Color, Character and Zero-Phaseness

Color Principles

"The total quantity of information recorded on a typical seismic line is enormous. It is virtually impossible to present all this information to the user in a comprehensible form." This quotation from Balch (1971) is even more true today than it was in 1971 and color has become an important contributor to the problem's solution. The human eye is very sensitive to color and the seismic interpreter can make use of this sensitivity in several ways. Taner and Sheriff (1977) and Lindseth (1979) were among the first to present color sections which demonstrated the additional information color can convey. Of equal importance is the increased optical dynamic range of a color section compared to its black and white variable area/wiggle trace equivalent. Both these properties are of great importance in stratigraphic interpretation.

Some understanding of color principles will help an interpreter maximize the use of color. It is helpful to visualize colors as a three-dimensional solid but there are three relevant sets of coordinates in terms of which the color solid can be expressed:

(1) the three additive primary colors — red, green, blue;
(2) the three subtractive primary colors — magenta, yellow, cyan; and,
(3) hue, saturation, density.

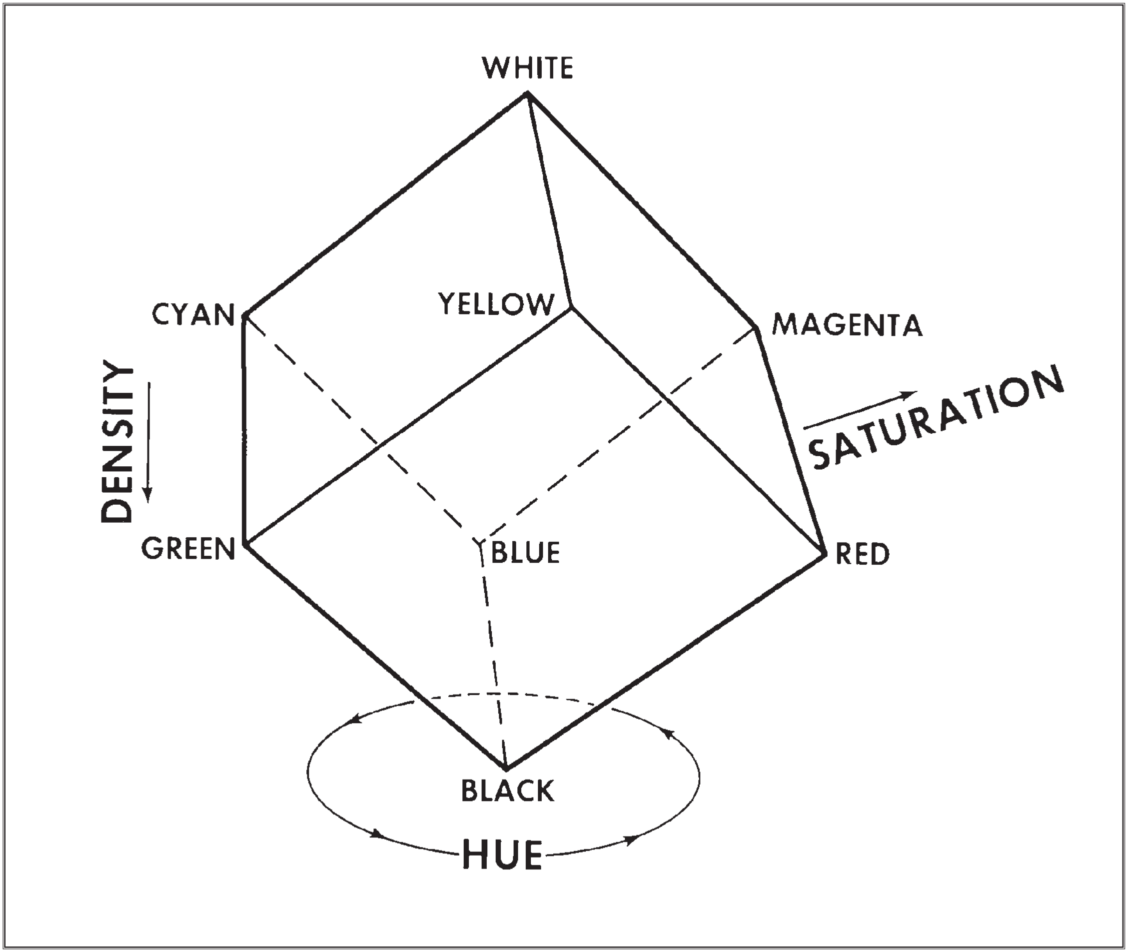
Figure 2-1 is a diagrammatic representation of a color cube showing the interrelationship of the above sets of coordinates. Figure 2-2 is a photograph of an actual color cube oriented to correspond to the diagram of Figure 2-1. Figure 2-3 is a photograph of the same cube from the opposite direction.

This cube was made using an Applicon color plotter, but the principles under discussion are independent of the plotting device. Any system which combines pigments employs the **subtractive primary colors** — magenta, yellow and cyan. Figure 2-2 and 2-3 show the *absence* of any color, which is *white*, at the top and progressively increasing quantities of magenta, yellow and cyan down the upper edges of the cube. These primaries, paired in equal quantities, give the **additive primary colors** — red, green and blue — at the three lower corners. All three subtractive primaries combined in equal quantities give black, seen at the bottom apex of the cube.

Any display system which combines light, such as a color monitor, follows the cube of Figures 2-2 and 2-3 from *bottom to top*. The *absence* of color is then *black*. Light of the three additive primary colors, red, green and blue, combine in pairs to make magenta, yellow and cyan and altogether to make white.

The cube photographs display only those colors on the surface of the cube. In fact, a much larger number of colors is inside. Down the vertical axis from white to black is the gray scale for which the **density** increases progressively (Figure 2-1).

Fig. 2-1. Diagram of a color cube showing the relationship of the subtractive primary colors (magenta, yellow and cyan) to the additive primary colors (red, green and blue) to the color parameters (hue, saturation and density).



The **saturation** measures the distance from this central axis, ranging from zero on the axis to 100% on the surface of the cube. The **hue** is the rotational parameter measuring the spectral content of a color.

For the color cube illustrated in Figures 2-2 and 2-3 there are 17 levels (0-16) of each of the subtractive primaries — magenta, yellow and cyan. The total number of colors in the cube is thus 17 × 17 × 17 or 4,913, of which 1,538 are fully saturated colors on the surface. One way of studying the colors available inside the cube is to slice it along a chosen density level. Figure 2-4 shows density level 16, which has maximum strength magenta, yellow and cyan at the corners and gray of density 33% at the center. This display clearly demonstrates the significance of hue as the rotational parameter and saturation as the radial distance from the gray axis. The additive primaries, red, green and blue, lie on density level 32 with gray of density 67% at the center.

Figure 2-5 is a color chart used in an interactive interpretation system (Gerhardstein and Brown, 1984). It is based on the mixing of light and hence involves the additive primaries — red, green and blue. All the colors displayed in Figure 2-5 are fully saturated; that is, they lie only on the surface of the color cube. The right half of the chart is a projection of a color cube similar to that of Figures 2-2 and 2-3 when viewed from the top. The left half of the chart is a view of the same color cube from the bottom. Interactive workstations make the selection and building of logical, efficient and intuitive color schemes easier if the selection chart is founded directly on the color cube, as in Figure 2-5.

Interpretive Value of Color

Today's interpreter uses color in two fundamentally different ways: with a *contrasting* or with a *gradational* color scheme. A map or a section displayed in *contrasting* col-

