Seismic attributes and the road ahead

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Summary

Seismic attributes were introduced to seismic interpretation four decades ago and now form a part of almost every seismic interpretation workflow. I predict of future of increasing interactive computer-interpreter linkage into areas that we now consider to be seismic processing. I also predict an increase in the use of cluster analysis and statistical correlation to completion processes and production data in resource plays.

Introduction

Seismic attributes were first introduced to the geophysical community almost 43 years ago when Balch (1971) proposed co-rendering three different bandpass-filtered versions of the seismic data (what we would call today "spectral components") against red, green and blue (Figure 1). Subsequent developments by Taner et al. (1979) of instantaneous attributes generated initial excitement, but seismic attributes didn't come into common usage until the advent of 3D interpretation workstations when Bahorich and van Bemmel (1994) showed that one could make maps of these attributes along interpreter-generated surfaces. The introduction and adoption of 3D seismic data was followed by the development of 3D "geometric attributes" such as dip-azimuth (Rijks and Jauffred, 1991), coherence (Bahorich and Farmer, 1995), and curvature (Roberts, 2001) such that in 2014 "attributes" - be they simple RMS maps or sophisticated waveform classifications - have become an integral part of almost all interpretation workflows.

I divide the future of attribute development into five categories – feature recognition, prestack attribute development, multiattribute cluster analysis, enhanced interpreter-computer interaction, and the statistical correlation of attributes to completion techniques and reservoir production.

A Prediction of Future Developments

Feature recognition

Attributes are integral to seismic interpretation. Much of interpretation is based on the identification of temporal and spatial variations in the seismic data. Early features such as bright spots were often mapped as envelope, RMS, or maximum trough in a window maps. Faults and channels were some of the first features seen in coherence and spectral decomposition volumes, while folds and flexures were the first features seen on curvature volumes. The recognition of other features took a little more time. Hoever, in 2014 the attribute expression of features such as karst, injectites, mass transport complexes, turbidites, sand waves, shale "dewatering", erosional unconformities, carbonate reefs, coal seam cleats, and differential compaction is fairly well documented. Attribute artifacts caused by acquisition footprint, fault shadows, migration swings, and missing data are also reasonably well documented, though they still provide a waiting pitfall for the intrepid interpreter.

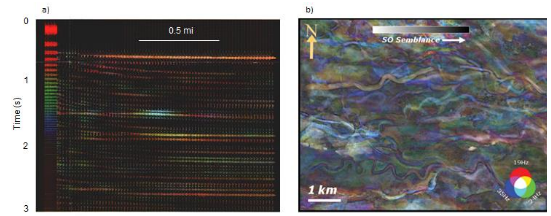

Figure 1. (a) One of the first seismic attribute displays – Balch's (1971) color sonogram displayed as three band pass filtered versions of the stacked data plotted against RGB. (b) Balch's work as implemented in modern commercial software showing a time slice through three spectral components (McArdle et al., 2014).

The subsurface is a complicated world and considerable work still needs to be done. Bueno et al. (2014) discuss the attribute expression of architectural elements of a carbonate terrain, using the Bahamas as a modern analogue. Others are generating depositional patterns using colored sand in flume tanks (e.g. videos produced by Heller and colleagues at the University of Wyoming) and linking structural deformation patterns to fractures by deforming clay models (e.g. Liao et al., 2013). The attribute expression of fractured basement, igneous extrusives and intrusives, hydrothermally altered dolomite, diagenetically altered chert, and paleo glide blocks, is not yet adequately documented. In short there is a host of "funny-looking things" in 3D seismic volumes that we do not yet understand. We see them on amplitude and can quantify their morphology and frequency response using attributes, but we still do not yet know what they are and how they impact our interpretation.

Prestack algorithm development

Prestack attributes have also been around for a long time. Interval velocities derived from moveout or migration

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analysis is obviously a prestack attribute, as are AVO slope and intercept. Although we normally think of P- and S-impedance as geomechanical properties, they obviously can be used much like any other attribute, and if the assumptions of wavelet and background velocity model are less than ideal, can have the same "softness" as the more easy-to-generate attributes.

Estimates of anisotropy needed for prestack imaging can also be used in interpretation. Fractured shales at their simplest exhibit orthotropic, and in general triclinic symmetry. Seismic imagers need a low frequency, smooth model that represents the entire subsurface volume to be imaged, while seismic interpreters are looking for a more detailed estimate on or about their target reservoir. These problems are coupled, and I suspect that they will be driven by the seismic imaging vs. seismic interpretation community.

Kozlov et al.'s (2004) provided one of the earliest studies in what is now called diffraction imaging. Coherence, Sobel filters and other "edge detection" attributes map discontinuities in the seismic data. Diffraction imaging in its simplest form, involves imaging and then somehow removing all specular reflections from the data, leaving diffractions and noise. These diffractions are typically weaker than the specular reflections, but are key to imaging fractures and stratigraphic edges that are otherwise buried in the specular signal. I categorize this technology, still in its early stages, as an "attribute" since seismic interpreters will integrate these images with other less computational intensive attributes.

