be to define a three-dimensional coordinate system so we can name components, refer to these directions, and know which senses are positive or negative. In an SEG report on multicomponent vibrator acquisition standards, Brook et al. (1993) state that the SEG subcommittee on 3C orientation has recommended the following coordinate system:

z: positive downward;
x: positive in the forward direction of the source vehicle;
y: positive to the right, ninety degrees clockwise from the forward direction.

NOMENCLATURE AND NOTATION

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

This usage could be extended to 3D if the inline and crossline directions are clearly defined. The terms radial and transverse (R and T), although they would be the same as X and Y in normal 2D work, are not, in general, the same in 3D. There, I reserve X (inline) and Y (crossline) for the horizontal directions of the survey layout. R (radial) is then reserved for the direction of the line from a given shot to a given receiver, and T (transverse) for 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.

We denote the vertical-component geophone as Z, consistent with normal Cartesian notation. I then define the displacement axes in the following way, consistent with the proposed SEG polarity conventions for multicomponent systems (Brook et al., 1993), 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 to designate horizontal components, like H1 and H2 (used e.g. by ProMAX), but I 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. 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 should be avoided. Another usage is: G for vertical geophone; I for inline geophone, and C for crossline geophone. Again, however, I 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 our 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. Our preference is to use W (for water) which also fits in cyclically as [W, X, Y, Z]. The problem with W is that it hasn't previously been widely used. However, W will be clear of problems once we're over an initial period of introduction.

VERTICAL GEOPHONE AND HYDROPHONE

Vertical geophone

In seafloor 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). In order to get the data in a form that will yield normal (positive) polarity throughout the subsequent processing chain, it is only necessary to ensure that the direct downgoing P wave, from a near-surface airgun array to a seabottom array of sensors, has been recorded with positive first breaks. 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 field polarity.

Figure 1 shows a vertical-component common-receiver gather from an offshore field. 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.

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 any other 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 processing 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