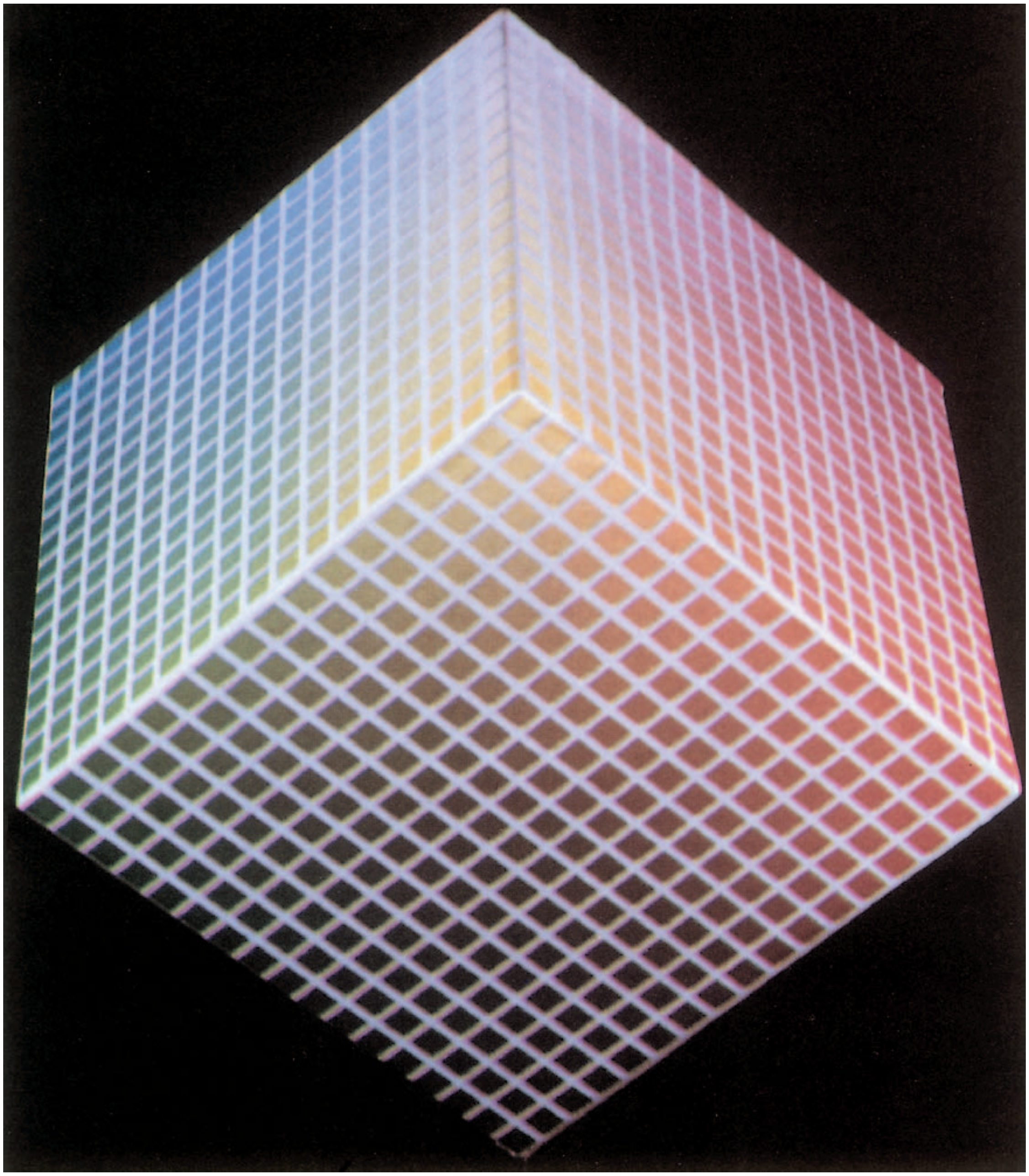


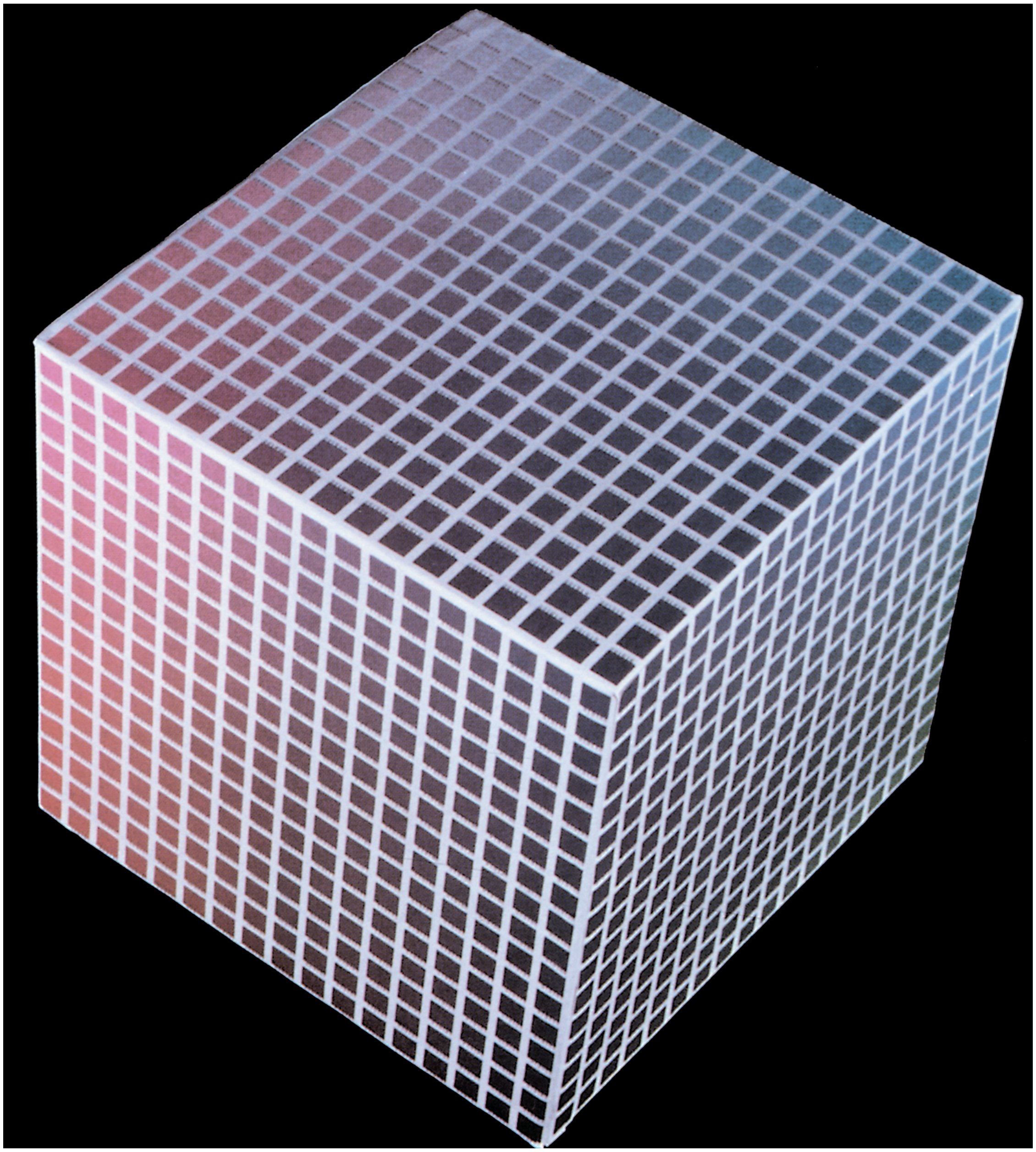
Fig. 2-2. Photograph of a color cube oriented the same as the diagram in Figure 2-1.

ors is normally accompanied by a legend, so the reader can identify the value of the displayed attribute at any point by reading the range of values associated with each color. Figure 2-6 is a structural contour map with a contour interval of 20 ms.

For an effective color display it is important that the range of values associated with each color, the number of colors used and their sequence, the contrast between adjacent colors, and the display scales are all carefully chosen. A color display must convey useful information and at the same time be aesthetically pleasing. For a map such as Figure 2-6 it is desirable to perceive equal visual contrast between adjacent colors, so that no one color boundary is more outstanding than another. A spectral sequence of colors was selected.

Figure 2-7 is a nomogram used for assessing visual color contrast. Visual contrast between two colors is, of course, somewhat subjective. Numerical color contrast is the sum of the absolute values of the differences in the amounts of the three primary colors. Zero density is white, maximum density (100%) is black, and density can have

Fig. 2-3. Photograph of the same color cube as in Figure 2-2 from the back.



either arbitrary or percentage units between these extremes. Figure 2-7 shows that, for a particular visual color contrast, numerical contrast should be approximately proportional to average density. In other words, a larger numerical contrast is needed between darker colors.

A *gradational* color scheme is used when the interpreter is looking for trends, shapes, patterns and continuity. Figure 2-8 includes a vertical section displayed with gradational blue for positive amplitudes (peaks) and gradational red for negative amplitudes (troughs). Absolute amplitude levels are unimportant but relative levels are very important. Much stratigraphic information is implied by the lateral variations in amplitude along each reflection. The blue and red give equal visual weight to peaks and troughs. If the display gain is properly set, only a few of the highest amplitudes reach the fully saturated color and the full range of gradational shades expresses the varying amplitudes in the data. This increased dynamic range gives the interpreter the best opportunity to judge the extent and the character of amplitude anomalies of interest.

Figure 2-8 also provides a comparison of gradational color and variable area/wig-

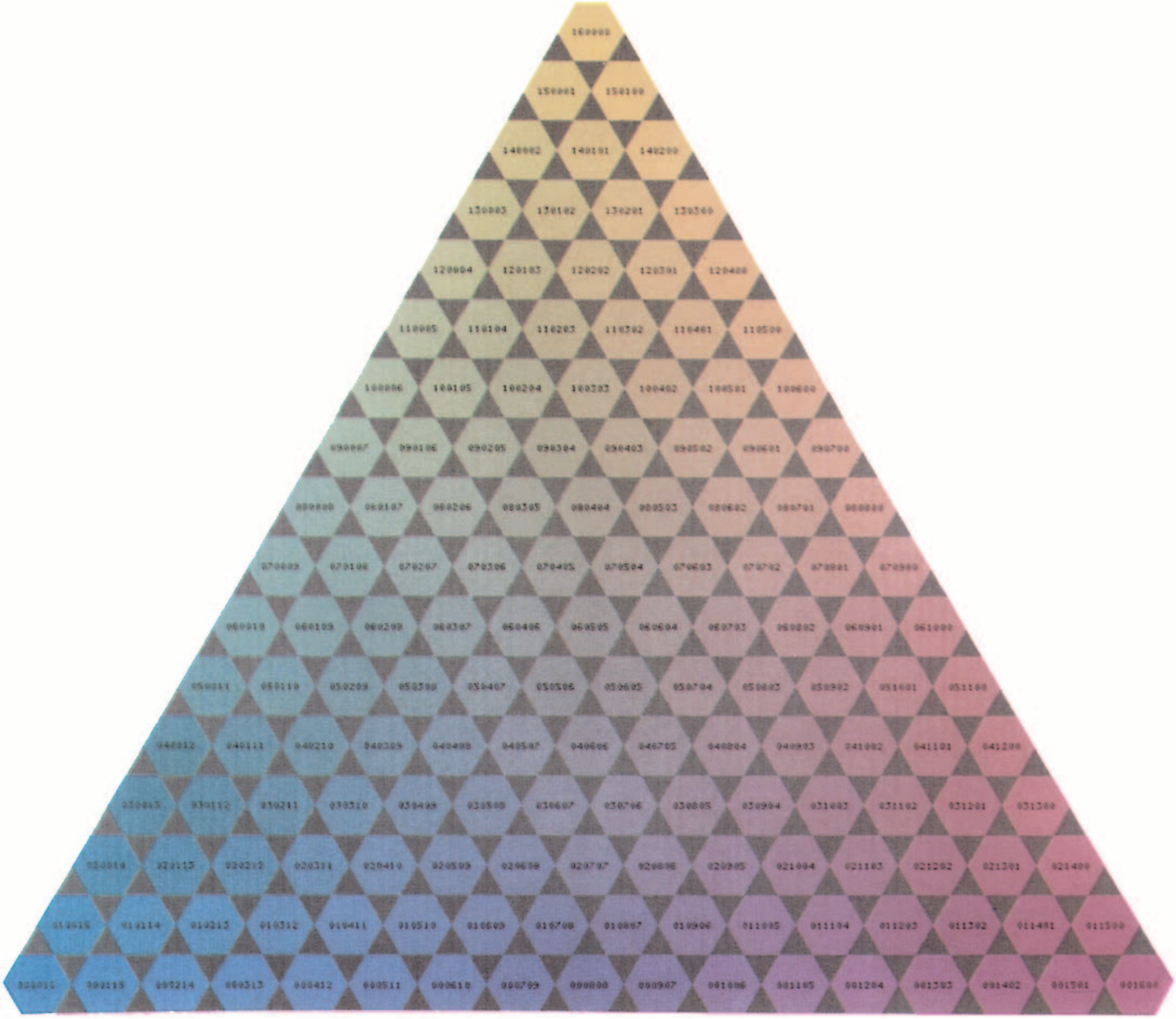


Fig. 2-4. Horizontal slice through the color cube at density level 33%, showing magenta, yellow and cyan at the corners and gray at the center.

gle trace for the same piece of data. The shortcomings in the variable area/wiggle trace display relative to the color section are: (1) the visual weights of peaks and troughs are very different, which makes comparison difficult and biases the interpreter's eye towards the peaks; (2) some of the peaks are saturated or clipped; and (3) the troughs, where they have significant amplitudes, are not visible beneath the depth points where they belong. The red flat spot reflection is clearly visible on the color section as are the relative amplitudes of peaks and troughs. At the extreme right of the section, coincident amplitude maxima in the peak and the trough indicate a tuning phenomenon (see Chapter 6).

Figure 2-9 provides a similar comparison between gradational color and variable area/wiggle trace. In addition, three different horizontal scales are used from which a further shortcoming of variable area/wiggle trace is apparent — that the dynamic range is limited and dependent on horizontal scale.

The color schemes of Figures 2-8 and 2-9 are more explicitly called double-gradational schemes with symmetry of blue and red about zero amplitude. The need for equal visibility of peaks and troughs has long been recognized. Backus and Chen

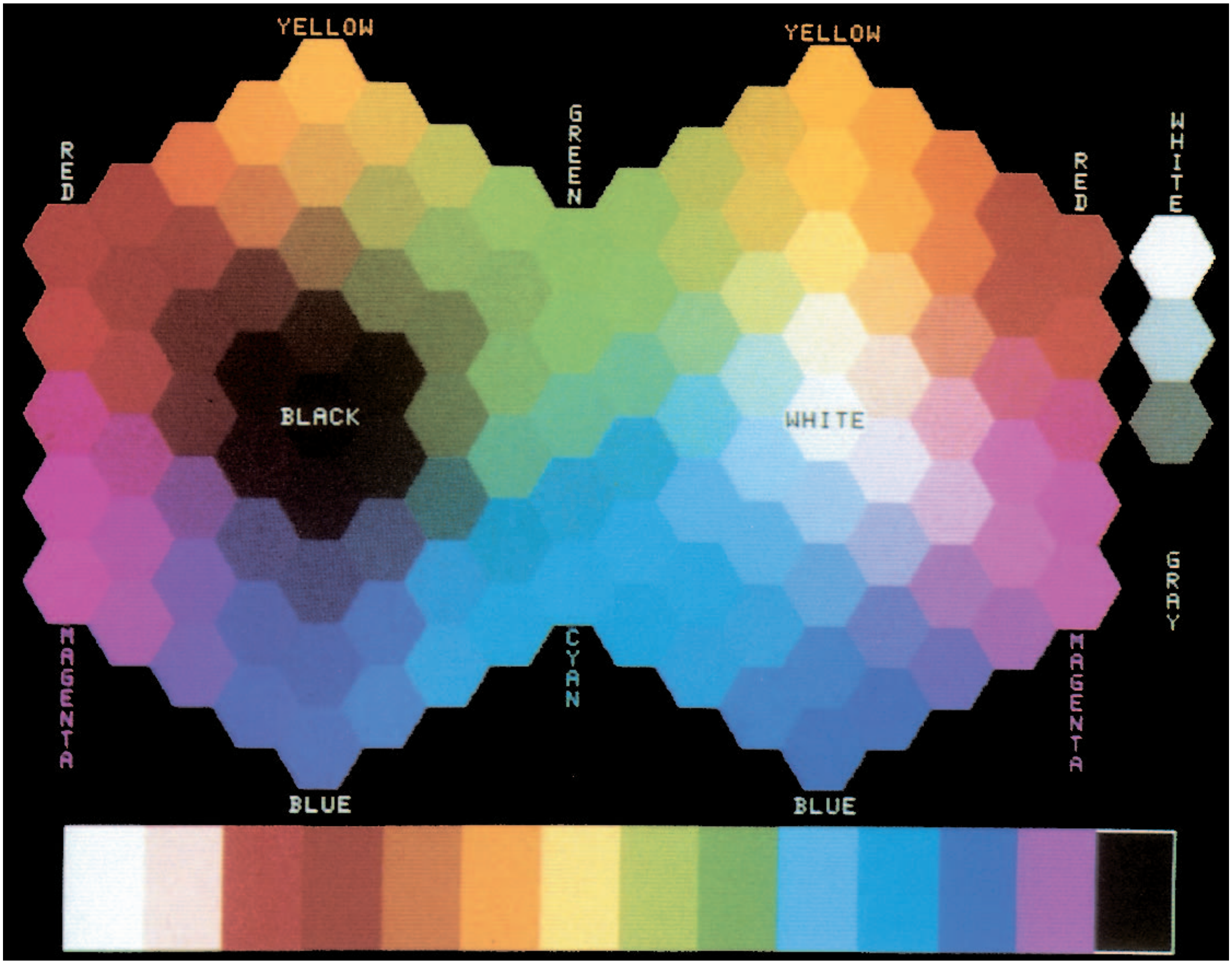


Fig. 2-5. Color selection chart from an interactive interpretation system. Note how its organization is based on the color cube.

