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Correlation data as an aid in fault interpretation: a case study

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Abstract: The prolific use of 3D seismic has only been a geophysical commonality since the mid 1980's. Since that time, 4D seismic (and beyond 4D), multi-component seismic, visualization, and other have emerged as the forebearers of future seismic interpretation state-of-the-art. However, while increased familiarity and improving economics are working to bring these successors to the forefront, there is still no shortage of new ideas for extending the range of uses for conventional 3D seismic data. One of these, of course, is the use of correlation, or coherency attributes.

While companies may have experimented with the technology earlier, correlation attributes really sprung to prominence within the geophysical community as recently as 1995 with compelling examples published in The Leading Edge. With its emergence as a viable, user-friendly tool, other similarly striking coherency examples have been quickly and ardently documented.

While 3D data clearly offers a significant advantage over 2D data for interpreting complicated fault patterns, correlation data goes at least one step beyond in terms of improved resolution or ease of detection. With great visual clarity, correlation slices demonstrate that faulting may be significantly more complicated, both in terms of number of faults and orientation, than previously interpreted from conventional 3D data.

Proponents of the technology point to the immediate interpretability offered by correlation time or vertical slices, as reason enough for generating correlation cubes on a routine basis. While conventional time slices often look like "wiggles" and can be dominated by the structural dip component, correlation slices bear a remarkable resemblance to "real geology", morphology, and sedimentary features are readily identifiable. Where an interpretation is fairly complete, horizon oriented correlation slices, too, can be very useful. Slices through shallow, relatively flat-lying, high frequency data often show valley, channel and levee features with clarity and beauty.

Multiple *en-echelon* faults, relay-ramps and cross-faulting producing compartmentalization are often immediately apparent on correlation data. The early identification of such features which may significantly impact field drainage patterns can affect important development decisions and economics. Correlation cubes are currently being used within SSB/SSPC and are proving to be a valuable part of the seismic interpretation portfolio. This paper documents some of SSB/SSPC's learning experiences with correlation data as a tool for assessing regional and local fault expressions and sedimentological features.

INTRODUCTION

While displays of fractals, chaotic behavior, and strange attractors have recently brought a refreshing measure of beauty and artistic form to mathematical-physics, correlation or coherency slices may be the current analogue for seismic-interpretation geophysicists. Geoscience journals now regularly document the utility and clarity of using correlation slices to expose subtle geologic features. Like Lorenz's second order equations and the Malthusian growth equation to "chaoticists" (or even the Zoeppritz equations to geophysicists), the mathematics of correlation or semblance are not particularly difficult and yet offer little compelling geometric insight at first glance. However, it is an evaluation of certain ranges of input data values that generates the very interesting correlation results. As pioneers with vibroseis data attest, it takes *seeing* the results of the correlation process on signal recognition to fully appreciate the power of the technique.

Whether the continuity attribute is the correlation or semblance coefficient, the mathematical expression of the equation to determine that attribute is of the form:

$$\Phi = \frac{\sum_{i\,=\,t-N/2}^{i\,=\,t+N/2} (A(i) * B(i+d))^{n}}{\sqrt{\sum_{i\,=\,t-N/2}^{i\,=\,t+N/2} (A(i)^{2} * B(i+dmax)^{2})}},$$

where: Φ is the normalized coefficient,
$*$ is the multiplication operator,

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A and B are traces to be compared,
i is the index of the summation over a time window of N samples, centered at time t, for dips between +/– d,
and n is equal to 1 or 2, depending on whether correlation or semblance is used.

The solution set of the equation is in the range of minus one to plus one, or zero to plus one.

While it is natural to interpret the "goodness-of-fit" of cross-correlation coefficients in terms of numbers very close to one, it is important to consider the factors which affect the value of the coefficient. The significance of the cross-correlation coefficient is a function of the product of both frequency band width and data window length. So, for long data windows and very broad bandwidth data, a correlation coefficient much less than one may hold statistical significance, and should not be merely interpreted outright as "noisy" or incoherent results. Similarly, for short data windows of narrow bandwidth, even the correlation of pure random noise can generate coefficients close to one, while not being representative of a truly good "data" or signal match. And in the limiting case, as the number of data samples in the window decreases to one, the value of the cross-correlation goes to the value of the data sample, or is normalized to a value equal to one. There is nothing substantive gained over conventional time slices, in terms of signal-to-noise improvement and resolution, by producing correlation slices using an excessively small time window. They simply show the domination of the dip component, just like the conventional time slices. Smaller data windows imply less computer processing time, but compared to other phases of seismic processing, the generation of correlation slices is not overly time consuming and care should be given to allow enough data into the analysis window so that the results are useful. For standard seismic data sets, with usable bandwidth out to about 70 Hz, experience indicates that about 60 to 80 ms of data are required for improved results over conventional time slices. The utility of continuity attributes is therefore predicated on a reasonable choice of data window length and properly processed (i.e., good signal-to-noise ratio, retaining broad bandwidth) seismic data.

The following time slices illustrate the impact of gate length and bandwidth on the quality of the resultant correlation slices. The conventional time slice (Fig. 1) shows the two large faults or drainage features clearly disrupting the dipping features, but not much clear geologic detail. A correlation slice for a very small window of data (8 ms) (Fig. 2), although clipped, is dominated by the dip overprint and resembles the conventional time slice to a large extent, highlighting primarily the changes from positive to negative sample values. No additional information about the nature of the two features is gained by generating such a slice. This display emphasizes the need for more appropriate length data windows to improve geologic resolution. On this figure and all other correlation slices shown in this paper, the dark blue color represents high, absolute correlation values while the red represents low correlation values.

A correlation slice using 60 ms of data and the same slice band passed back to the 20–40 Hz range, a correlation slice using 500 ms of data, and a correlation slice using 1,000 ms of data are also shown in order to assess the effects of varying processing parameters. From the 60 ms data window slice, which constitutes more than one cycle (Fig. 3), the two disruptive features are obviously identified as turbidite channels, rather than faults. The channel-levee and valley outlines are sharply defined. Meandering and possibly over-bank deposits are also recognizable. On the bandpassed data set (Fig. 4), which may represent either poorly processed or extremely deep data, the different between signal and noise has become less, and the channels' details are poorly defined. Yet, the meandering and over-bank deposits are not totally obscured.

The slice generated from 500 ms of data (Fig. 5) still plainly identifies the canyon features, because being turbiditic in origin and associated with on-going, later faulting, it does indeed affect hundreds of milliseconds of section. The canyon edges are badly smeared and resolution is poor. Evidence of meandering and over-bank deposits has been lost. The faults and "pock" marks are fewer and less crisply shown. That slice and the slice using 1,000 ms of data (Fig. 6), where the canyon feature is still recognized, but smeared even further, represent extreme parameter choices and illustrate that no real advantage is to be gained at the expense of all the additional processing time required to generate long-gate correlation slices. The correlation data therefore has its maximum impact when generated using good quality seismic, over an optimally chosen (and fortunately for processing time and cost considerations) small time window.