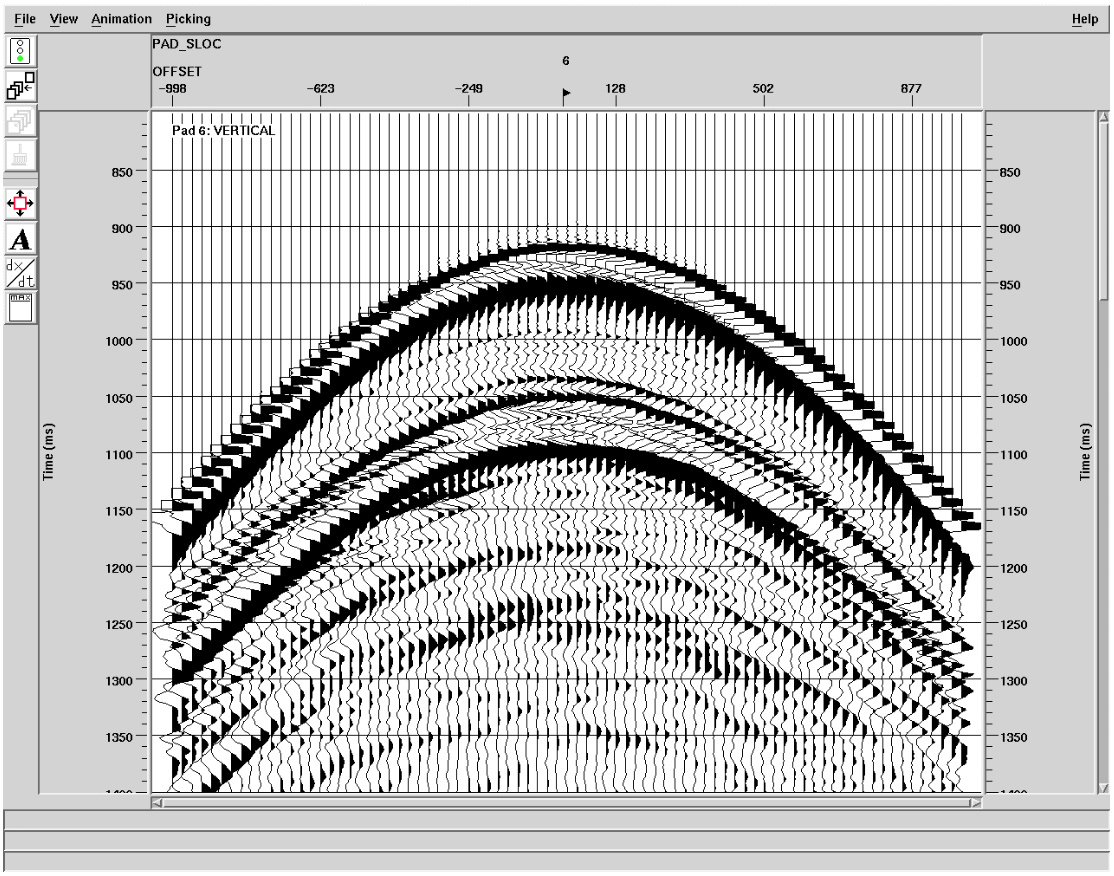

Fig. 1. Vertical-component (Z) common-receiver gather.

example, a rock interface might have a downward increase of acoustic impedance, representing a positive reflection coefficient at normal incidence. But a reflection coefficient varies with angle of incidence (or offset) and could 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, I 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 or of particle motion, the foregoing requires that all compressions register as negative breaks. In particular, the direct downgoing P wave, with compressional first motion, should then be recorded with negative onsets.

Commonly, however, the hydrophone field polarity has been set up such that a compression (positive pressure change) registers as a positive trace excursion. This,

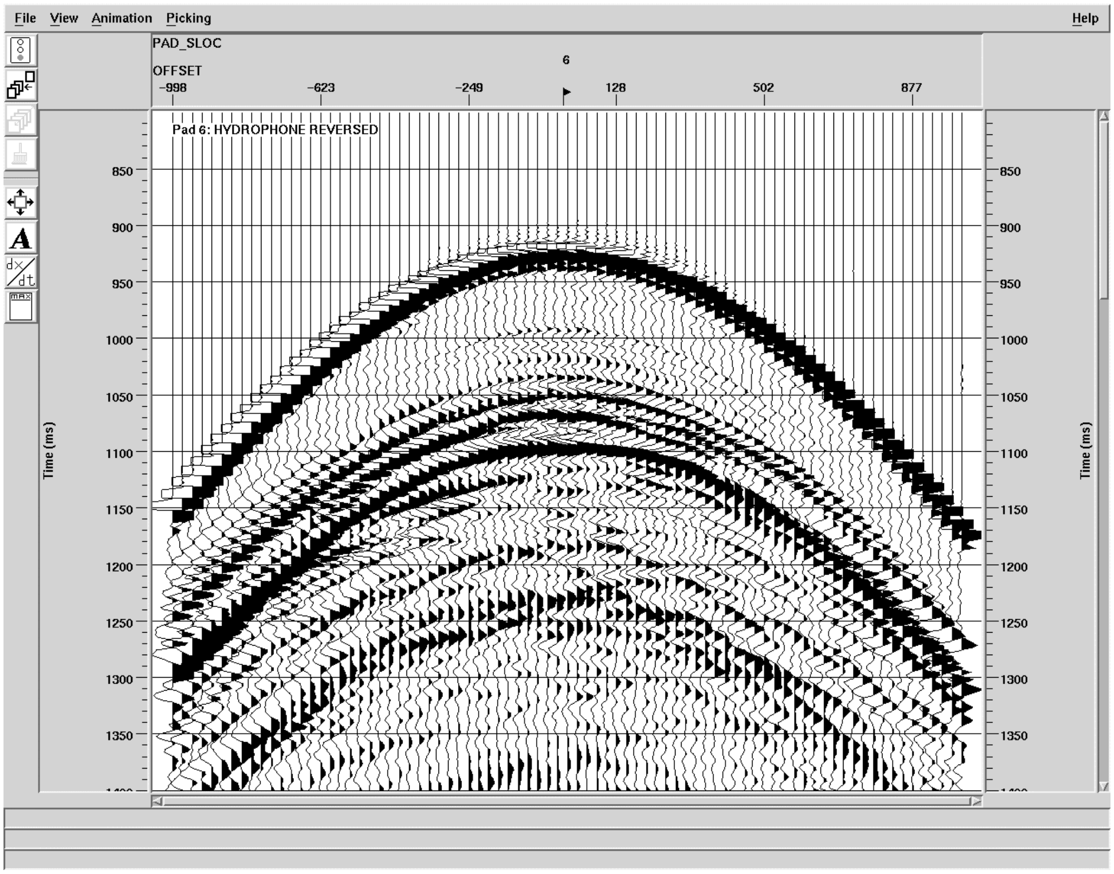

Fig. 2. Hydrophone (W) common-receiver gather, field polarity reversed.

however, 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 is shown with this polarity, which I will henceforth refer to as *normal hydrophone polarity* in 4C processing.