(1975) generated dual polarity variable area sections with the peaks in black and the troughs in red. Figure 2-10 is an example of this display from Galbraith and Brown (1982). These were early attempts to generate symmetry or balance between positive amplitudes (peaks) and negative amplitudes (troughs).

Before continuing the discussion on different color schemes, it is important to understand why balance between positives and negatives is important. Consider a sand reservoir encased in shale. There is a reflection from the shale/sand interface at the top and a reflection from the sand/shale interface at the base. These are the two reflections from this reservoir, and both of them contain information about the reservoir. If some reservoir property (fluid, porosity, etc.) changes, then both reflections are equally affected. Thus the amplitudes of top and base reflections vary in unison, and the observation of this is called *natural pairing*. Observation of natural pairing requires a balanced double-gradational color scheme and is an important aspect of reservoir reflection identification (see Chapter 5).

The double-gradational blue-white-red color schemes of Figure 2-8 and 2-9 are balanced; pure primary blue is at one extremity and pure primary red is at the other extremity. This is the most universally applicable color scheme for interpreting seismic data. Figure 2-11 shows an extension of this with an additional gradation of cyan for the higher positive amplitudes and an additional gradation of yellow for the higher negative amplitudes. This has enhanced dynamic range compared with the blue-

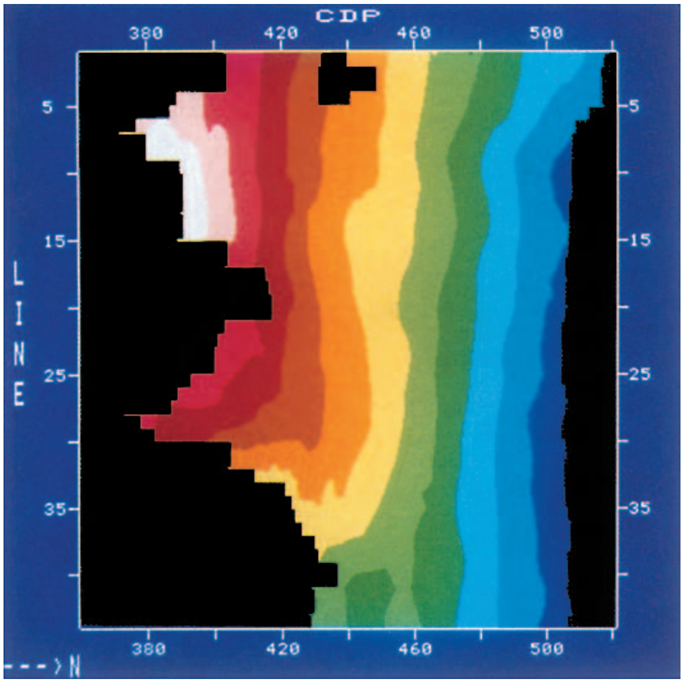


Fig. 2-6. Time structure map displayed in a contrasting spectral color scheme.

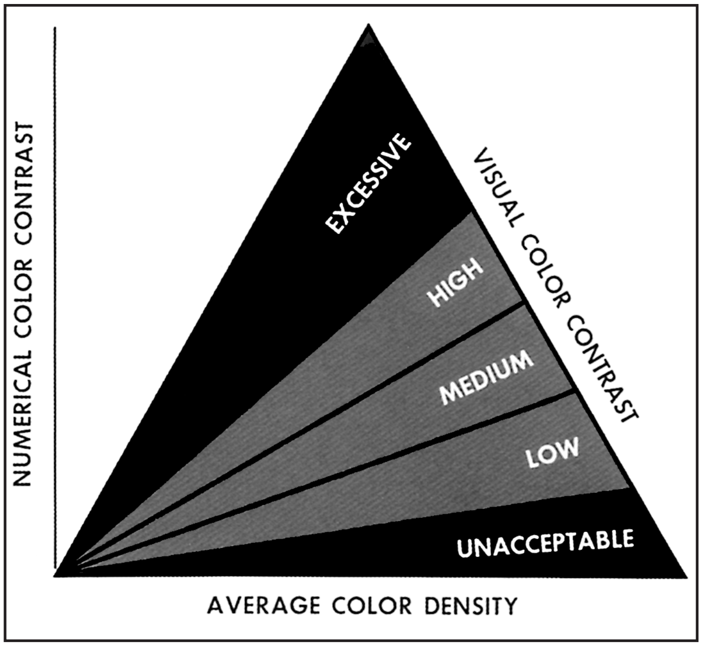


Fig. 2-7. Contrast-density nomogram used for establishing a color scheme with acceptable visual contrast between adjacent colors.

white-red but still has perfect balance on the color cube. Blue and red are both additive primaries, and cyan and yellow are both subtractive primaries. These balanced double-gradational color schemes are particularly important for reservoir reflection identification and recognition of hydrocarbon fluid effects.

Figure 2-12 shows a single-gradational gray scale with black at maximum positive and white at maximum negative. A single-gradational color scheme enhances low-amplitude events and thus is useful for general structural interpretation and recognition of subtle faults.

Figure 2-13 shows the same piece of data with four color schemes. The lower left is the standard blue-white-red. In the upper left, some contrasting colors have been added to highlight the highest amplitudes. This is usually not a good idea. Contrasts attract the eye to that particular amplitude level, whereas interpretation of amplitude actually entails the study of amplitude trends, patterns, and relativities. A much better way to add dynamic range to a double-gradational color scheme was illustrated with the additional gradations of cyan and yellow in Figure 2-11. The upper right panel of Figure 2-13 has too few gradations. The excessive contrasts of the lower right panel demonstrate how contrasting color schemes are inappropriate for seismic data.

The multiple color bars of Figure 2-14 show examples of what to do and what not to do. A is the quasi-standard blue-white-red, properly balanced with primary blue at one end and primary red at the other. F is a common variant using a non-primary blue and reddish brown; this is marginally inferior. G uses black and red, which is inferior because these colors are not balanced on the color cube. B is the enhanced dynamic range double-gradational color scheme with added cyan and yellow. Depending on the amplitude statistics of the data, this scheme may need to be adjusted, as shown in C. This kind of compression or expansion of the color scheme is important to maintain visibility of amplitude variations. Too much color scheme compression, however, such as in K, can obliterate amplitude variations and give the same impression as data clipping. H has the cyan and yellow but with contrasting

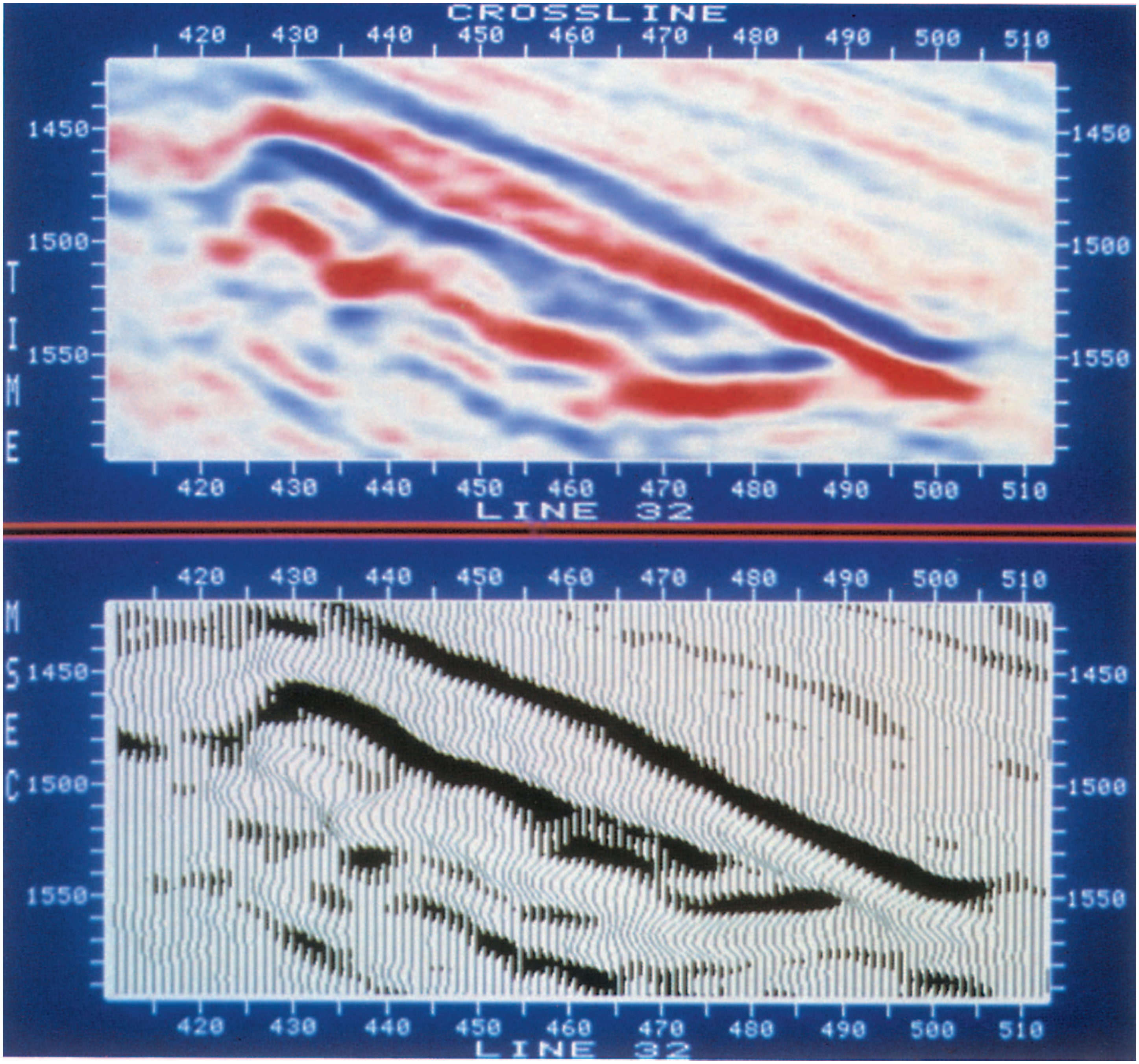


Fig. 2-8. Vertical seismic section displayed with gradational blue for peaks and gradational red for troughs compared to same section displayed in variable area/wiggle trace. (Courtesy Chevron U.S.A. Inc.)

color boundaries, so this is not recommended for normal use. J is unbalanced about zero and is thus a most confusing color scheme. D and E are both single-gradational color schemes useful for structural interpretation and fault recognition.