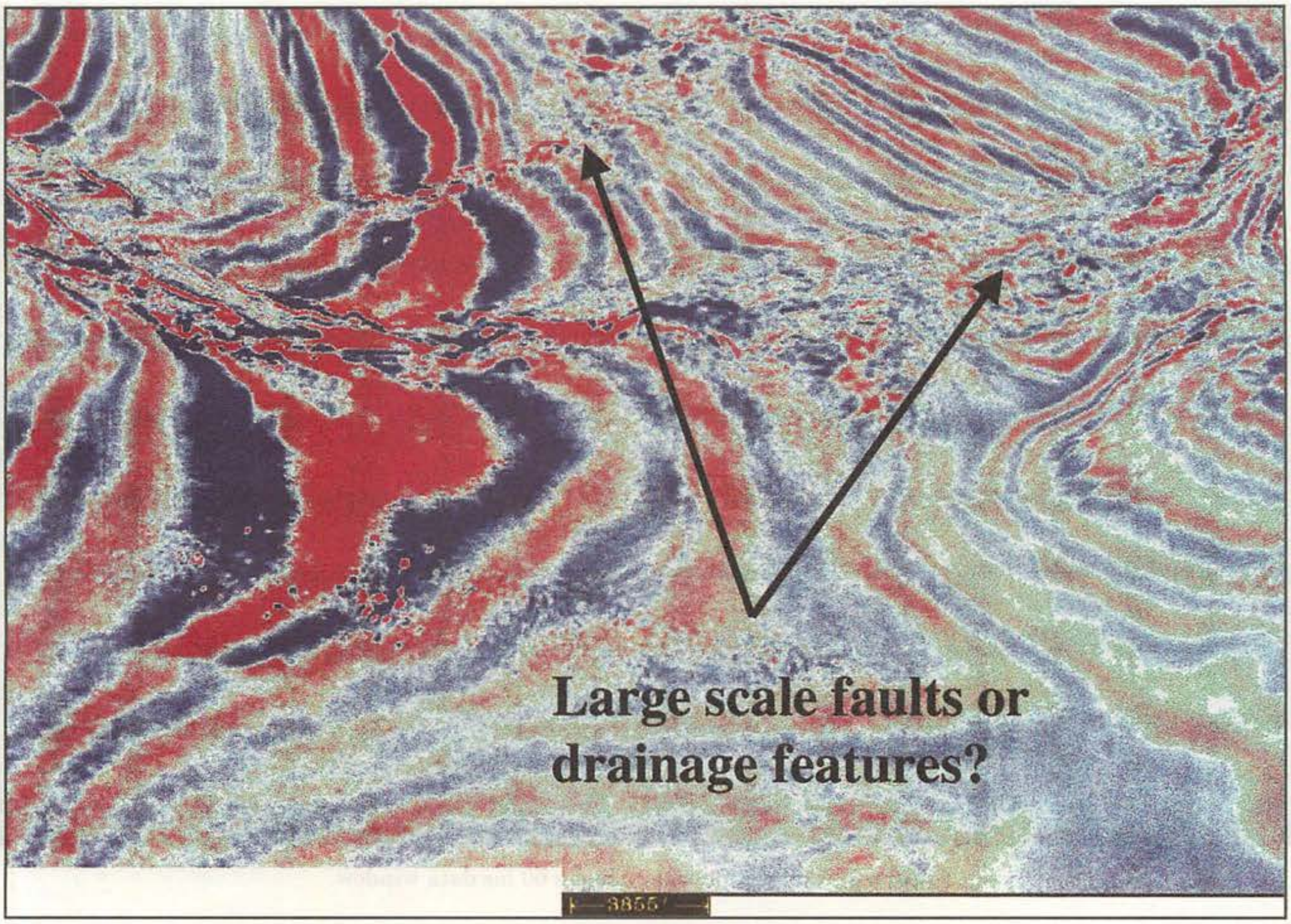

Figure 1. Conventional time slice.

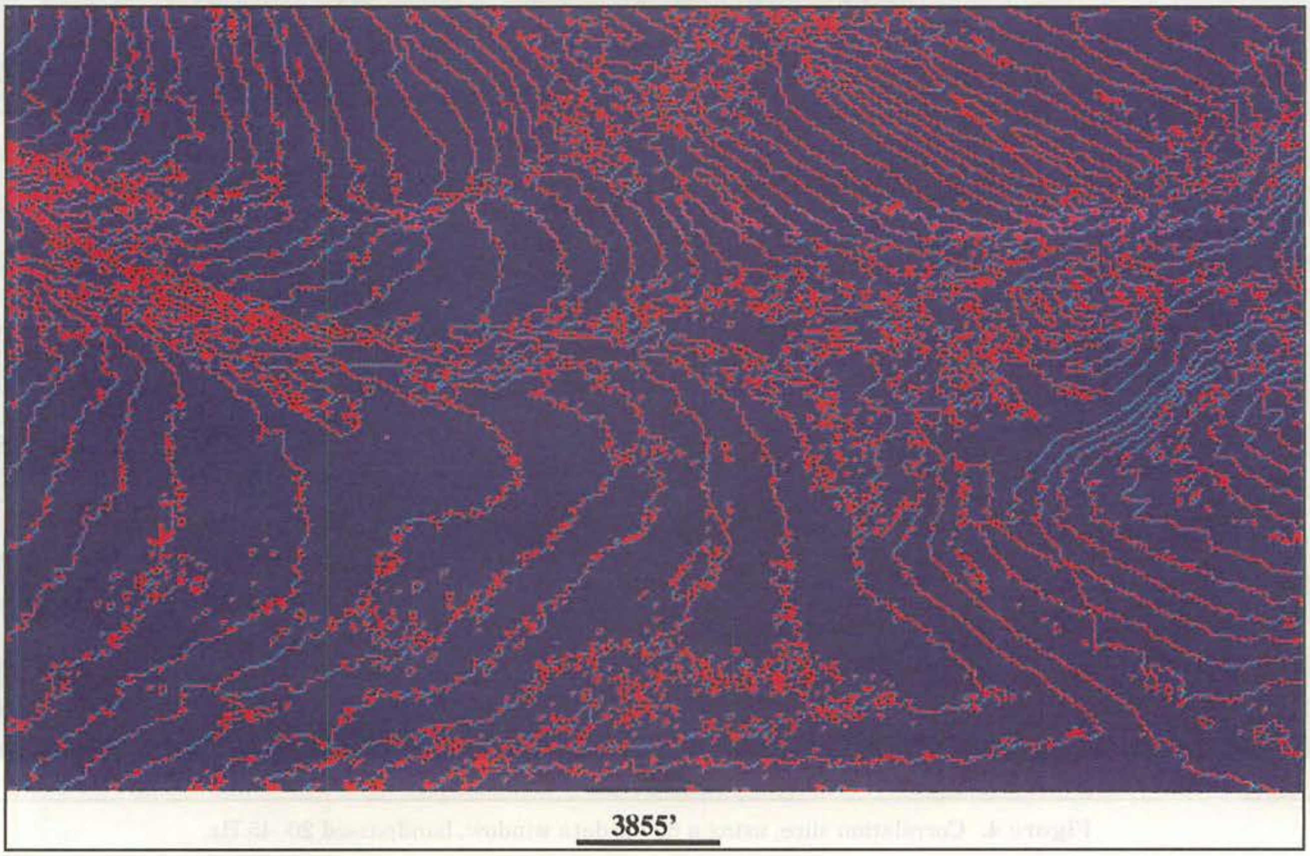

Figure 2. Correlation slice, using an 8 ms data window.