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 positive break, the opposite of the vertical component. In fact, this entire first-arrival wavelet, with a duration of about 60 ms, is very highly negatively correlated between the vertical and the hydrophone 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 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 (dark grey shade) where the hydrophone and vertical gathers (Figures 1 and 2) have the opposite sign and +1 (light grey shade) where they have the same sign. In other words, where downgoing energy is arriving the gather should show dark grey and where upgoing energy is arriving the gather should show light grey.

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

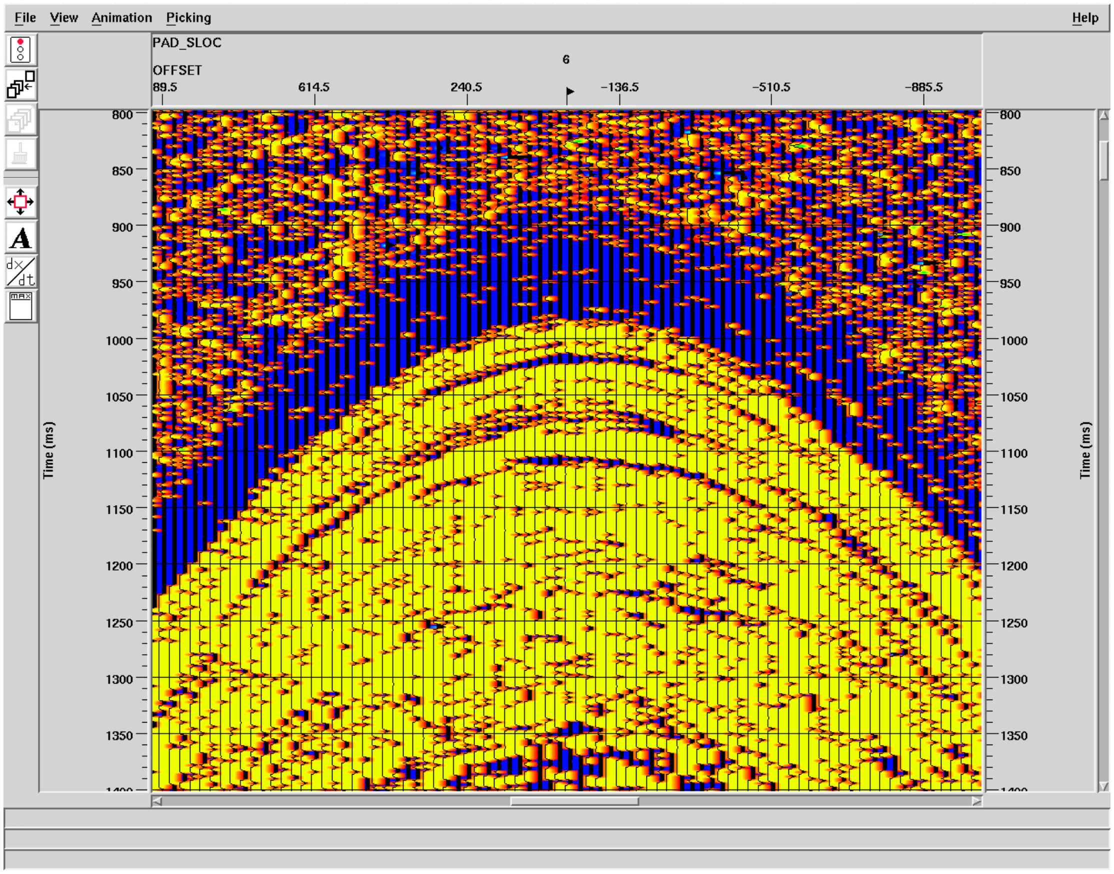

Fig. 3. Blow-up from Figure 4: binary gather showing dark grey where hydrophone and vertical have opposite sign and light grey where they have the same sign.