The recognition of channels, bars and other depositional features on horizontal sections and horizon slices is important for the stratigraphic interpreter. Here again the proper use of gradational color coded to amplitude helps the detectability of these features because of the eye's ability to integrate a wide range of densities. Figures 2-15 and 2-16 illustrate an inferred channel on a horizon slice (see Chapter 4) and the use and abuse of color for its detection. A well at about Line 55, Crossline 250, indicates that at least the lower part of the areal bright spot (Figure 2-15) is a sand-filled channel. How extensive is this channel? It seems probable that it extends to include the central zone between Lines 70 and 80 and between Crosslines 180 and 270. However, after crossing two faults, a curvilinear feature can be seen continuing

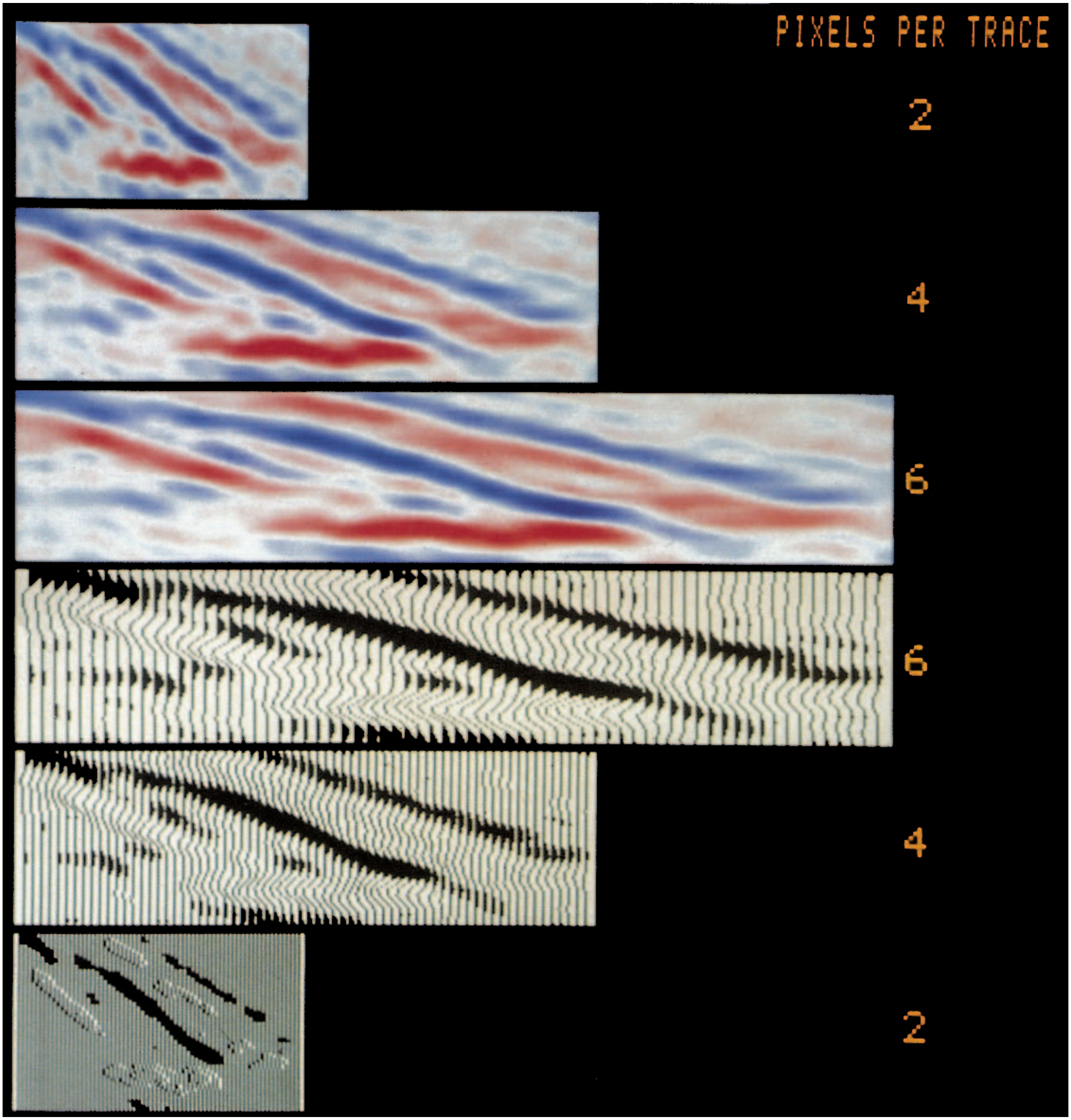


Fig. 2-9. Comparison of double-gradational blue and red with variable area/wiggle trace display illustrating respectively independence and dependence of dynamic range on horizontal scale.

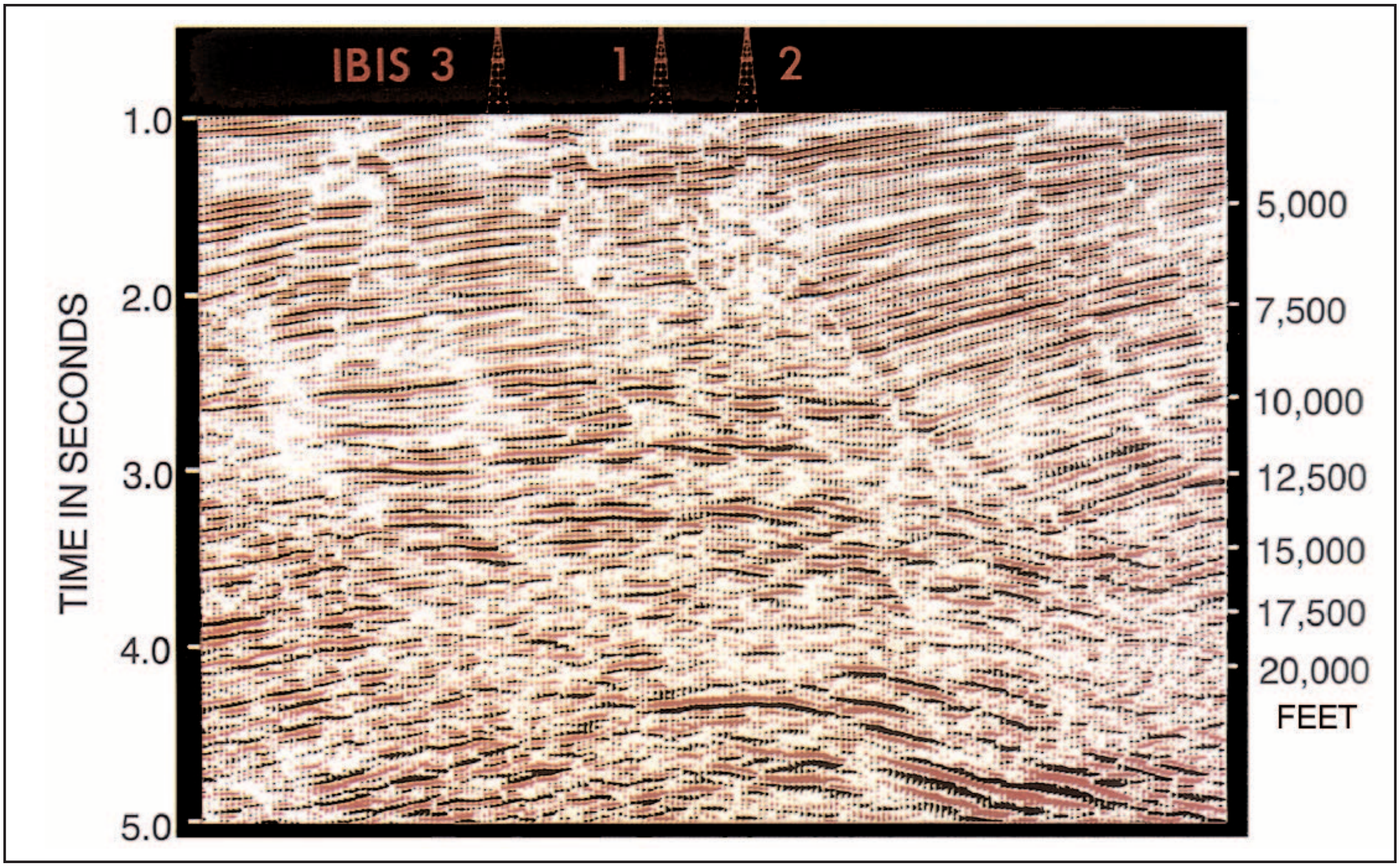


Fig. 2-10. Vertical section displayed in dual polarity variable area showing fault definition. (Courtesy Texaco Trinidad Inc.)

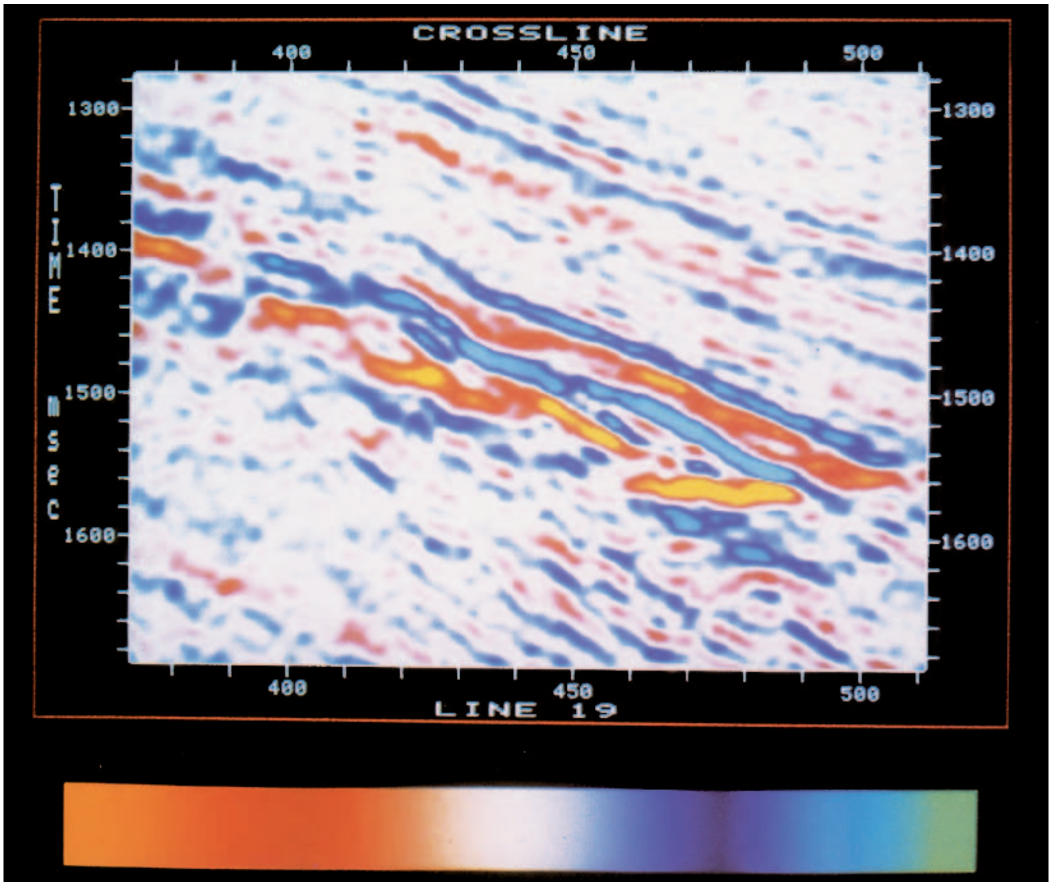


Fig. 2-11. Enhanced dynamic range double-gradational color scheme where cyan has been added for the highest positive amplitudes and yellow has been added for the highest negative amplitudes. (Courtesy Chevron U.S.A. Inc.)