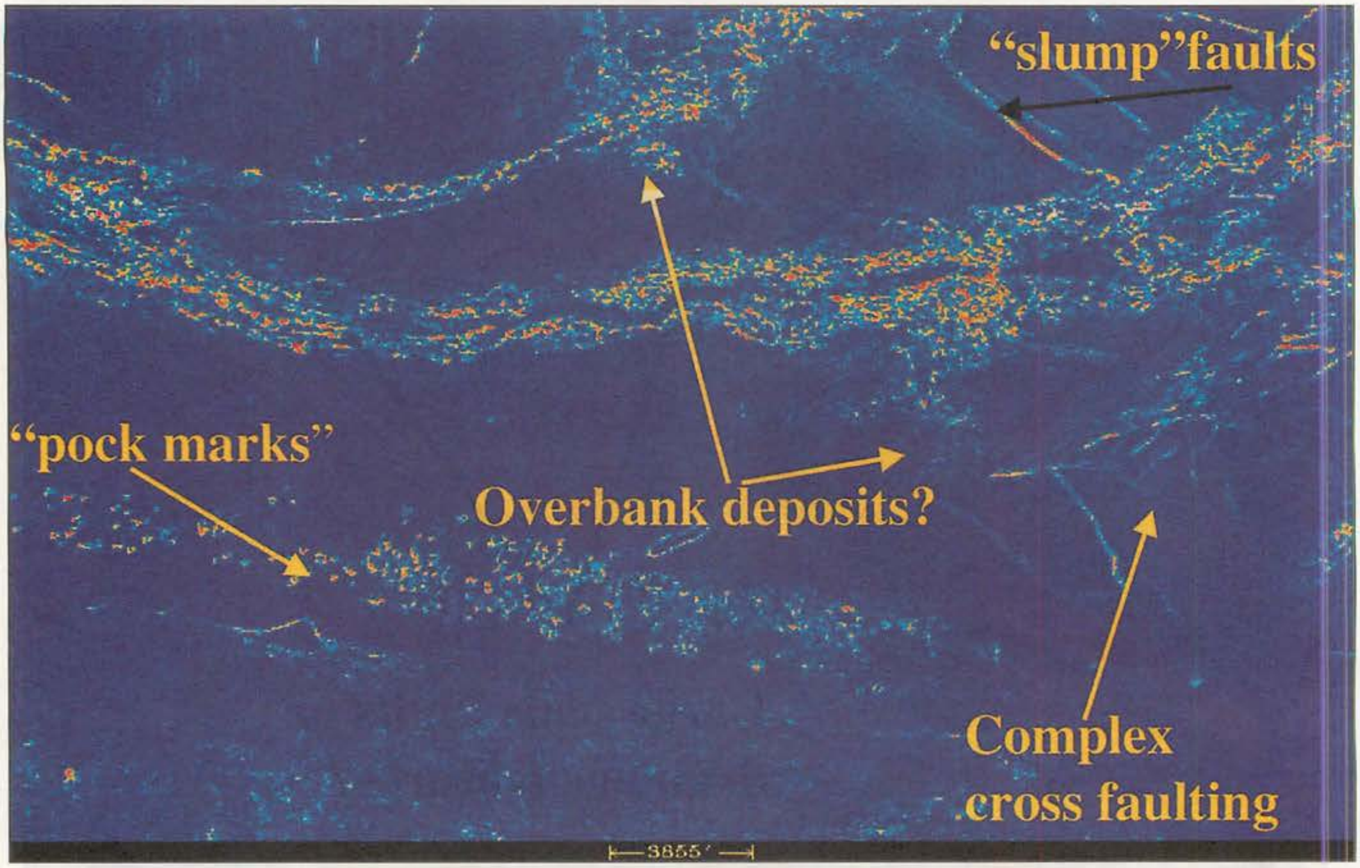

Figure 3. Correlation slice, using a 60 ms data window.

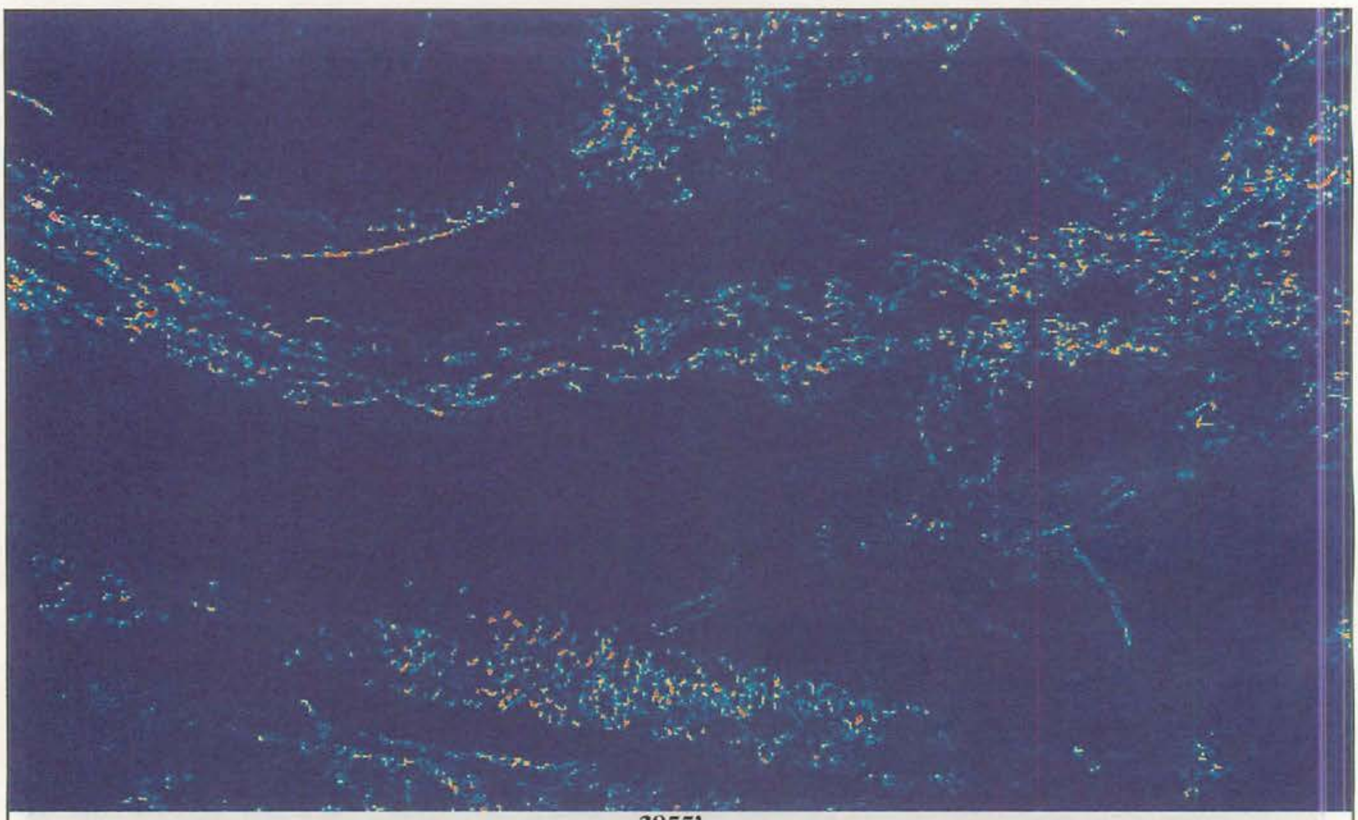

Figure 4. Correlation slice, using a 60 ms data window, bandpassed 20–45 Hz.