Figure 4 shows a larger portion of the same gather as Figure 3, with trace-lines removed. One can see in Figure 4 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 processing but it is preferable to acquire the data with the correct polarity already on the field tapes so that fixed, standard processing routines can proceed. The question of hydrophone polarity is further examined below.

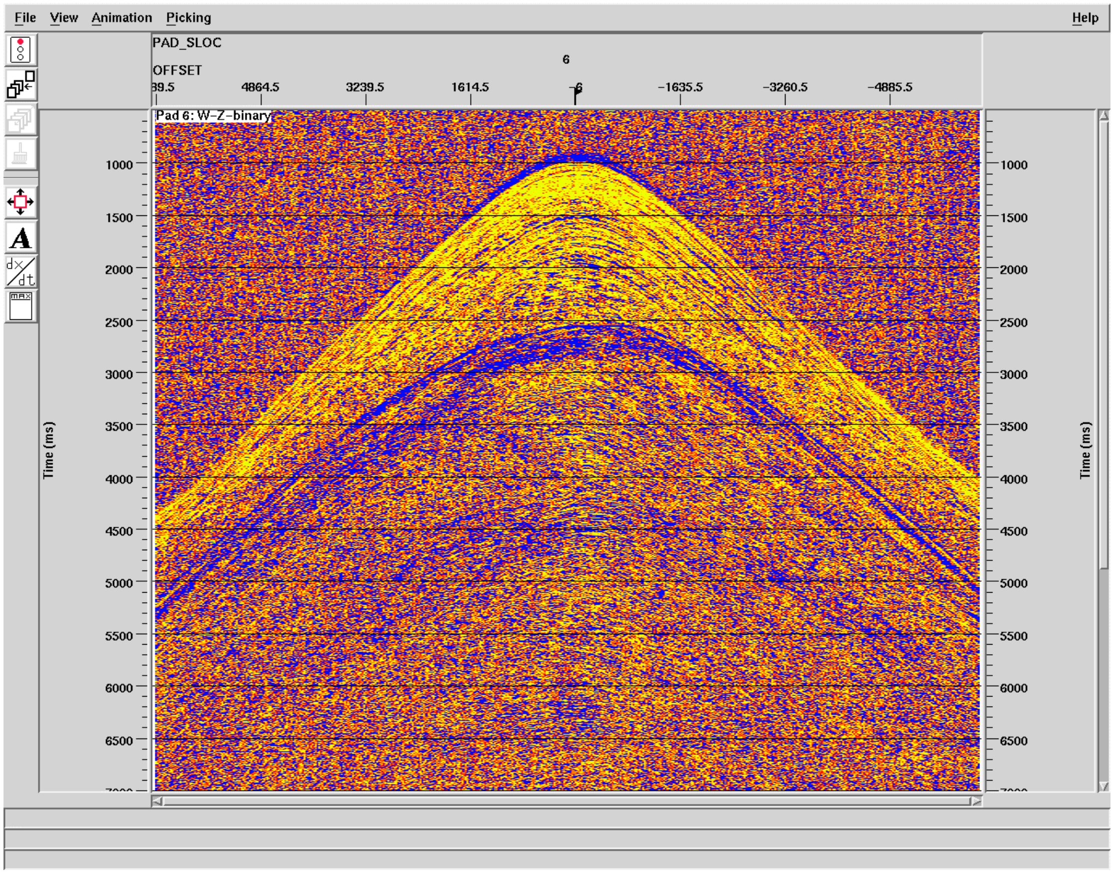

Fig. 4. Binary gather showing –1 (dark grey) where hydrophone and vertical have opposite sign and +1 (light grey) where they have the same sign.

Vertical-geophone records versus hydrophone records

There is a temptation to think that the seismic sections produced from seafloor hydrophones and vertical-geophones 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.

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 wave-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.

Another 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, a vertical geophone will record the sum of the vertical components of the three waves in the seabed, shown in grey (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 the transmitted P wave propagating up through the water. A hydrophone, on the other hand, will record the scalar magnitude of this transmitted P wave in the water, shown in black (Figure 5); actually, its omnidirectional pressure.

