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Exploration '84: New Technology Is Emerging

Part I

Seismic stratigraphy moves towards interactive analysis

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20-second summary

Seismic stratigraphy aids interpretation of complex geology, particularly by helping effectively identify the right geologic environment for potential hydrocarbon traps. This introductory article, the first in a three-part series, discusses some of the factors affecting interactive seismic stratigraphic interpretation, including phase effects, resolution and color softcopy.

SEISMIC SECTIONS have traditionally been used to define subsurface *structure*. However, the trend towards increasing seismic spatial and temporal sampling is providing data ideal for seismic *stratigraphic* studies; as evidenced by the new multi-channel systems being used for two-dimensional (2-D) seismic acquisition,[1] as well as the increasing number of three-dimensional (3-D) seismic surveys being shot.[2] In addition, recent developments in data processing have resulted in improved seismic resolution and data quality. These improvements are allowing more detailed geological interpretations from seismic sections, and the extraction of information concerning the stratigraphic relationships of the subsurface.

Stratigraphy

Seismic sections are said to show structure, but they really show the form of reflections. Reflection form relates directly to the results of tectonics (i.e., folding, faulting, diapirs, etc.) and to sedimentary processes (i.e., reefs, erosions, turbidites, thinning, thickening, etc.). Seismic reflections represent time or isochronous surfaces (e.g., bedding planes) and unconformities. Analysis of reflection form not only illuminates the tectonic framework onto which hydrocarbon migration and entrapment occur, but also allows insight into the sedimentary processes that determine the disposition of reservoir rocks, trap rocks and source rocks—seismic stratigraphy.

TABLE 1—Hydrocarbon associations in relation to sequence boundaries[3]

Geologic sequence	Source rocks
Downward migration of hydrocarbons into underlying reservoir below an unconformity	Onlapping units
Carbonate buildup of reservoirs	Transgressive phase of the sequence
Belts of interfingering facies	Basal onlap phase of the sequence
Basal sandstones and shelf carbonate reservoirs	Basal onlap phase of the sequence
Marine source rocks and reservoirs	Maximum onlap of the sequence

Further, new understanding of similar worldwide time-stratigraphic patterns is providing a framework within which to unravel stratigraphy with seismic. It is understood that sequence boundaries* are related to past systematic changes in sea level that affected each kratonic plate throughout the world. In fact, Visher has summarized how seismic stratigraphy can improve the chances of successful drilling, by predicting the distribution of hydrocarbons in relation to stratigraphic sequence boundaries (Table 1).[3]

Although it is hard to identify these hydrocarbon associations on seismic sections, the increased use of seismic stratigraphy this last decade is due to the increased difficulty of finding new oil fields. Fortunately, more information is being derived from seismic data, particularly due to new technological developments including improved CMP (Common Mid-point) methods, non-linear Vibroseis,† 3-D seismic techniques, improved processing, pre-stack migration, wavelet processing, seismic attribute measurements (e.g., velocity, amplitude, frequency, phase, and polarity), and improved displays.

A common theme among these new technologies is the positive impact new computer developments are having on their growth. Improved computer technology is affecting everything from non-linear Vibroseis control units, to super computers and big array processors for seismic processing improvements like pre-stack migration, to computer graphics systems for softcopy display and interactive interpretation. Many, in fact, believe the rapid advancement of seismic stratigraphy is closely tied to the advancement of computer technology.

Phase effects

The most important aspect of a seismic stratigraphic study is the ability to accurately define the geologic significance of a seismic feature. This requires that seismic data are compared with known geology, which is usually achieved through synthetic seismograms at well locations. Synthetic

* A seismic sequence is a depositional sequence identified on a seismic section by mapping the bounding unconformities. A seismic facies unit is sometimes substituted for a seismic sequence.

† Vibroseis is a trademark of Conoco, Inc.

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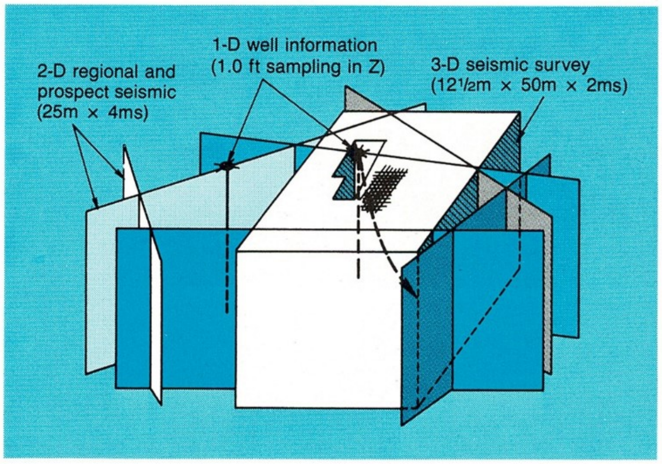

Fig. 1—Temporal (vertical) and spatial (horizontal) resolution parameters are critical factors for the seismic stratigrapher. Shown are typical spatial and temporal sampling intervals.