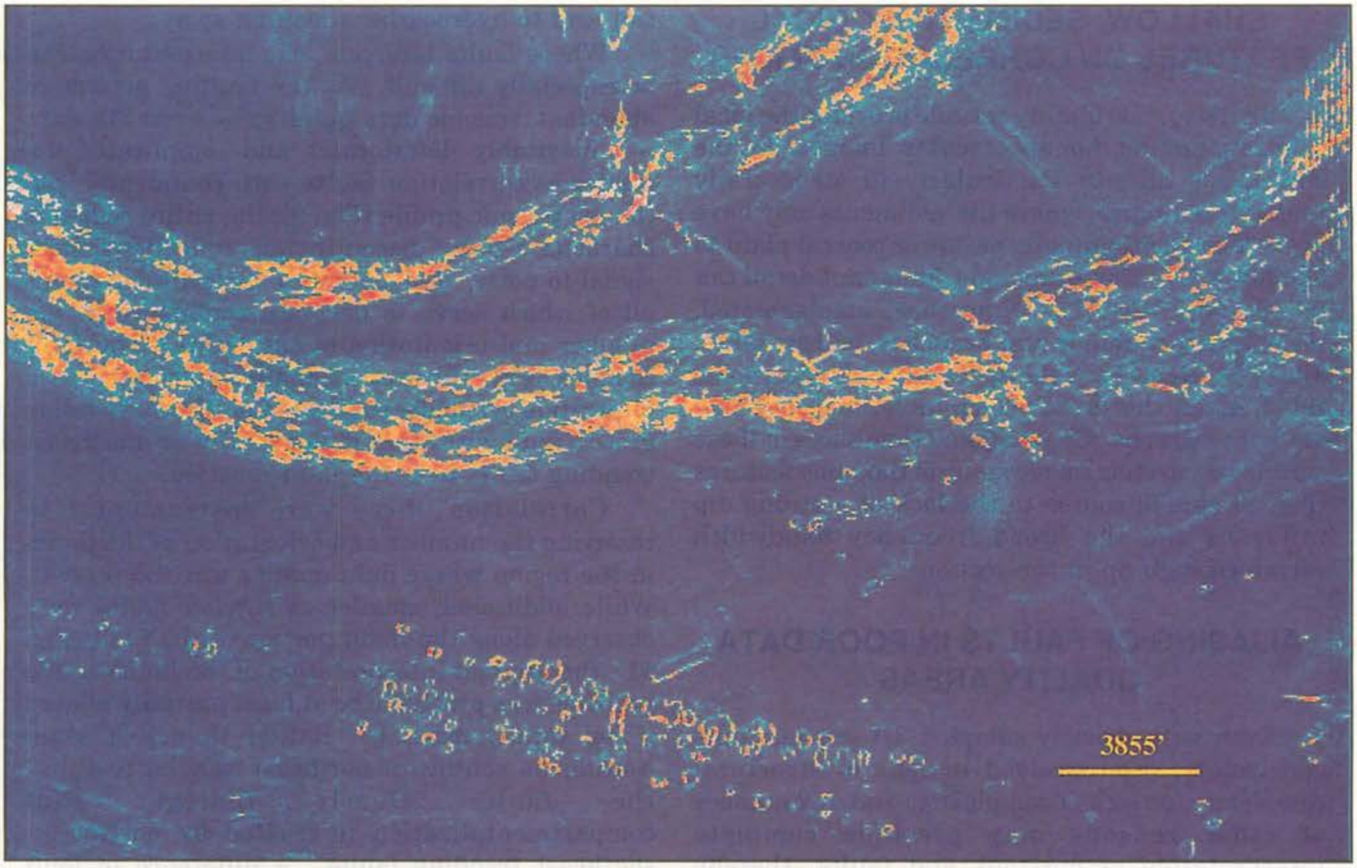

Figure 5. Correlation slice, using a 500 ms data window.

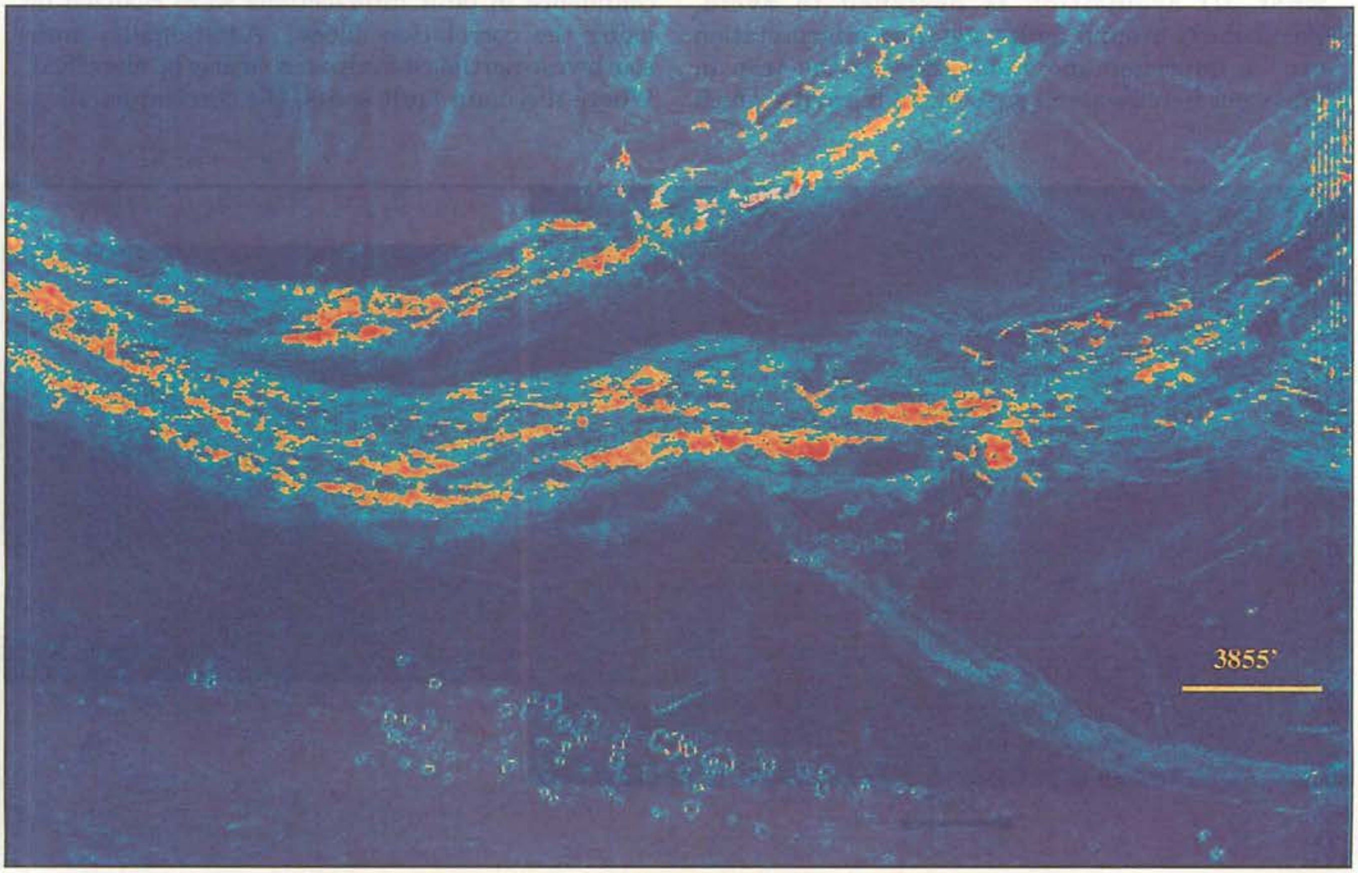

Figure 6. Correlation slice, using a 1,000 ms data window.

SHALLOW, SEDIMENTOLOGICAL FEATURES ON CORRELATION SLICES

Shallow, good quality seismic provides the ideal hunting ground for spectacular images on the correlation slices. Particularly in structurally undisturbed zones, where the sediments may have been deposited in quiescent, lower coastal plain to shallow marine environments, abundant detail can be observed (Fig. 7). Numerous, amalgamated, meandering channels and branches, ox bow lakes, and fan systems have the appearance of topographic relief, given the proper color table, and look like aero-photographs. Conventional time slices in these settings accurately image many of the same features (Fig. 8), due of course to the lack of a strong dip influence and the broad frequency bandwidth retrained high up in the section.

ALIASING OF FAULTS IN POOR DATA QUALITY AREAS

Even with densely sampled 3D seismic, time constraints, pre-conceived notions of structural complexity (or lack of complexity) and any number of other reasons may preclude complete interpretation of horizons and faults, thereby leading to aliased interpretations — precisely what 3D acquisition is designed to avoid. Particularly around faults, detailed interpretation can be important for understanding the trap in order not to miss small gaps or relay ramps which can lead to hydrocarbons leaking away.