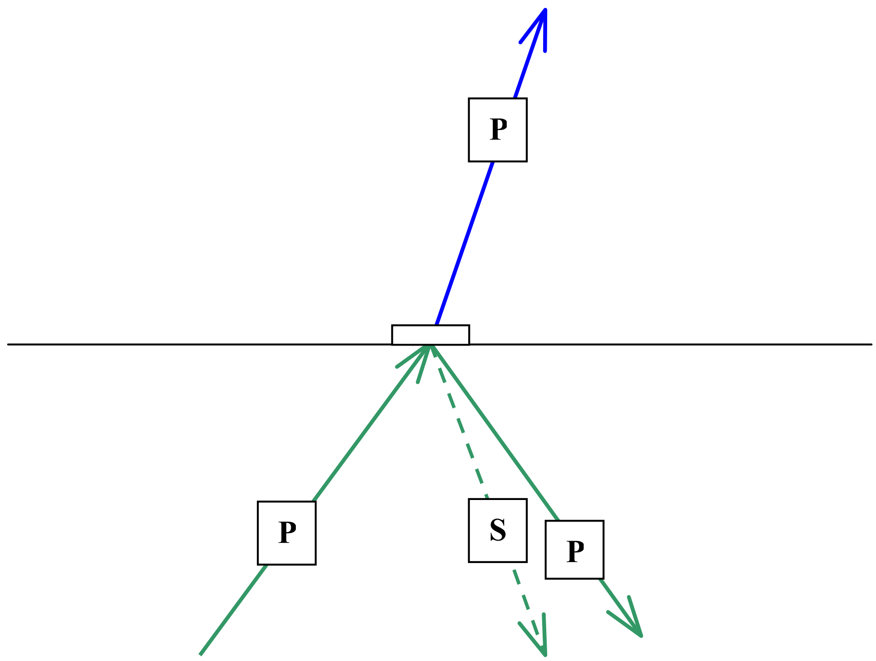

Fig. 5. P wave incident at seafloor from below. A hydrophone records the black phase; a vertical geophone records the sum of vertical components of the grey phases.

Recall that S-wave particle motion is perpendicular to propagation direction, 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 (grey) phases, in this case the transmitted P and S waves. The hydrophone will record the scalar sum of the (pressure) amplitudes of the water (black) 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.

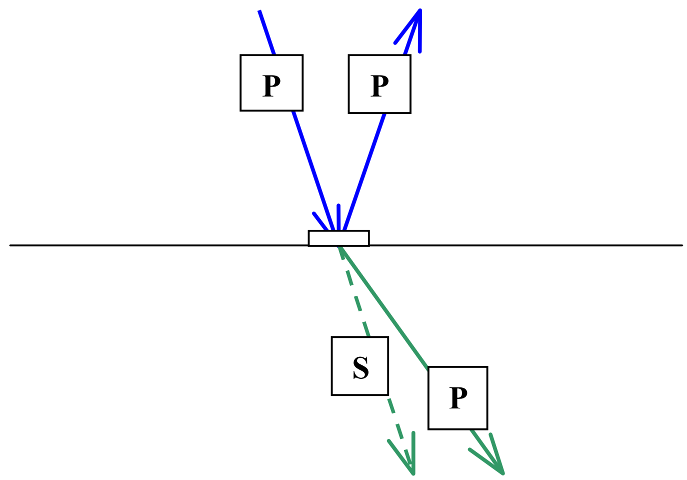

Fig. 6. P wave incident at seafloor from above. A hydrophone records the scalar sum of pressures of the black phases; a vertical geophone records the sum of vertical components of the grey phases.

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, a full-blown universally accepted polarity standard for 4C data still does not exist to tell us what constitutes normal field polarity for the horizontal components. Even in the case of the hydrophone, there is still some ambiguity. 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 early step in processing the inline component. It is often expressed as: ‘reversing the polarity of the trailing spread’. The question should be asked, however: "To get *normal polarity*, should I reverse the polarity of the trailing or leading spread?" In order to answer this, one has to consider the signs of first breaks of reflection arrivals.

First it is necessary to establish what is meant by positive and negative phase, or positive and negative R_{PP} and R_{PS}. I am 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}, I have used a program that computes all 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, we can specify *normal* or *positive polarity* for inline data in such a way that a particular interface will appear on the processed inline section with the same polarity as on the hydrophone and vertical sections – *most of the time*. The goodness of this assumption is examined more closely below.