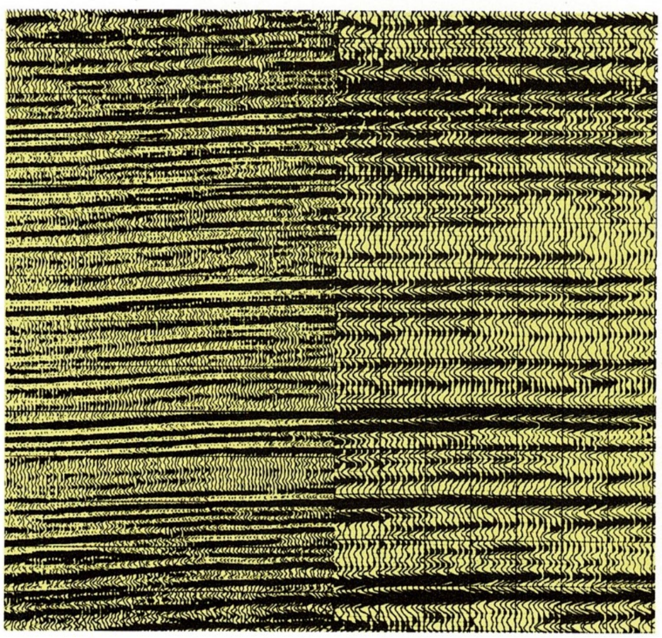

Fig. 2—Increasing signal-to-noise bandwidth improves resolution of a seismic sample. Illustrated is a comparison of a recent broad-bandwidth nonlinear Vibroseis section with a 1978 narrow-bandwidth linear Vibroseis display.[8] About 1.4 sec. of data are displayed from 1.1 to 2.5 sec.

seismograms are generated from well velocity and density logs, and usually assume a band-limited, zero-phase wavelet. It is in this last aspect that problems arise, since seismic data are rarely (if ever) zero phase.

This is because the phase of seismic data depends upon a variety of data collection and processing parameters, including source and receiver characteristics, recording instrument filters and deconvolution parameters, among others. In addition, various physical processes within the earth (e.g., absorption and transmission effects) alter the phase of the seismic pulse.

Shoenberger, however, has shown that zero-phase wavelets provide optimum resolution and timing accuracy.[4] As a result, most advanced seismic processing is aimed at collapsing the complex wavelet of the raw seismic data to zero-phase.[5] The success of these techniques is extremely data dependent, but for seismic stratigraphy a post-processing compensation is usually required to provide adequate ties to zero-phase synthetic seismograms. This compensation can take the form of a phase-shift filter, which adjusts the seismic data to give an optimum tie to the synthetic. The design of such filters involves a cross-correlation of the synthetic and seismic data, and the design of an appropriate cross-equalization filter. Although this filter can be used to apply a frequency-dependent phase-shift, a constant shift for all frequencies is usually preferable, since this is less liable to introduce spurious effects.

Where stratigraphic studies involve the use of data from several collection/processing vintages, this cross-equalization approach can be used to minimize character variations between vintages and optimize the character tie to synthetic seismograms. This allows greater confidence in interpretation of stratigraphic changes based on seismic character variation.

Resolution

Another critical factor in seismic stratigraphy is temporal and spatial resolution. Generally, an interpreter will start with one-dimensional information from a well and extrapolate out along a 2-D seismic line or through a 3-D seismic volume (Fig. 1). The closer the seismic traces are to each other, the easier it is to follow events and tie seismic reflection form to geology. Since most stratigraphy involves thin layers, the sampling must also be decreased in time to resolve seismic energy reflected from the top and bottom of a thin bed of interest.

Temporal (vertical) resolution refers to the frequency of the wavelets recorded on a seismic trace. The sampling theory tells us that there must be two samples per cycle for the highest frequency present. For a seismic trace sampled every 4 ms or 250 times per second, the Nyquist frequency is 125 Hz. Frequencies above the Nyquist frequency will alias as lower frequencies. The higher the frequency the thinner the beds that can be represented. This is why it is not uncommon for seismic to be collected with a sample rate of 2 ms or less.