Where faults bifurcate, the interpretation can be especially difficult. As the faulting gets more abundant, seismic data quality — even 3D data — inevitably deteriorates and complicates the matter of correlating faults with confidence. On the 3D seismic profile (Fig. 9), the entire region is characterized by discontinuous reflections, poor signal-to-noise, and potential ray-path problems all of which serve to decrease confidence in the number and orientation of the faults. The fault complex (Fig. 10) was originally interpreted as a bifurcation of a major southwest-northeast trending growth fault with other minor southwest-northeast trending faults near the fault junction.

Correlation slices were instrumental in resolving the number and orientation of the faults in the region where data quality was the poorest. While additional, smaller *en-echelon* faults were observed along the main portion of the fault (Fig. 11), the original interpretation of the faults in the problem area proved to be at least partially aliased if not totally missing. Rather than just semi-continuous, southwest-northeast trending features, the faults clearly indicate that compartmentalization is created by northwest-southeast trending faults. A difference in fault orientation of greater than 45 degrees and confidence in fault intersections were realized by using the correlation slices. Additionally, more southwest-northeast faults can clearly be identified. Where the main fault splits, the correlation slices

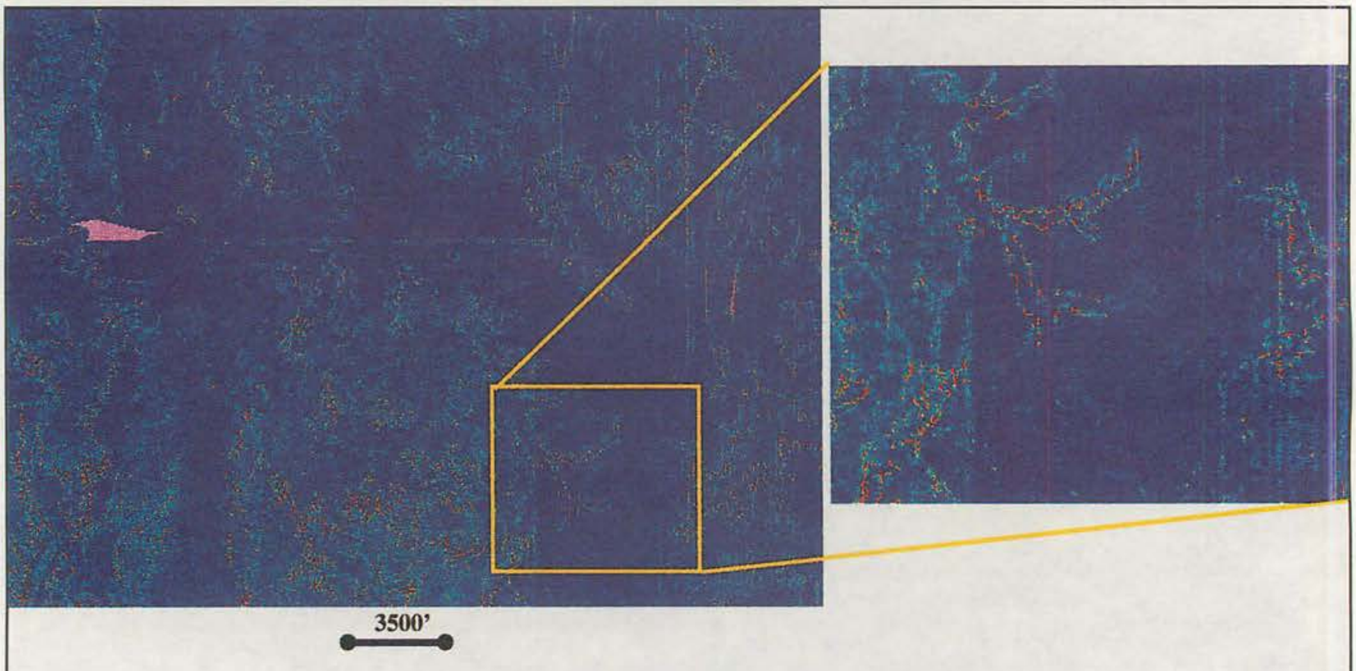

Figure 7. Shallow correlation slice, showing dendritic drainage patterns.

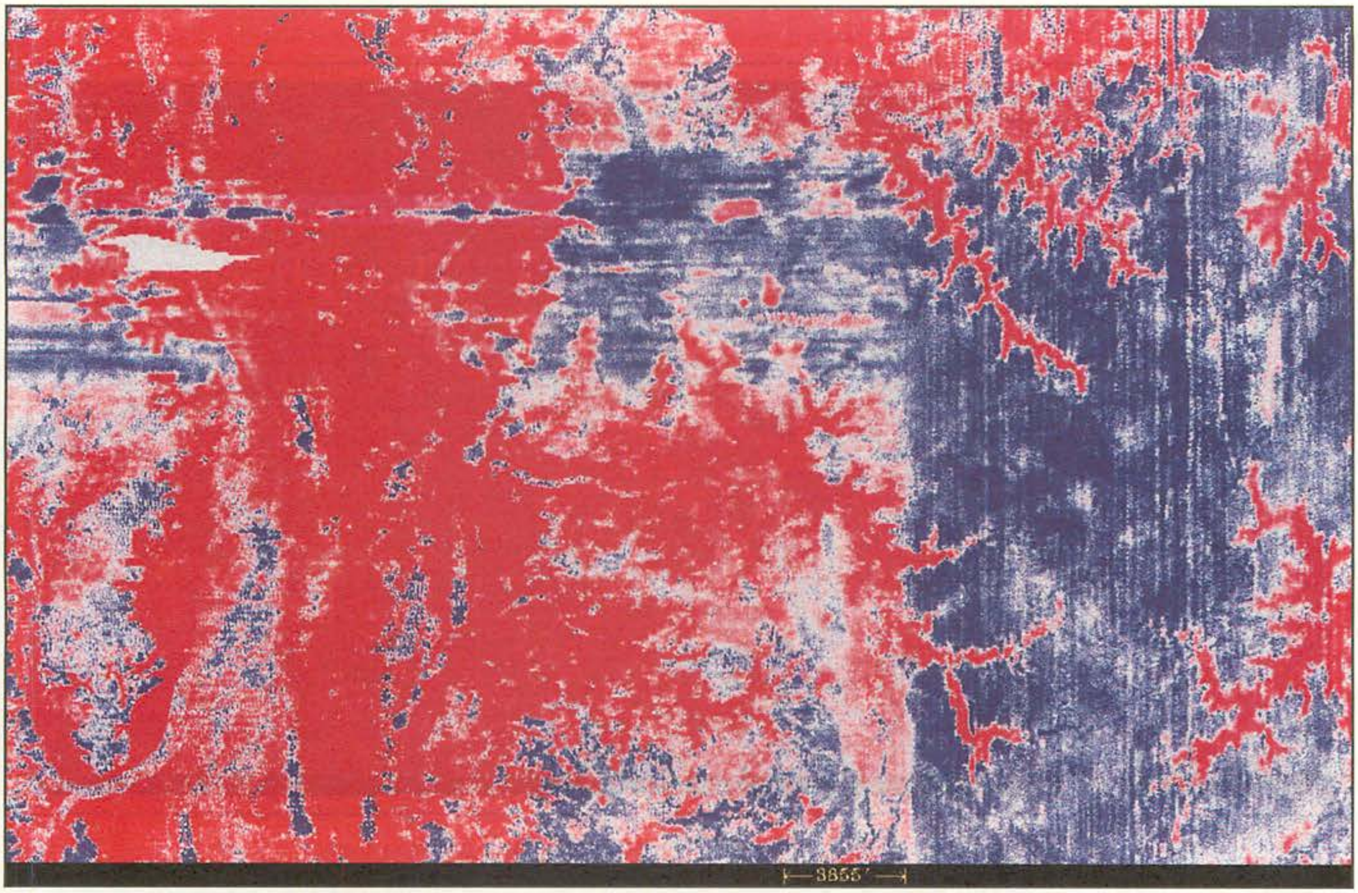

Figure 8. Shallow conventional time slice.