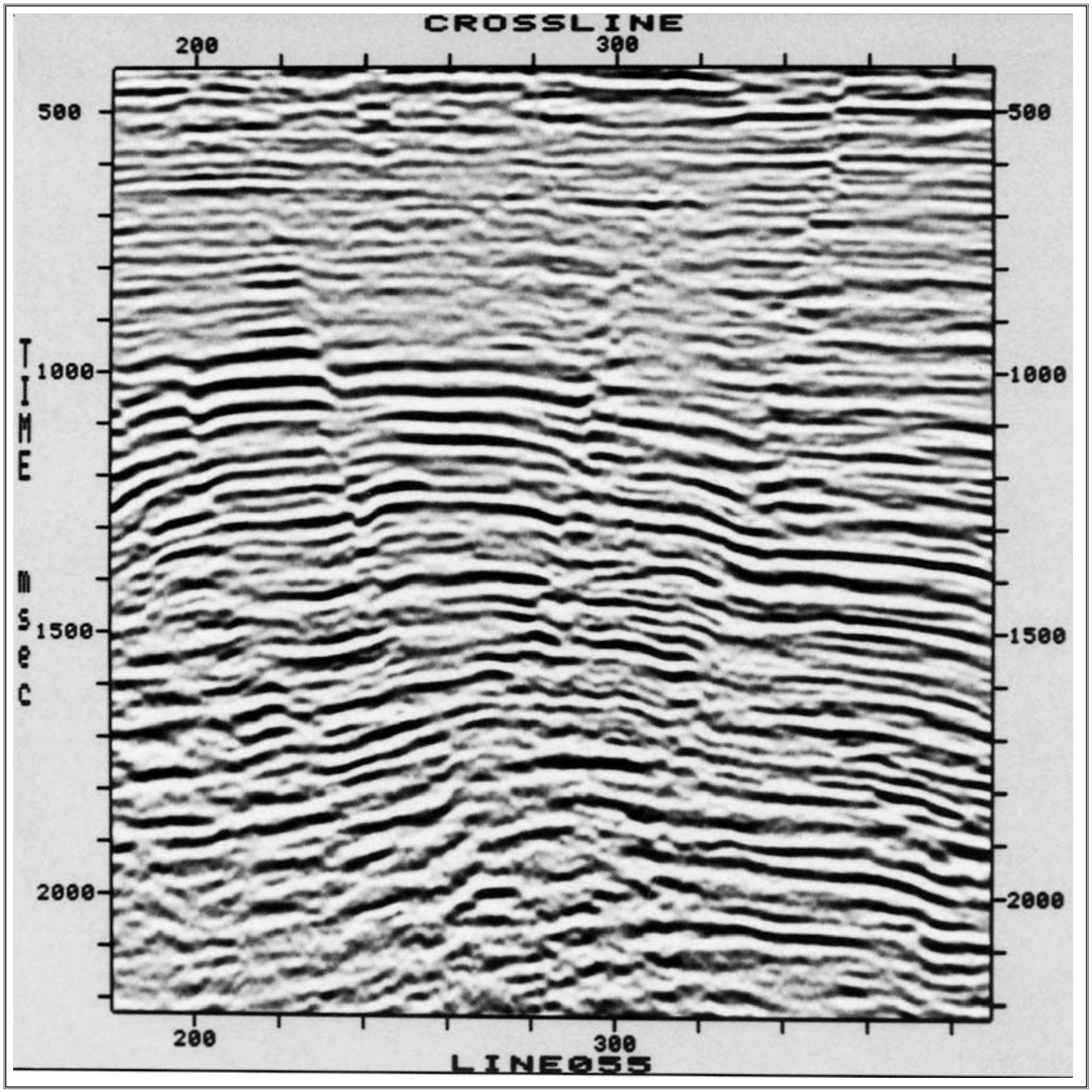


Fig. 2-12. Vertical section displayed with single-gradational gray scale in order to enhance low amplitude events. (Courtesy Texas Pacific Oil Company Inc.)

to the upper right to Line 122, Crossline 330. Is this a continuation of the channel system even though the amplitude is much reduced? We do not know the answer to this question, but we have been able to observe the continuity of this extensive curvilinear feature because of the use of gradational color.

Figure 2-16 shows the same section in contrasting colors and the detectability of the inferred channel is much reduced. In fact the eye tends to be drawn to the red and pink circular maxima at Crossline 250 between Lines 45 and 60 rather than the longer arcuate high amplitude trends. When applying a gradational color scheme to a horizon slice showing the spatial amplitude distribution of one trough, as in Figure 2-15, a gradational color scheme should be used to match the one-sided range of amplitudes. For the horizon slice for a peak (for example Figure 4-28) the same principle applies but the color scheme should be inverted. In order to aid the understanding of amplitudes, horizon slice colors should be matched to vertical section colors!

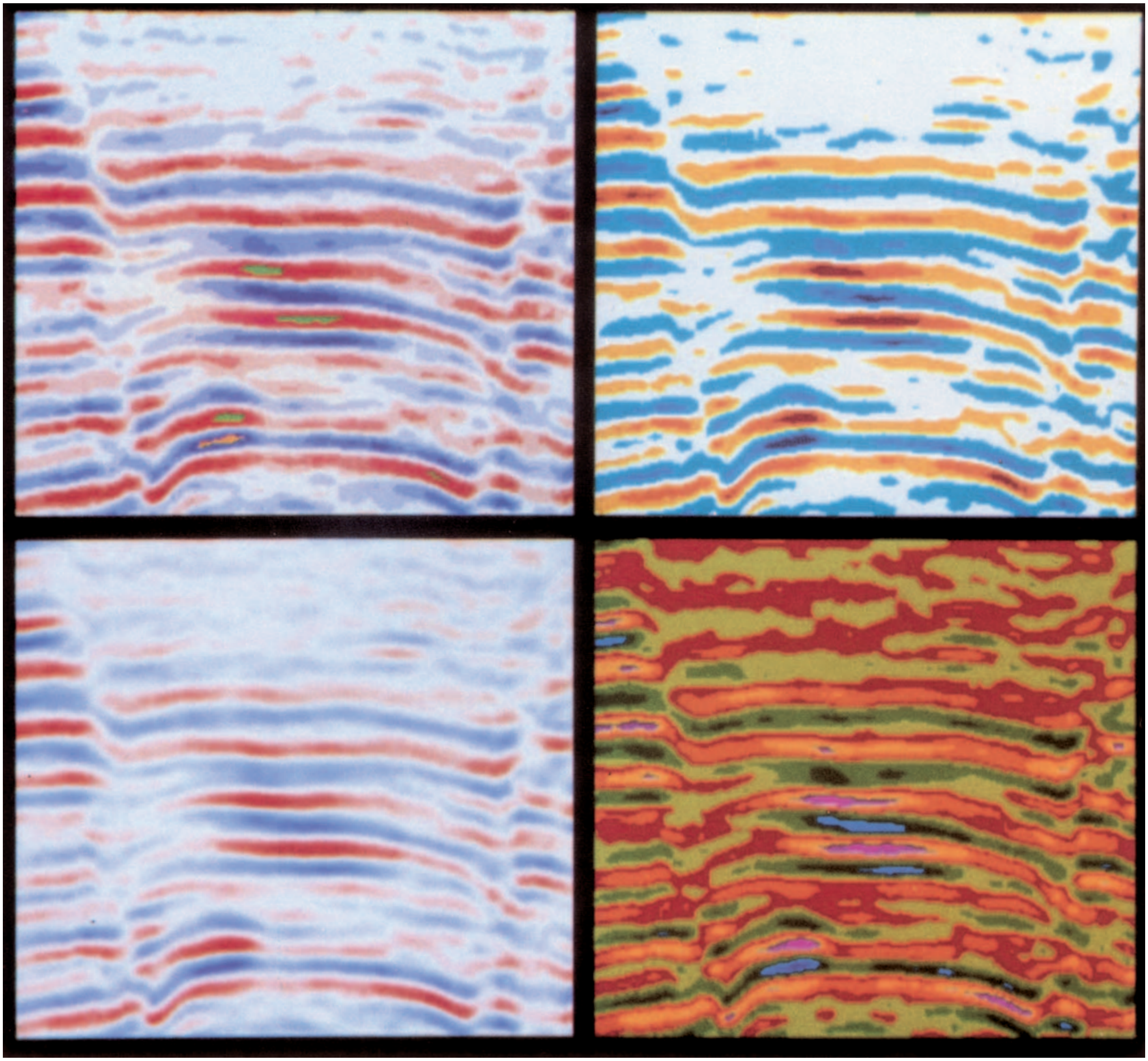


Fig. 2-13. Four different color schemes applied to the same vertical section segment. (Courtesy Texas Pacific Oil Company Inc.)

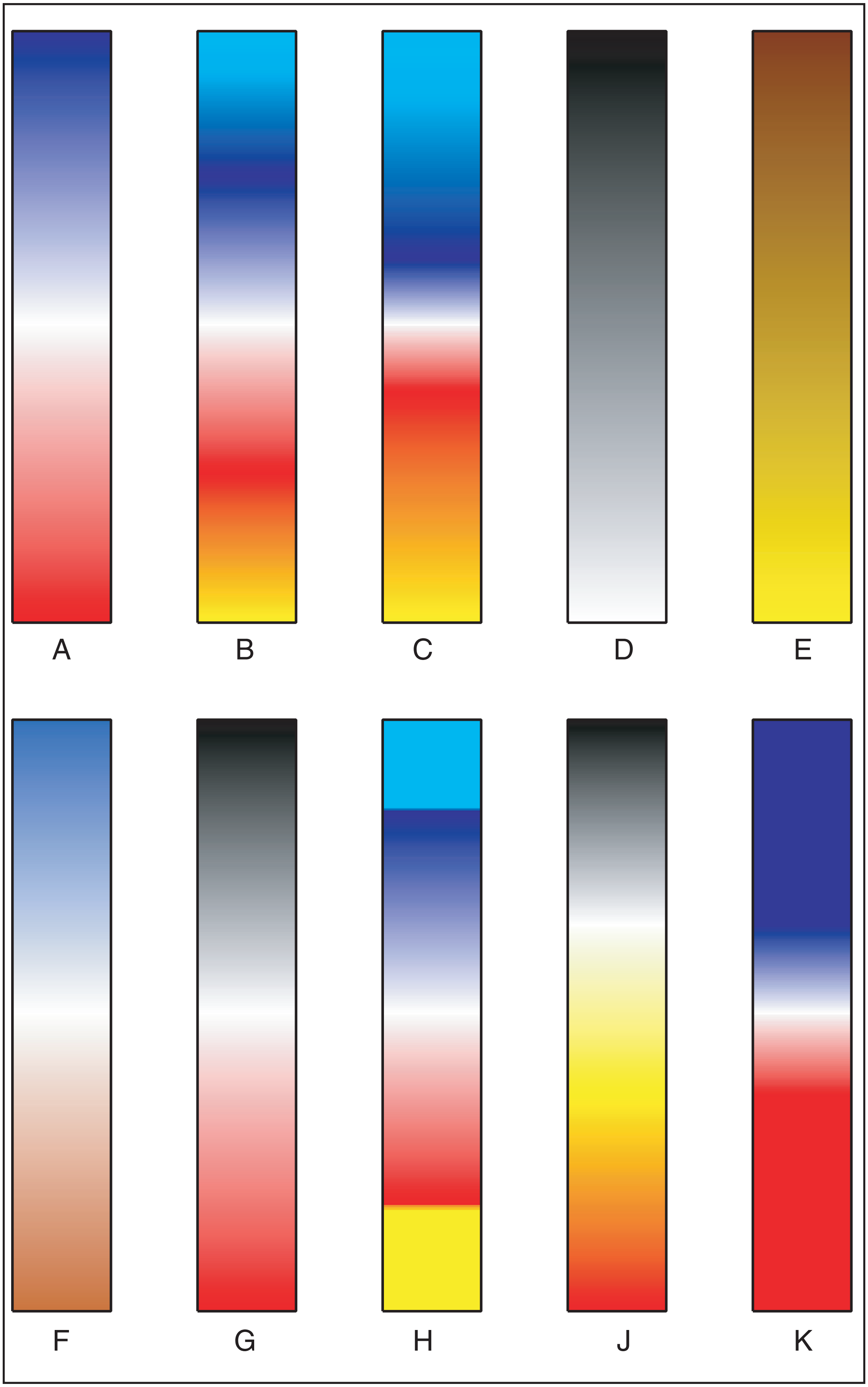


Fig. 2-14. Multiple color schemes, some good and some bad, for seismic data.