As an example of temporal resolution, for a predominant frequency of 40 Hz, and a formation velocity of 3.5 km/sec, the limits of resolution are between 17 and 22 m.[6] At a 70 Hz dominant frequency the vertical resolution improves to between 8 and 12 m.

Spatial (lateral) resolution limitations (along the seismic line) are proportionally the same as temporal resolution limitations. Spatial frequency is known as wavenumber, and is the number of wave cycles per unit of distance in the direction of the receiver spread. The limits of spatial resolution as defined by the diameter of a Fresnel Zone,** which increases with depth. At a reflection time of 2 sec the depth would be between 2,466 and 3,244 m (average velocity between 2,466 and 3,244 m/sec and the formation velocity at 2

** Fresnel Zone is the area of reflection points (secondary sources as defined by Huygens Principle) within which constructive interference occurs providing the total observed reflection energy from a subsurface reflector. The diameter of this zone increases with depth.

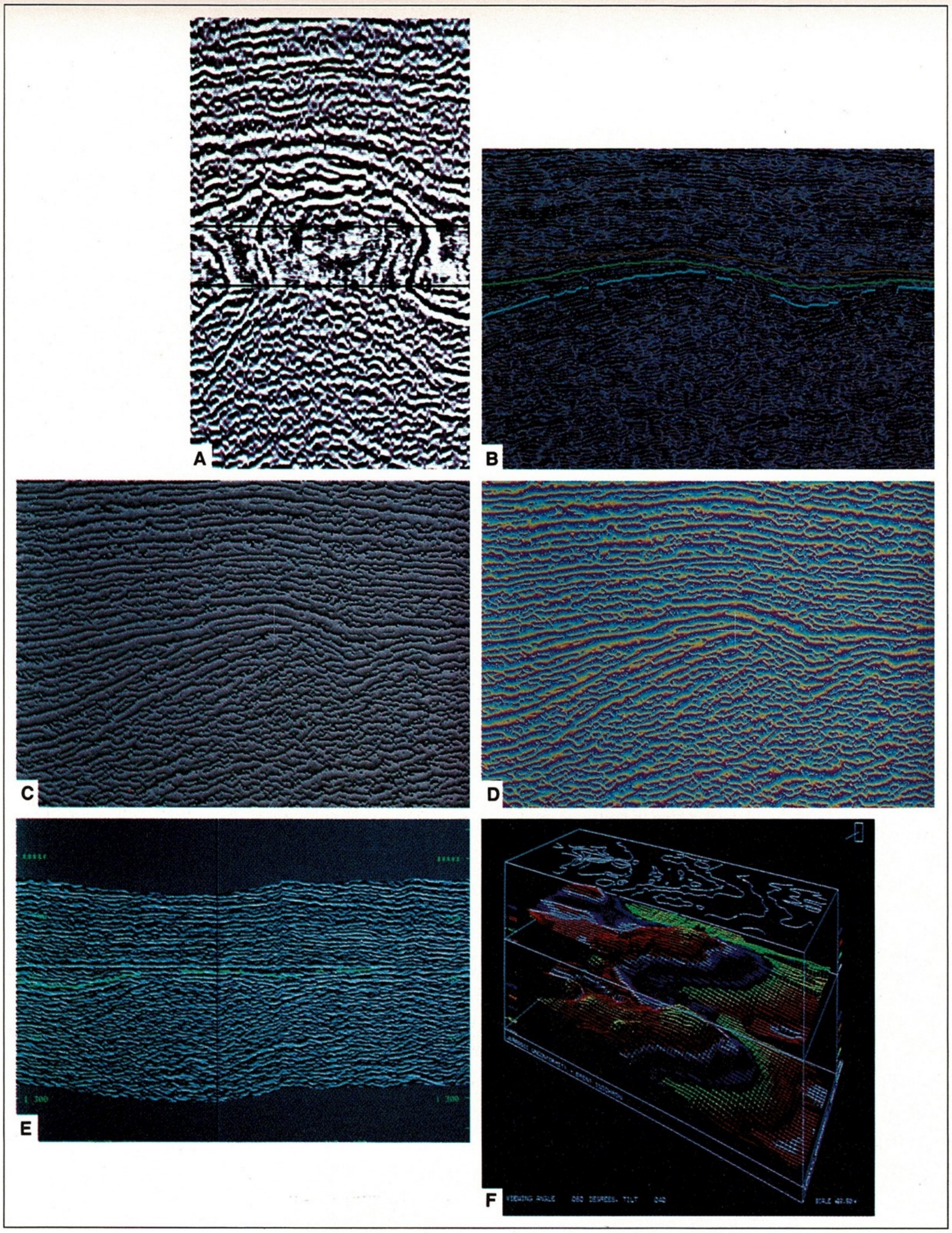

Fig. 3—Problem solving from a digital data base on an interactive graphics workstation allows an interpreter to apply many different techniques to the same data set. This sequence of six maneuvers illustrates this ability. (A) Softcopy display of time-slice and time-series data from a digital movie. The time-slice is in the center, with the connecting section on the bottom going down in time and the connecting section on the top going up in time. (B) Horizons overlain on a time-series seismic section. (C) Instantaneous phase display showing improved resolution of the location of different seismic sequence boundaries. (D) Softcopy color display of the instantaneous phase display shown in (C). (E) Flattening of a seismic horizon on a seismic sequence boundary to show paleogeology. (F) Perspective display of horizons picked at two seismic sequence boundaries, with an isochron contour showing thickening of the sequence.

seconds between 3,280 and 4,122 m/sec).[6] For a 40 Hz signal at this depth, the Fresnel Zone diameter would be between 318 and 410 m; while for a 70 Hz signal the diameter at this same depth would be between 240 and 310 m.

Acquisition. Resolution of seismic reflections is closely tied to acquisition. In an effort to improve spatial resolution, typical marine 3-D acquisition has gone from 50-m trace spacing and 100-m line spacing a few years ago, to 12.5-m trace spacing and 50-m line spacing today. Another important procedure is to increase the signal-to-noise bandwidth.[7] An example of this is the introduction of land acquisition techniques like nonlinear Vibroseis. Fig. 2 is a comparison of broadband, nonlinear Vibroseis and 1978 vintage narrowband, linear Vibroseis.

Softcopy evaluation

More efficient and thorough seismic stratigraphic analysis has been made possible through softcopy display and the use