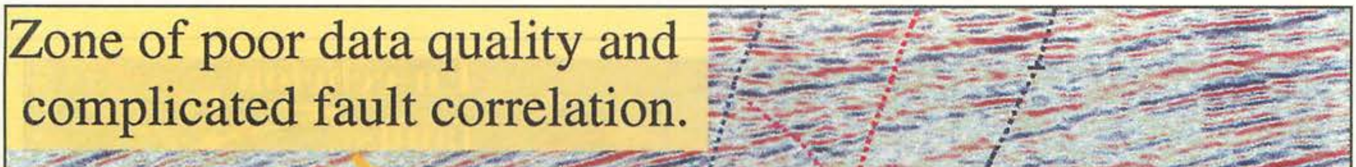

Figure 9. Arbitrary 3D seismic profile across a complex fault junction zone, showing data quality deterioration.

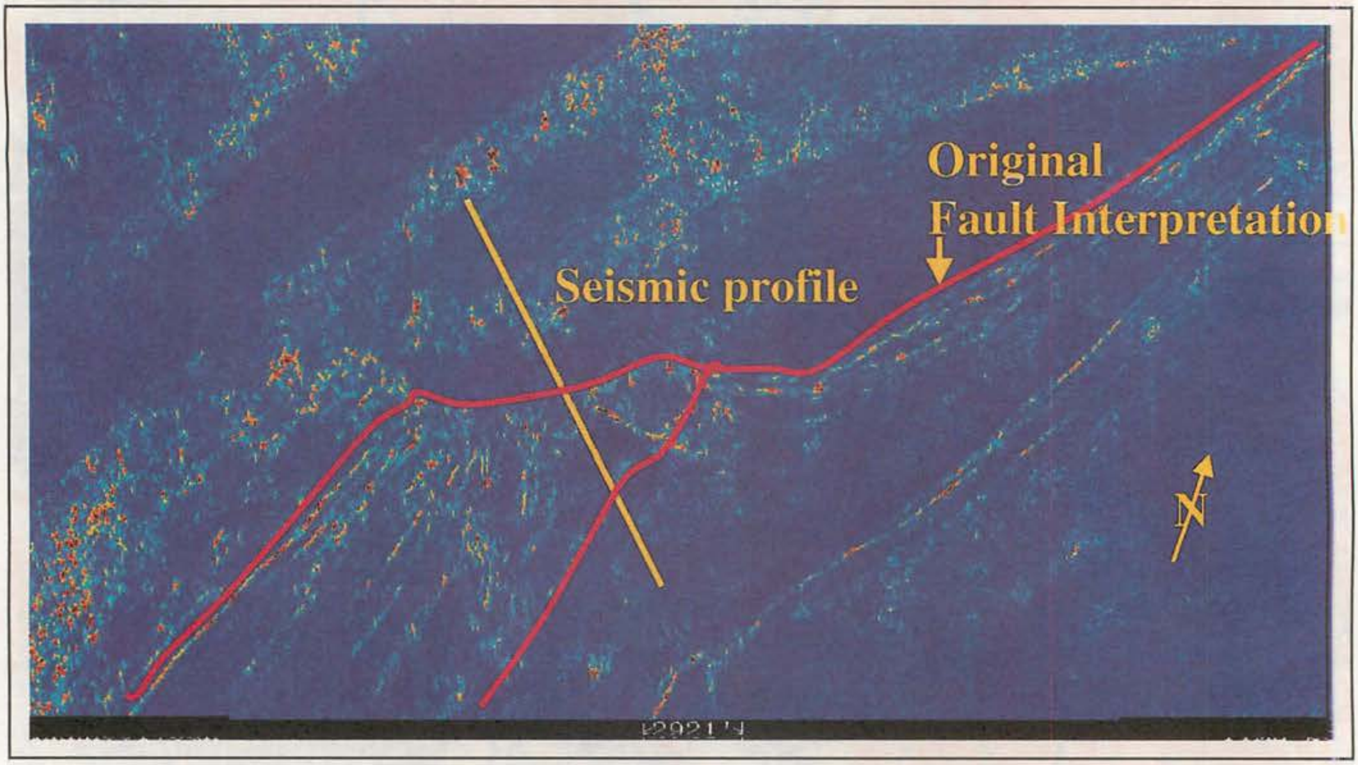

Figure 10. Correlation slice near a complex fault junction zone.

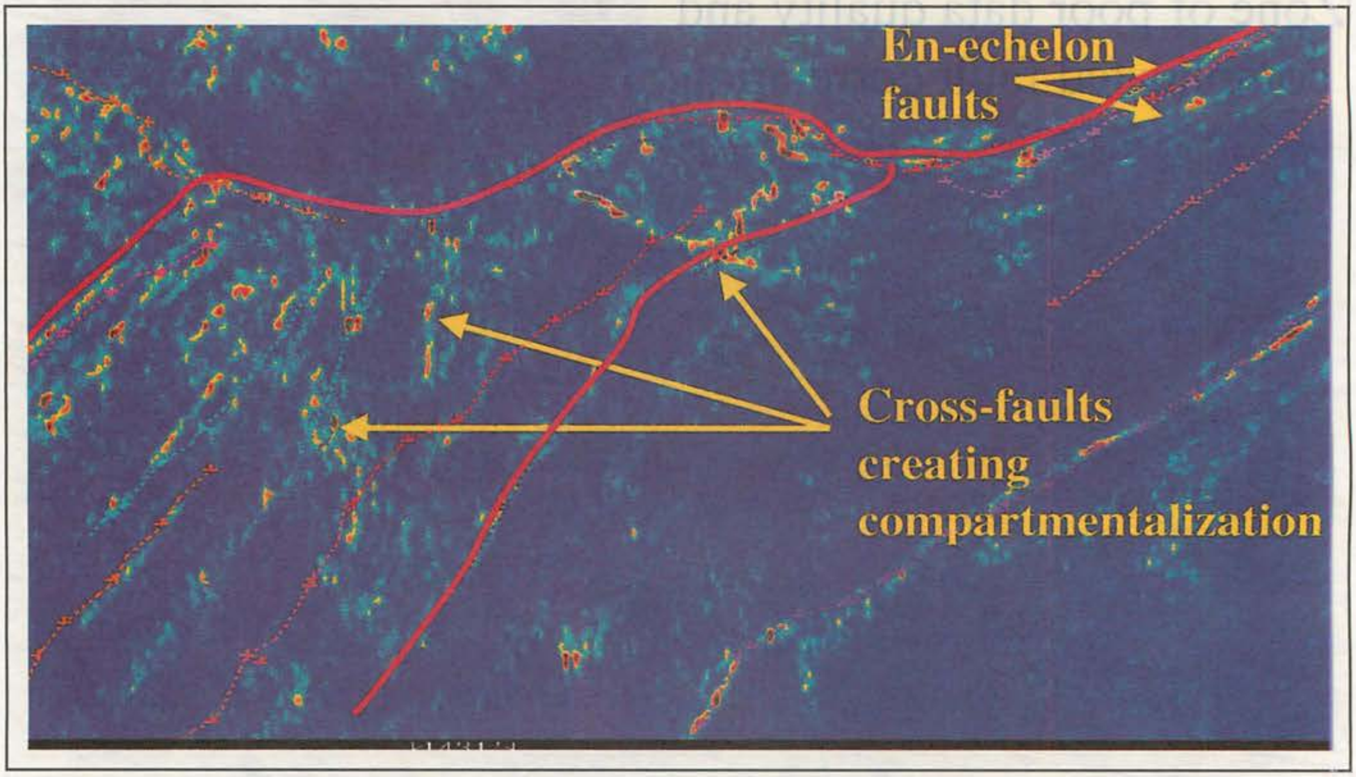

Figure 11. Area zoom around fault junction zone, showing complicated cross- and *en-echelon* faulting.

show that the transition is abrupt and offset at a high angle.