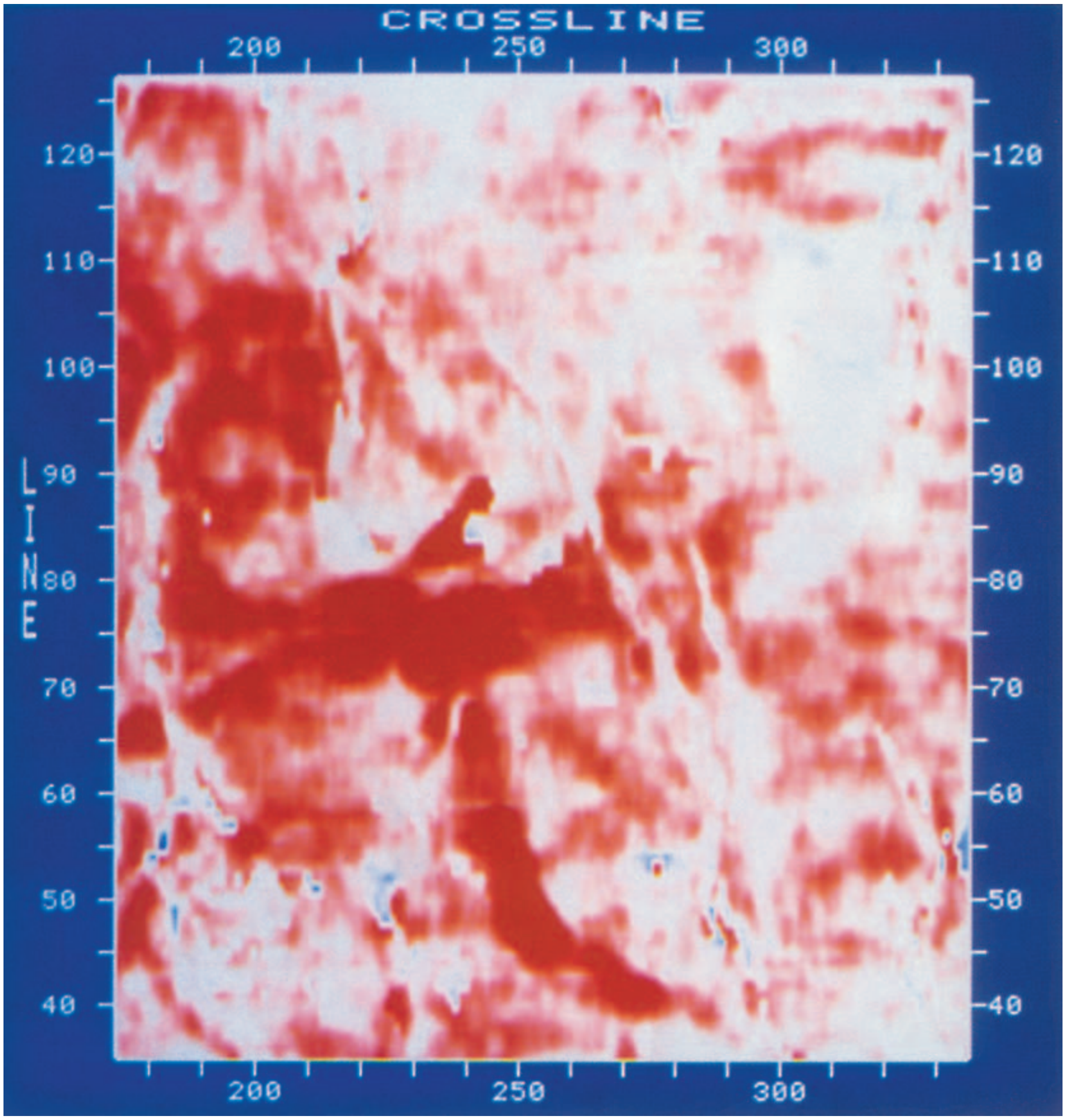


Fig. 2-15. Horizon slice showing an inferred channel system displayed with a gradational color scheme. (Courtesy Texas Pacific Oil Company Inc.)

Assessment of Phase and Polarity

Most interpreters today prefer zero-phase data. The reasons they give to support this preference include the following:

(1) the wavelet is symmetrical with the majority of the energy being concentrated in the central lobe;

(2) this wavelet shape minimizes ambiguity in associating observed waveforms with subsurface interfaces;

(3) a horizon track drawn at the center of the wavelet coincides in time with the travel time to the subsurface interface causing the reflection;

(4) the maximum amplitude occurs at the center of the waveform and thus coincides with the time horizon; and,

(5) the resolution is better than for other wavelets with the same frequency content.

Much data processing research has been devoted to wavelet processing, which can be defined as the replacement of the source wavelet, the receiver response, and the filtering effects of the earth by a wavelet of known and desirable characteristics. Wood (1982) outlined the principles of wavelet processing and the properties of zero-phase wavelets, and Kallweit and Wood (1982) addressed the issues of resolution. Some relevant processing issues are discussed in Appendix A. Today's interpreter, particularly one who has a stratigraphic objective, wants to be able to assess whether the data provided have been properly deconvolved to a zero-phase condition. This can be done in many ways. Cross-correlation of a synthetic seismogram with the seismic trace at the

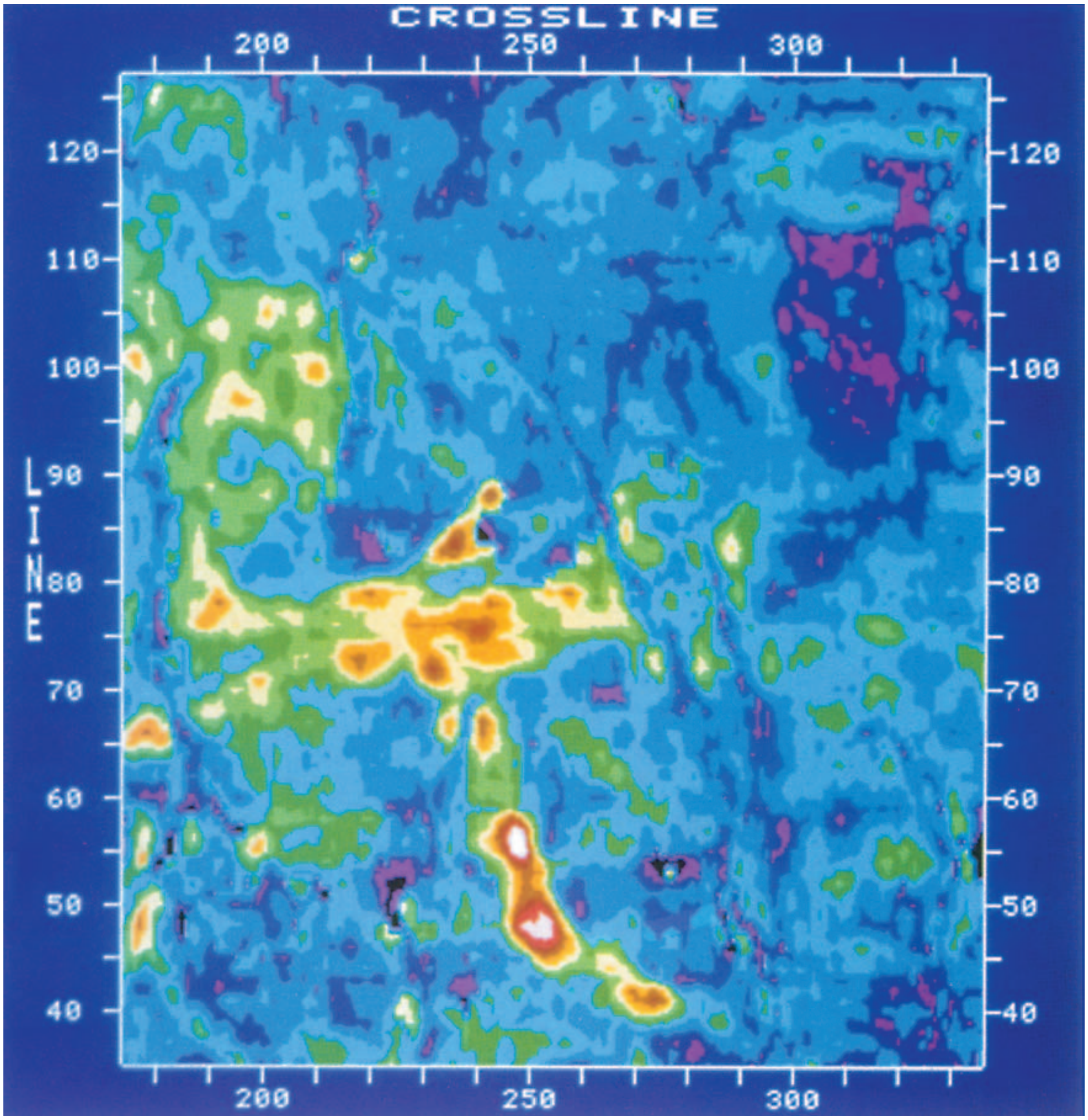


Fig. 2-16. Same horizon slice as in Figure 2-15 displayed with a contrasting color scheme, which reduces visibility of the channel system. (Courtesy Texas Pacific Oil Company Inc.)

well location is an analytical technique. So is the extraction of a wavelet from the data and the study of its shape. But whatever is done, today's interpreter needs an increased awareness of zero-phaseness and the ability to recognize it, or other phases, in his or her data.

Understanding wavelet phase gives increased importance to the understanding of polarity. For processed seismic data, polarity convention is confused, and in addition color display introduces the need for conventions in color usage. In presenting an interpretation using colored sections, the critical issue is to communicate the polarity and color usage for that data. It is less important what conventions are used because peaks and troughs are equally visible in color display. The author has developed a subjective appraisal of the polarity and color conventions in use today and these are diagrammed in Figure 2-17. American polarity is preferred in the Americas but is by no means universal in this region. European polarity is preferred in Europe and the rest of the world but again is by no means universal there. If we are diligent in always using blue for positive amplitude and red for negative amplitude, then only two choices remain. Are the data American or European polarity? This becomes a very important, and hopefully straightforward, determination for today's interpreter.

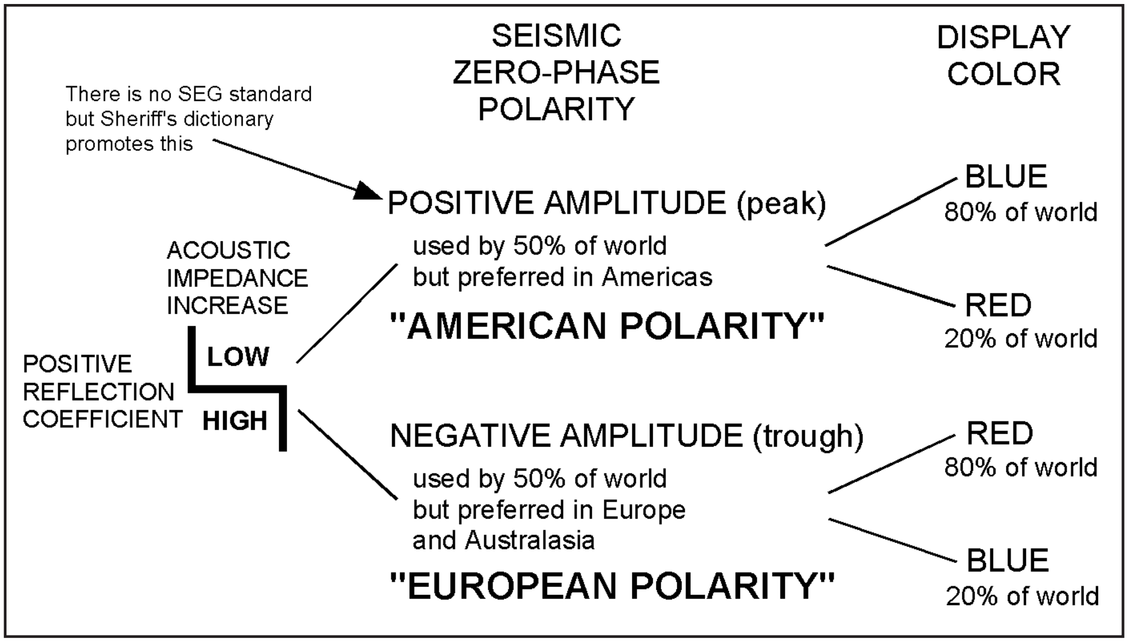


Fig. 2-17. Polarity and color conventions, and definition of American and European Polarity.