Inline geophone

It would be best to establish a procedure that will give 'normal' polarity, even if the field polarity is 'reversed' (although correct field polarity would be best of all; see below). That is, 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. If R_{PP}/R_{PS} normally is negative, then when this wave is on its way down as a P wave, it should hit the inline geophone with the opposite, or positive, onset; so we should arrange for this direct downgoing first break to be positive. This means that the polarity should be reversed on those inline traces that have negative onsets for the direct downgoing P wave. If offset is defined in the conventional way, as the distance vector from shot to receiver – not the opposite – then polarity should be reversed on inline traces at negative offsets.

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? I have computed R_{PP} and R_{PS} for about 200 different interface models, some more geologically realistic than others, to be sure, but I 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, 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.

Example 1: the 'normal' situation.

$\alpha_1 = 2.00$ $\beta_1 = 0.80$ $\rho_1 = 1.90$
$\alpha_2 = 3.50$ $\beta_2 = 1.80$ $\rho_2 = 2.40$

i_P (deg)	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.

$\alpha_1 = 3.60$ $\beta_1 = 2.40$ $\rho_1 = 2.60$
$\alpha_2 = 4.50$ $\beta_2 = 2.50$ $\rho_2 = 2.10$

i_P (deg)	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.

$\alpha_1 = 2.15$ $\beta_1 = 0.86$ $\rho_1 = 2.20$
$\alpha_2 = 1.75$ $\beta_2 = 1.25$ $\rho_2 = 1.95$

i_P (deg)	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

Despite the existence of these so-called exceptions to the normal rule, 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 meaning for horizontally layered sections and isotropic media. Still, a good initial rule is to treat crossline geophone data in the same way as inline-geophone data. For a flat seafloor, and assuming exactly correct acquisition geometry (geophone orientations, shot positions, receiver positions) there should not be any crossline component to the direct downgoing P wave. And if, in addition, the geology 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 the 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. That is, 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. If, by virtue of the acquisition geometry, there are clear first breaks or onsets of the direct downgoing P wave, then one should arrange for the polarity of the direct-P first breaks to be positive.

In other cases, one might try to determine the cause of any significant energy on the crossline component before deciding how to proceed, especially in those frequent cases where there is low energy on the first breaks (direct P) or no consistent pattern to their polarities. If one is sure that anisotropy is not a factor, comparison of corresponding reflections on the crossline and inline components might enable one to sort out polarities. However, the main reason for including a crossline component is usually to detect anisotropy, and to assume at the outset that there is none would be self-negating.

In cases where some significant arrivals may be due to anisotropy, I would recommend using the field polarity to keep track of positive and negative senses of direction. The recommended directions of the positive x and y axes should follow the SEG field-polarity standards described above and in the next section. The correct procedure would be to flip crossline trace polarities exactly as was done for the inline traces. 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. So, at this point we should flip the crossline trace polarities to achieve 'normal crossline polarity'. We could also compare polarities of equivalent reflectors on X and Y, being careful to keep the dynamic time delay between fast and slow arrivals in mind, just for confirmation.

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 proportions of fast and slow shear waves on the two sections, so for certain geometries we could be comparing the fast S wave on one section with the slow S wave on the other. Any conclusions on polarity thus made would be invalid.

A FIELD POLARITY STANDARD FOR MULTICOMPONENT DATA

A multicomponent field-polarity standard consistent with Thigpen et al. (1975) and Brook et al. (1993), should recommend that: (1) motion in the forward line direction [i.e. the positive inline or x direction] give positive output from the inline geophone; (2) motion 90° clockwise to the forward line direction [i.e. the positive crossline or y direction] give positive output from the crossline geophone; (3) downward motion [i.e. the positive vertical or z direction] give positive output from the vertical geophone; and (4) a dilatation give positive output from the hydrophone. Call this the *multicomponent field-polarity standard.* This requires correct definition of the directions x, y and z, including their senses, as stated above. These lower-case symbols are used to denote the Cartesian axial directions, whereas the upper-case characters, W, X, Y and Z, are used to denote the four different recorded components.

CONCLUSIONS

To ensure a particular polarity on any one of the 4C 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. Confining oneself to common-receiver gathers is a good idea because each individual receiver will normally have the same recording polarity throughout a survey, short of rewiring or replacement of sensors or cables.

To ensure positive or normal polarity for the vertical (Z) component, this means ensuring that the direct downgoing P have positive onsets. For normal polarity on the hydrophone (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 inline (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 e.g. to anisotropy, inhomogeneity, or asymmetric geometry – there are special considerations.

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