EXPRESSIONS OF TURBIDITE SYSTEMS ON CORRELATION SLICES

Seismic bandwidth reduction with increasing depth serves to decrease both the temporal and spatial resolvability of geologic features. These losses are attributed to a whole host of earth, acquisition and processing factors such as absorption, imaging, noise, statics, stretch, and residual NMO. The clarity of resolution of shallow dendritic drainage patterns, channel edges, meander belts, and ox-bow lakes is often strikingly apparent on correlation slices and make for illustrations with immediate visual impact (Fig. 7). Many of the subtle and detailed stratigraphic expressions easily identified shallow in the section on convention time slices or correlation slices, often go undetected deeper in the section — which is unfortunate given that most significant hydrocarbon accumulations are in the deeper section.

While small-scale channel or fault systems may not be easy to detect at depth, large scale channel and fan features associated with deep-water turbidite systems, whose areal extent is on the order of miles, are often readily identifiable on correlation slices. Complete valley and channel system outlines, over-bank deposits, basin floor fans, as well as longitudinal, medial bars, are clearly identified (Figs. 12 and 3). The extreme narrowness of some of the canyons cutting into the slope can clearly be seen. Even the lower correlation values in the chaotic, upper portion of the huge, basin-floor fan compared to the lower fan region may be indicative of differences in sand and shale distributions within the lobe. Shelf edge slumping, where the dip expression is usually very strong on conventional time slices, is often easy to discriminate from faulting on the correlation slices. Sea-bottom "pock-marks" on local, structurally high features may indicate something about fluid migration along fault planes, seal integrity, or overpressured, shale-cored anticlines.

REGIONAL STRUCTURAL STYLE IDENTIFICATION ON CORRELATION SLICES

A large amount of information concerning regional structural style and prospect targeting can be derived using correlation cubes early in the exploration process, before any interpretation is done. Although similar information can be gleaned from dip and azimuth maps, these however presuppose a significant amount of prior event interpretation, presumably based at least in part upon a preconceived structural model.

The following slide (Fig. 13) illustrates the large scale, extremely linear expressions of several thrust fronts, and their abrupt, almost ninety degree junctions with smaller, offsetting faults. The lack of coherency within the thrust zone attests to the complexity of the thrust, and not necessarily overall data quality. Potentially hydrocarbon bearing structures in front of the thrusts, and the complexity of crosscutting faults which may compartmentalize the accumulations are easy to identify. A swarm of fault outlines characterized the region dividing major synclines. The geometry of impressive turbidites shed from these highs (Fig. 14) out into the basin is unmistakable and helps to explain anomalous amplitudes in the synclines which may be more indicative of lithologic make-up, i.e., sand or soft silt presence, rather than hydrocarbon content.

CONCLUSIONS

Correlation slices are a simple and natural extension of the conventional time slice technology. They can serve as a relatively inexpensive and potentially very powerful additional to the standard seismic interpretation tool kit. Correlation slices offer many of the same benefits (and sometimes more) to structural interpretation as dip and azimuth maps without the added overhead of prior event interpretation. Early identification of subtle structural or sedimentological features, sometimes exposed on correlation slices, around hydrocarbon accumulations can help to reduce risk in assessing prospect or development plans.

The correlation of complicated fault systems in areas where vertical sections are ambiguous can be improved through the use of correlation slices. Large, regional, structural elements and hydrocarbon prospects can be scoped early in the interpretation exercise and direct immediate attention to priority areas. Added resolution and/or event recognition are realized through the apparent high frequency enhancement of correlation slices compared to conventional time slices.

The use of relatively small data windows and well processed seismic are vital factors affecting the utility of correlation slices. Conventional time slices are extremely useful in good quality seismic data areas, unaffected by significant dip overprinting. While shallow sedimentological

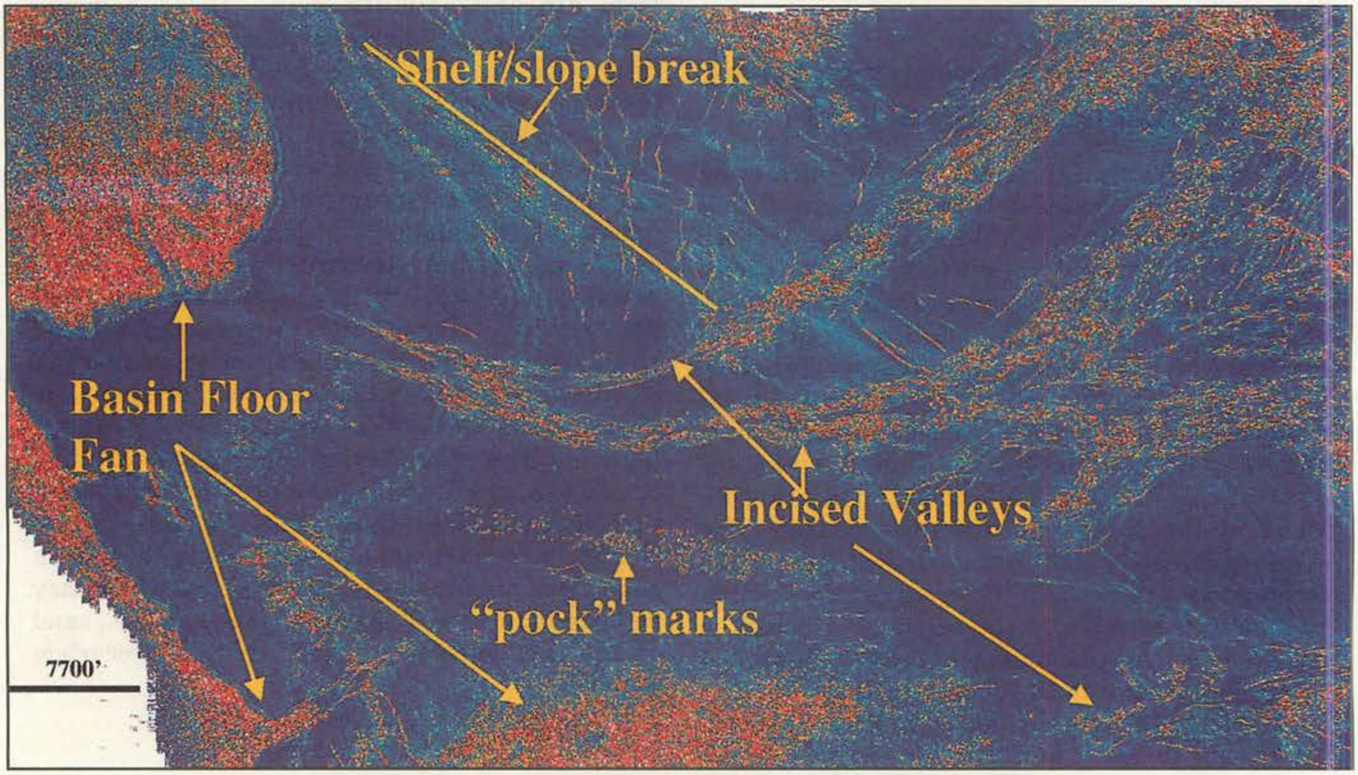

Figure 12. Large scale turbidite expressions on a correlation slice.