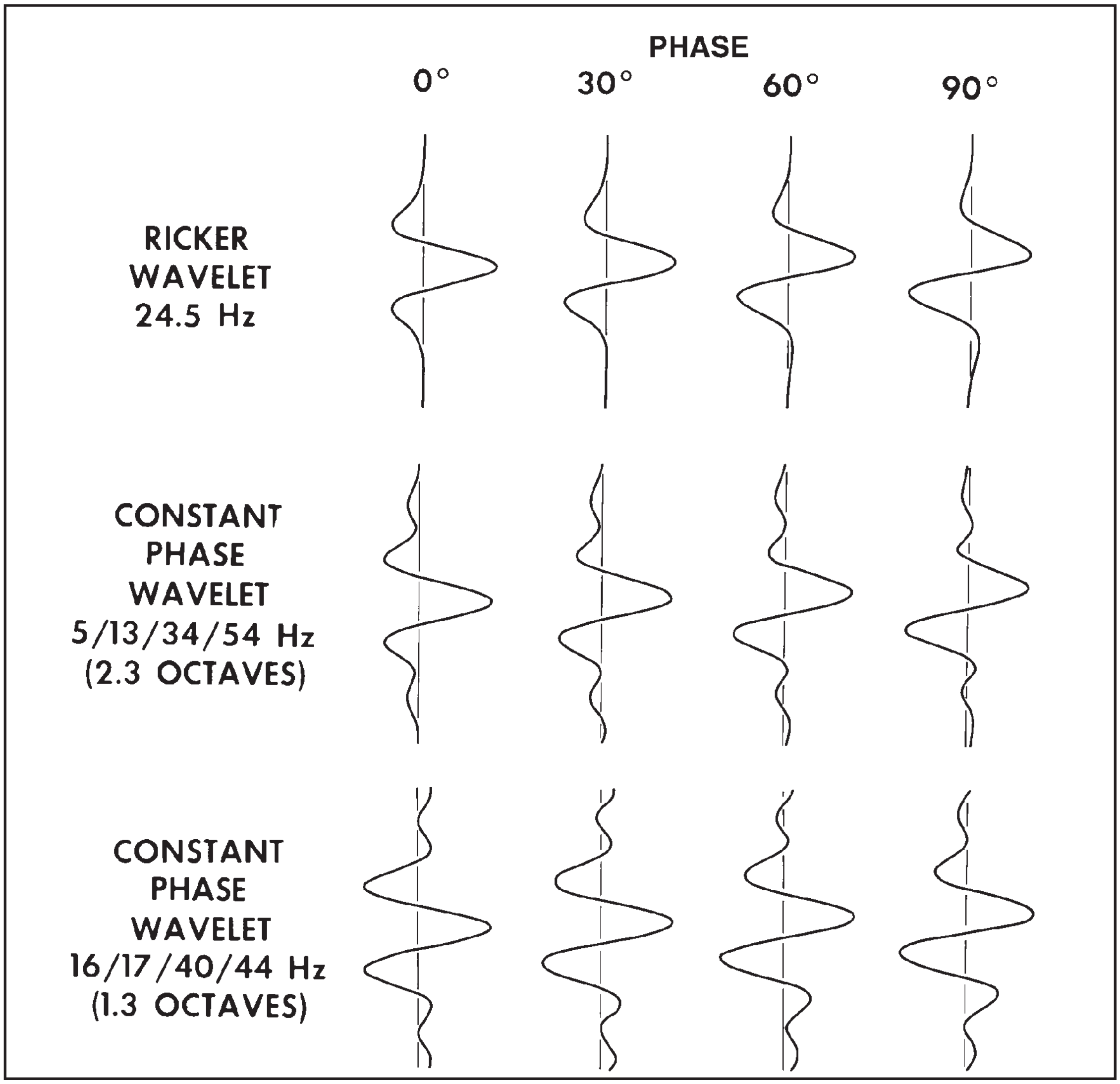


Fig. 2-18. Effect of phase shifting constant phase wavelets.

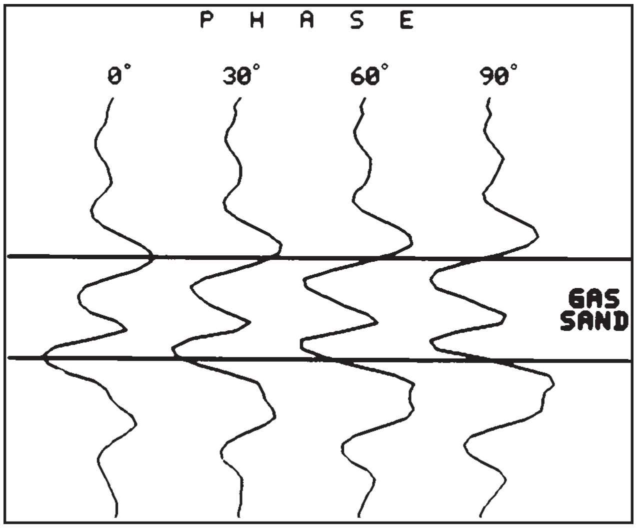


Fig. 2-19. Effect of phase shifting a real data trace showing reflections from the top and base of a gas sand. (Courtesy Chevron U.S.A. Inc.)

Fig. 2-20. Bright reflections from the top and base of a gas sand with constant phase shifts applied. (Courtesy Chevron U.S.A. Inc.)

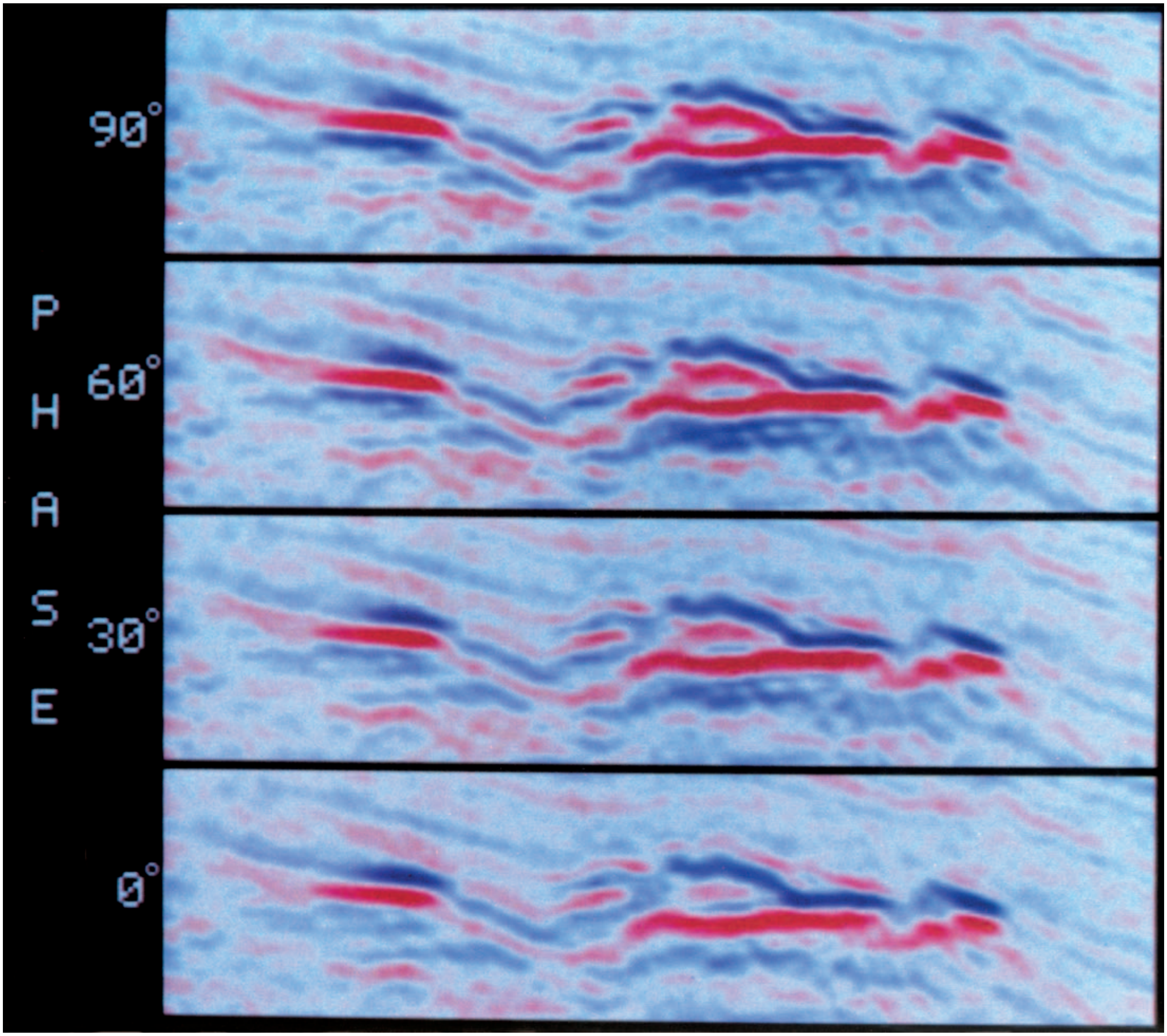


Fig. 2-21. The principal phase and polarity conditions that we should look for in our data. The responses illustrated are for a low-impedance interval with significant contrasts at top and base, such as a hydrocarbon sand.

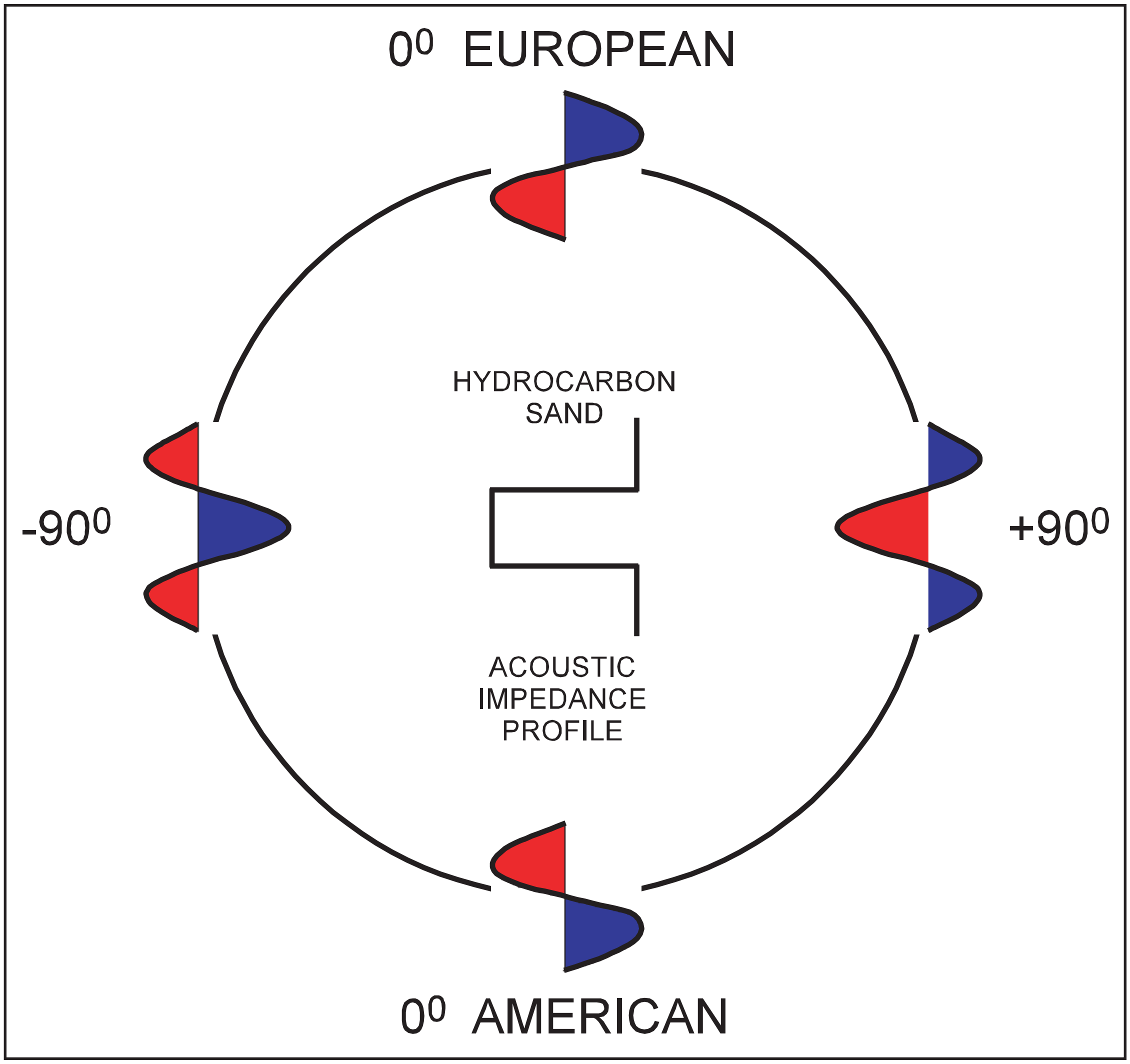
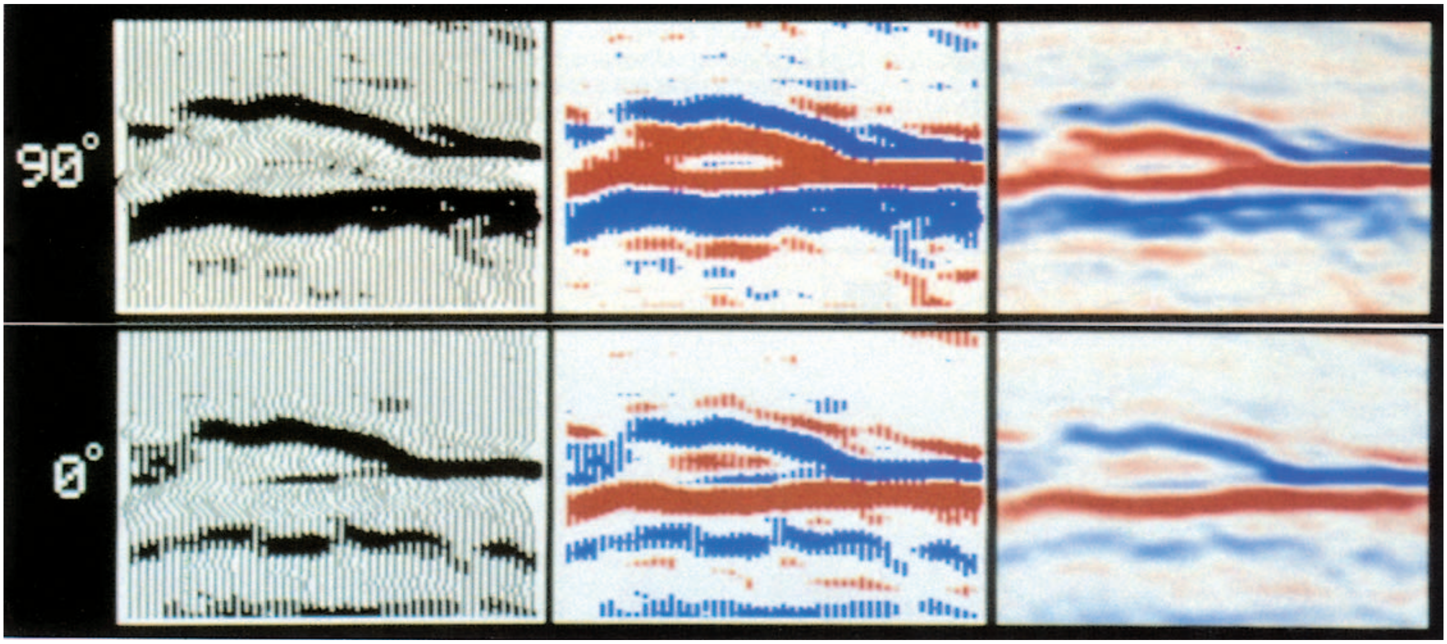