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of interactive computer graphics systems.[9] Softcopy response time has improved dramatically in the last few years making it possible to look at much more data, in more detail, in the same amount of time. By problem solving from a digital data base using a computer graphics system, explorationists can apply many more variables in an effort to solve increasingly complex geologic problems (Fig. 3). For example, digital movies from a 3-D seismic survey allow interpreters to quickly overview prospects, see anomalous patterns unnoticeable on a single section, observe paleogeological changes when animating a sequence of parallel sections flattened on a critical horizon, study 3-D geological relationships, or find artifacts from inadequate processing by removing all motion of non-geologic origin.

Interactive processing also ties directly to seismic stratigraphic analysis. Animating digital seismic files allows juxtaposition of sections before and after processing, or with different processing parameters (like varying stacking velocities or filters).[10] In addition, digital sections can be zoomed by controlled pixel replication steps with graphics hardware, or smoothly zoomed using an interpolation scheme.

Color is one of the key enhancements softcopy interpretation provides. Color adds another dimension to the data, allowing enhancement of anomalies of specific interest. For example, color can be used as a function machine to filter the data, visually AGC (automatic gain control*) a section, provide a perception of texture with shadows, maximize dynamic range, or enhance detailed attribute analysis. In addition, color allows the superpositioning of data, such as overlaying a well log or synthetic on seismic. Areas of interest can be emphasized by modulating a color overlay or outline.

Scale. A perceived problem with softcopy or interactive stratigraphic analysis is the scale of the display. Seismic stratigraphers generally feel the need for large scale displays.[8,11] Computer graphics monitors are typically 19-in. diagonally, although there are 26-in. monitors available. The same scaling as large paper sections can be achieved by zooming in on anomalies of particular interest. To study relationships to other events on the section, the zoom scaling can be reversed. When a large paper section is needed, a computer graphics workstation can be interfaced to a color electrostatic plotter, as has been done at Hunting Geology and Geophysics in London. New developments promise softcopy projection display devices with the same or better resolution as a large electrostatic plotter.

Series topics

This article has introduced key concepts behind seismic stratigraphy including phase effects, resolution, and the expected effect of color softcopy interpretation on the science. The second article (to appear in the March issue) will review three of the four key approaches to interpreting stratigraphy from seismic, namely seismic facies analysis, seismic sequence analysis and reflection character analysis. The third article (April issue) will review advanced geophysical techniques including direct hydrocarbon indicators, shear waves and seismic modeling (the fourth key seismic stratigraphy approach).

* Gain—an increase or change in the reflection strength (amplitude) from one sample to another down a seismic trace. Automatic gain control adjusts the amplitude of the sample in a moving window proportionally to the highest and lowest amplitude in the window.

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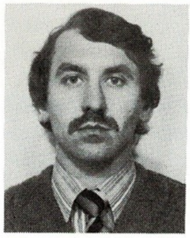

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