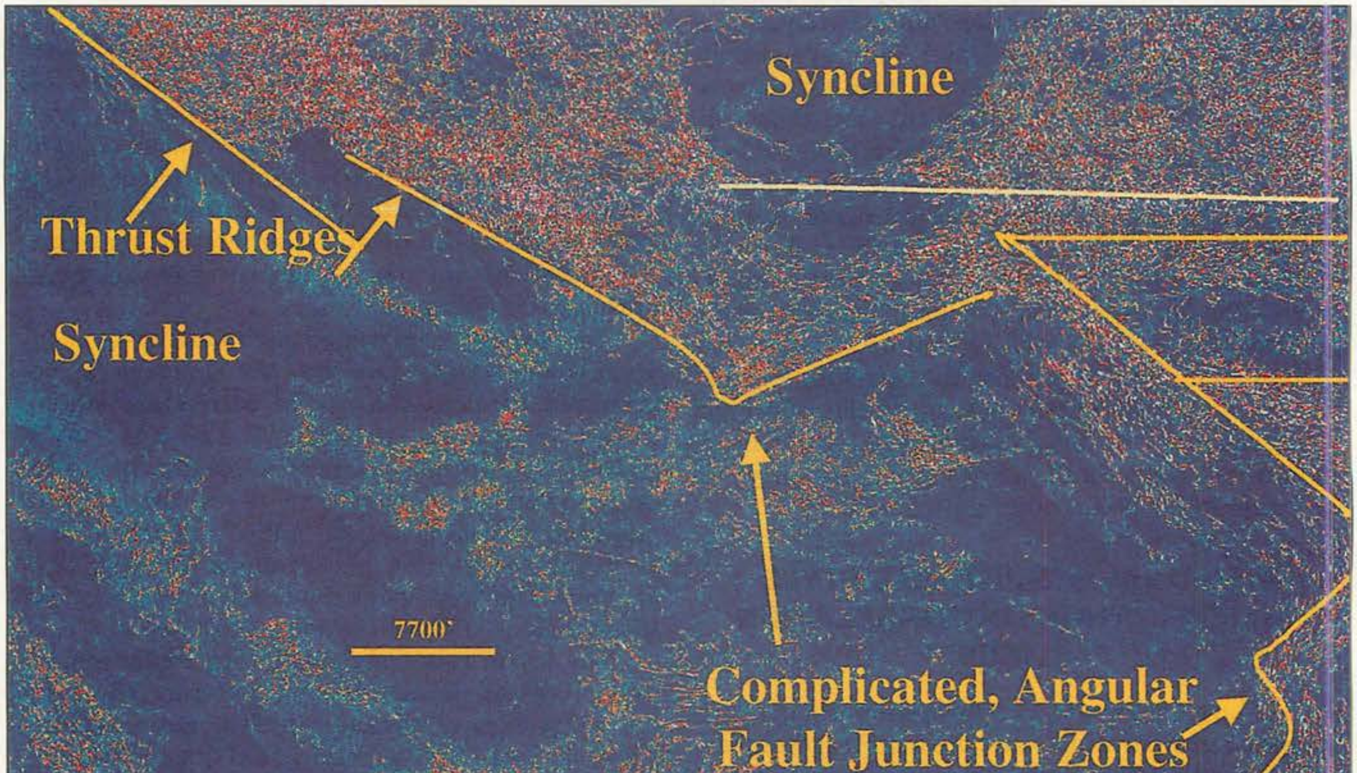

Figure 13. Regional structural expression of thrust fronts.

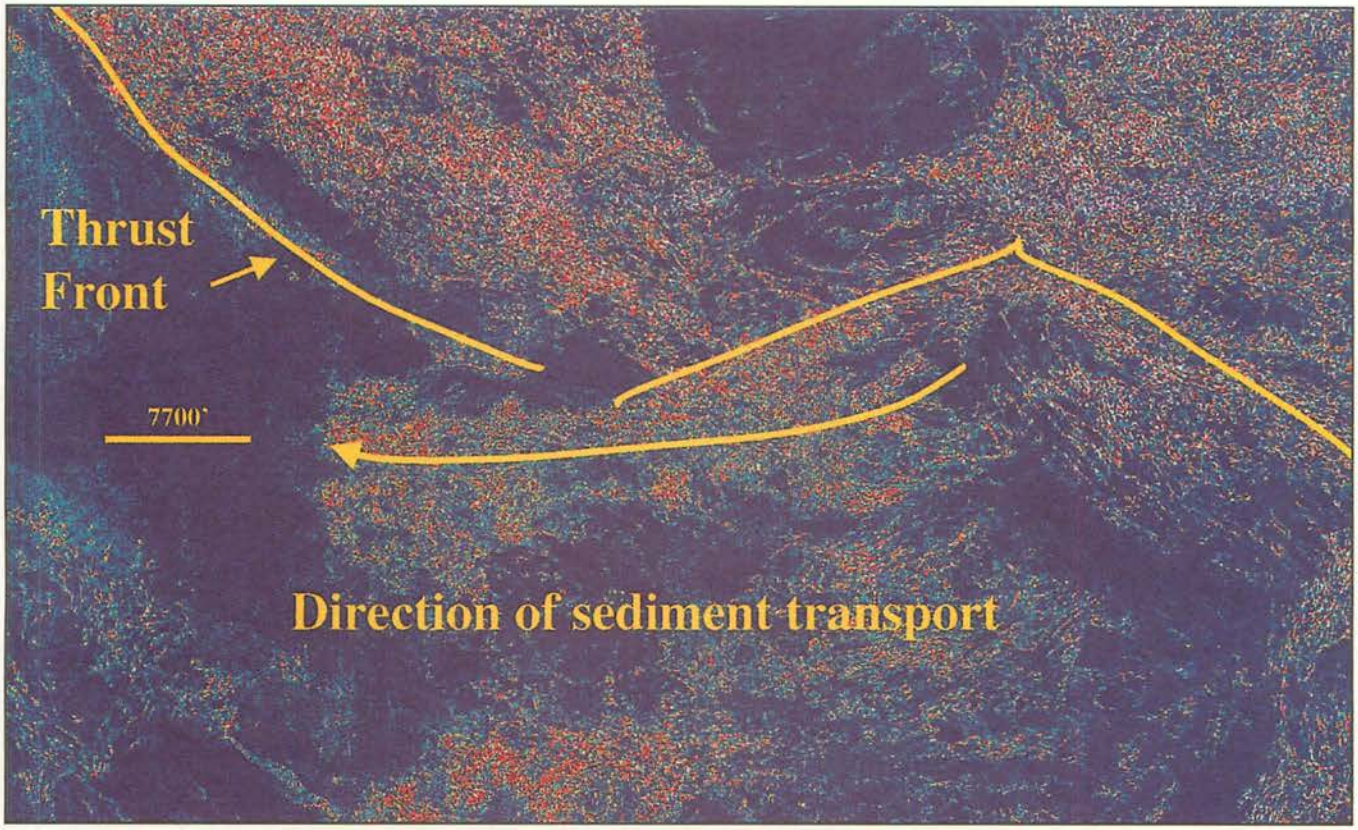

Figure 14. Turbiditic sediments shed from highs along the front of fault zones.

features are often brilliantly portrayed on correlation slices, improved resolution at depth is key to most explorationists. Therefore, seismic processing must be focused on maintaining bandwidth and lateral and temporal resolution in order for correlation slices to have maximum impact on evaluating deeper hydrocarbon prospects, structural or stratigraphic elements.

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