Fig. 2-22. Comparison between variable area/wiggle trace, dual polarity variable area, and gradational color for the interpretive assessment of data phase. (Courtesy Chevron U.S.A. Inc.)



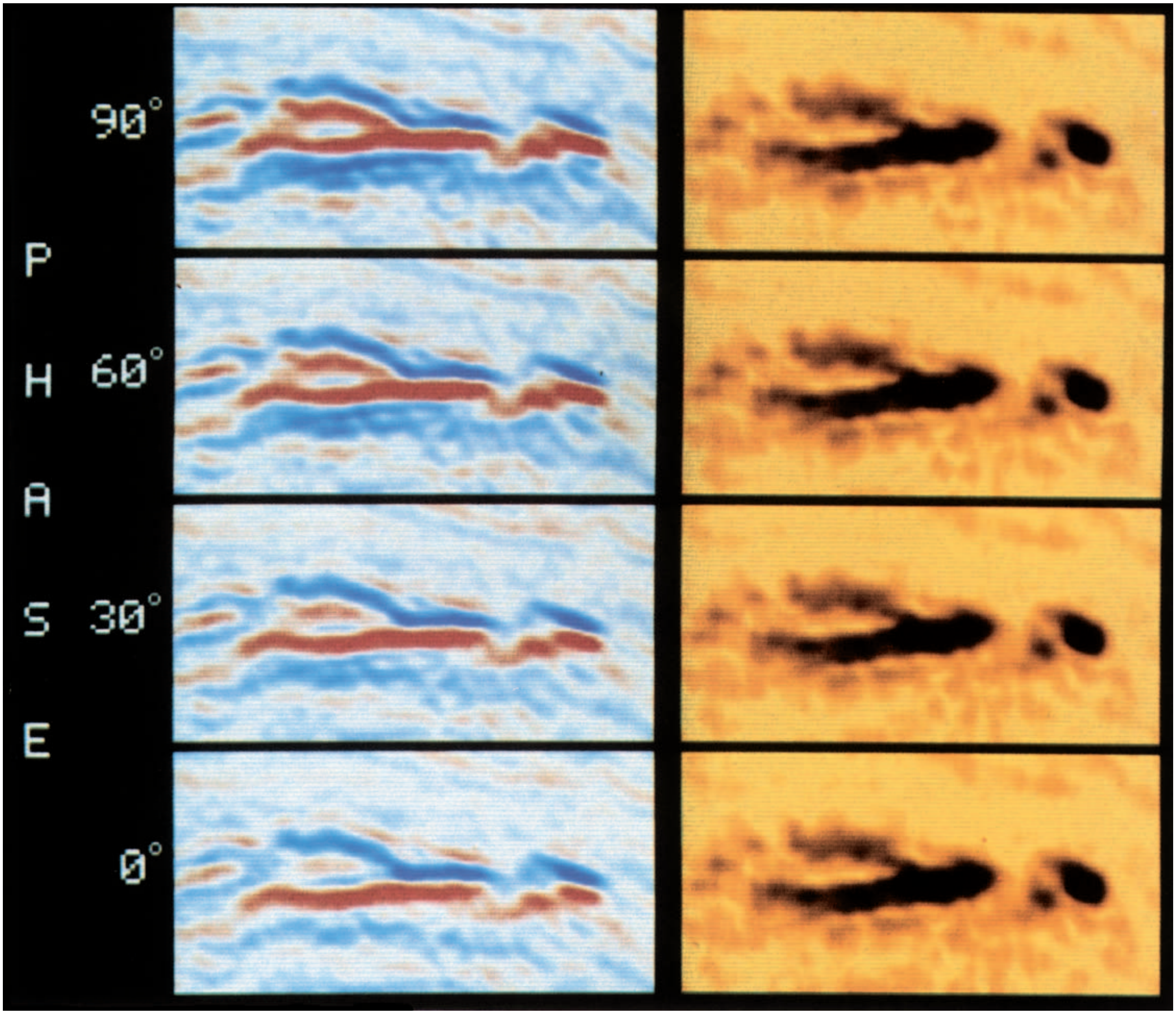


Fig. 2-23. Use of reflection strength or envelope amplitude to obscure the effects of phase distortion. (Courtesy Chevron U.S.A. Inc.)

The interpretive assessment of zero-phaseness requires high signal-to-noise ratio reflections and maximum dynamic range color display. But first zero-phaseness will be considered on model data. Figure 2-18 shows three zero-phase wavelets and their equivalents shifted by 30, 60, and 90 degrees. The first is a Ricker wavelet, the second is derived from a bandpass filter of 2.3 octaves with gentle slopes, and the third is derived from a bandpass filter of 1.3 octaves with steep slopes. The common property of these three wavelets is that the separation of central peak and first side lobe is the same for each — 16 ms. The Ricker wavelet has no side lobes beyond the first. The 2.3 octave wavelet is a good wavelet extracted from actual processed data and has low side lobes. The 1.3 octave wavelet is a poor wavelet with relatively high side lobes.

The visual assessment of zero-phaseness amounts to a visual assessment of wavelet symmetry. In these model examples 30° of distortion is visible for all the wavelets but the higher side lobe levels of the narrower band wavelet make the distortion less pronounced. For the larger distortions, for example at 60°, the central peak and the larger side lobe are more easily confused for the narrower band wavelet, so in practice it may be difficult to decide whether the peak or the trough is the principal extremum.

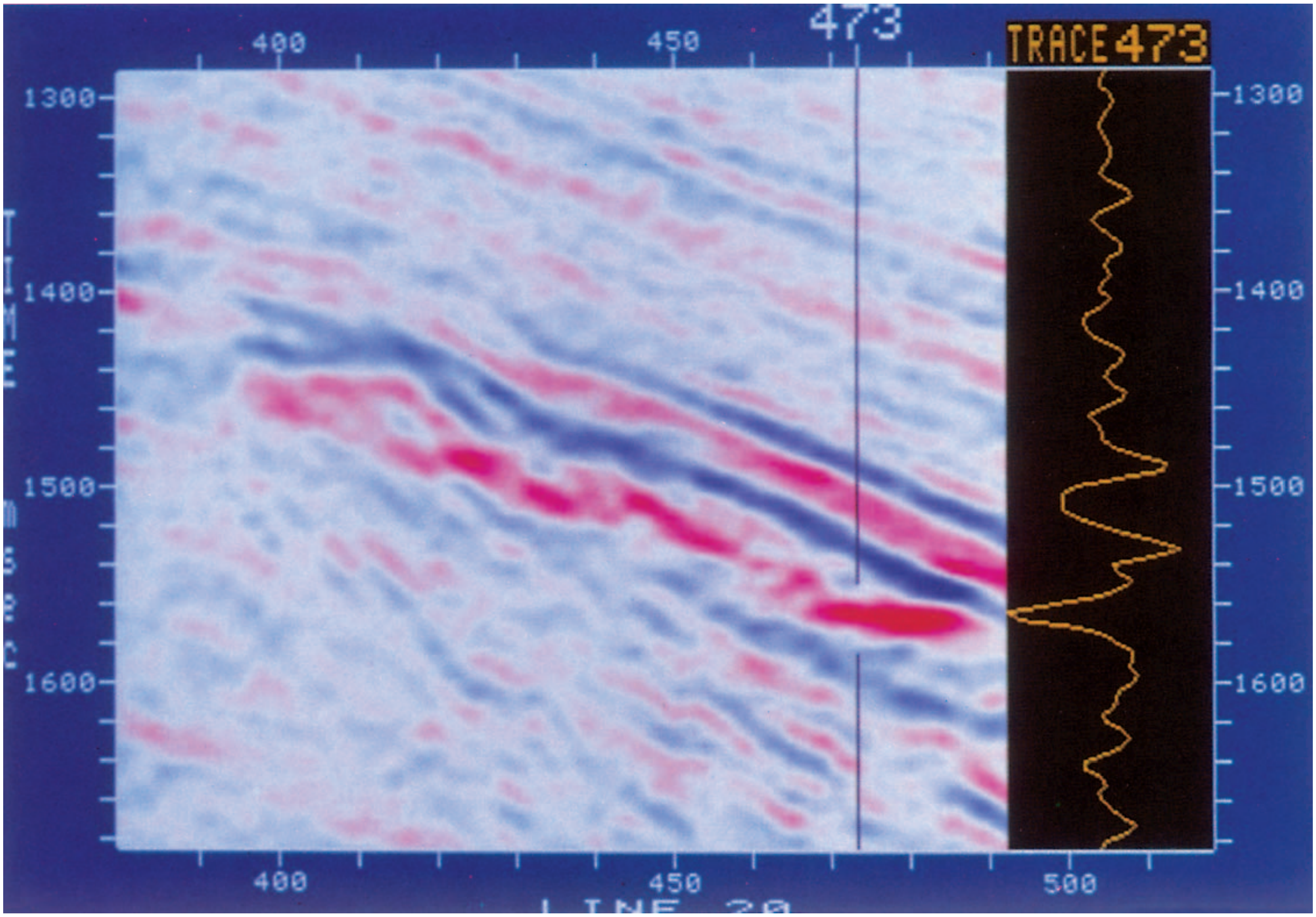


Fig. 2-24. Flat spot reflection displaying zero-phaseness, visible in gradational red for many traces and in wiggle format for one trace. (Courtesy Chevron U.S.A. Inc.)

At a distortion of 90° the time horizon lies at the zero crossing between the largest amplitude peak and trough, and these are of equal size.

Figure 2-19 is a single trace example from real data where there was a known low-impedance gas sand. The top of the low-impedance zone is a peak and the base a trough (European polarity). The trace labelled 0° shows peak and trough each symmetrically placed over their corresponding interfaces. The phase distortions are again evident when presented in this way.

In practice, interpreters must assess zero-phaseness on a section containing many traces in case one trace is unrepresentative. We select a high amplitude reflection, which, on the basis of a simple model, can be related to a single interface. The interpreter can then assume that the interference of events from adjacent parallel interfaces, multiples or noise is small. Figure 2-20 illustrates a bright spot from a gas reservoir where it is assumed that the above conditions hold except that there are two interfaces at the top and at the base of the reservoir. In the panel labelled 0° there is one blue event from the top of the reservoir and one red event from its base, and they have approximately the same amplitude. Side lobes are low and symmetrical as far as can be determined. This is the signature expected for the zero-phase response of a gas sand.

For the 90° case in Figure 2-20 the top of the gas sand has a signature of blue-over-red and the base one of red-over-blue. This confirms the modeling illustrated in Figure 2-18 and certainly shows a more complex character than the zero-phase section. The intermediate levels of phase distortion show the progression from the 0° to 90° condition. Observation of these more complicated phase characteristics can be followed by experimental phase rotation of the data.