Anyone who has held a DVD in the light has seen the rainbow of backscattered colors (Gao, 2012). This suggests that prestack spectral analysis (frequency vs. angle) can be a measure of rugosity. Trumbo and Rich (2013) found that frequency vs. azimuth is a simple but accurate measure of azimuthal anisotropy. In her distinguished lecture Lynn (2004) hypothesized that one can estimate open fractures by measuring Q (1/attenuation) as a function of azimuth. Geophysicists have been estimating Q for at least 35 years, usually based on a simple constant $Q(f)=Q_0$ model. This simple model might work on the near-angle stack; applications to the full-angle stack often generate unphysical negative Q values. Q from naturally and hydraulically fractured rock will be quite complicated. Applications of spectral ratio Q estimation to a hydraulically fractured survey provide negative Q models, which indicate that we need a better model (Figure 2). Laboratory rock physics efforts will continue at their own pace. In the meantime, we interpreters need more robust measures of attenuation that represent both scattering and absorption.

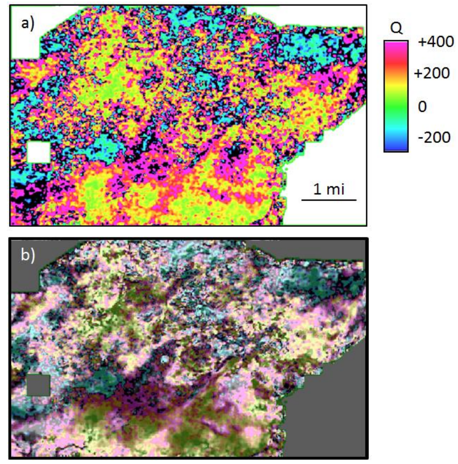

Figure 2. (a) An estimate of Q across a the Lower Barnett Shale after hydraulic fracturing by over 400 wells. Note the inaccurate negative Q estimates in blue. (b) The overlay with confidence of the spectral ratio fit shows a poor fit in many areas (dark colors) suggesting the constant Q attenuation model is inappropriate. (Image courtesy of Fangyu Li, OU).

Multiattribute cluster analysis

After 43 years of attribute development, it should not be surprising that many of these attributes are redundant, and some are even useless (Barnes, 2007). Multiattribute analysis is part of everyday interpretation, where the human beings manipulate Venn diagrams in their head (structurally high, continuous, low frequency, negative amplitude => gas sand?). Phrases like "big data", "data mining", "pattern recognition", and "trend analysis", are familiar to all who shop on the internet or use a merchant's loyalty card. Clustering falls into two general categories – unsupervised (let the data find its own "natural" clusters) and unsupervised (ask the data to find clusters similar to those that I provide it). Neural networks is currently the most well established supervised clustering algorithm, with the less commonly used support vector machine algorithms also showing promise. Self-organizing maps is currently the most well established unsupervised clustering algorithm, with generative topographic mapping being a more recent improvement (Wallet et al., 2009). At the end of the day, the resulting cluster can be envisioned as a linear or nonlinear combination of input attributes, what some call a "meta-attribute". Meta-attributes need not be mysterious. The recently popular sweetness attribute is simply the ratio of the envelope over the square root of the instantaneous frequency, and happens to be quite effective in

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differentiating sand-filled channels from a surrounding sand matrix in Tertiary basins.

One of the advances in cluster analysis that needs to be made is to better link a mathematical cluster (say from PCA, SOM, SVM, GTM, or ANN) to the original seismic amplitude. This link is made in the forward direction by the ANN community, but the backwards link has been limited to color overlays. Figure 3 shows a preliminary example whereby the opacity applied to the seismic data is associated with the user-defined polygon in the cluster latent space.

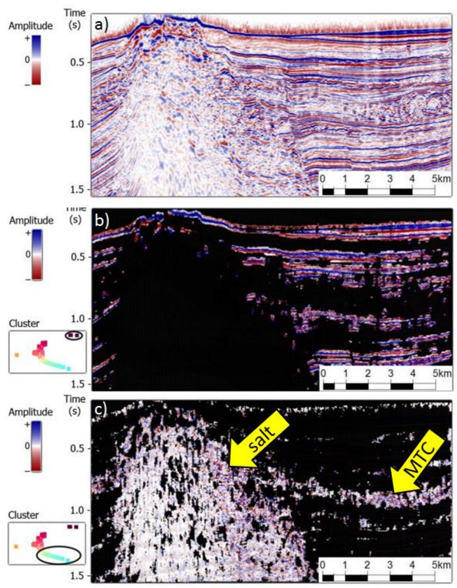

Figure 3. Visualization of seismic amplitude patterns associated with a given cluster. (a) Original seismic amplitude. Seismic amplitude corresponding to (b) the violet clusters associated with strong, coherent reflectors and (c) blue-green clusters associated with chaotic salt and mass transport complexes. (Figure courtesy of Thang Ha, OU).

I predict that cluster analysis will grow more rapidly than any of the five attribute technologies described here. Advances will be pushed by ever more focused and compartmentalized marketing strategies (with targeted television ads based on your recent DVR television recording history), and of course the search for "bad guys" be they drug dealers or terrorists. I also predict cluster analysis to be enabled by the next area of progress (interpreter-computer interaction), and driven by the last one (statistical analysis of resource plays).

Improved interpreter-computer interaction

The choices in attribute selection and attribute parameter selection are approaching the level of those used in conventional seismic processing. To paraphrase a comment made recently by an oil company practitioner "the choices in a certain kind of attributes is reminiscent of the dozens of choices offered in deconvolution in 30 years ago. We need a way to rapidly view alternative attributes and the effect of alternative parameters on maps." Until recently, most volumetric attributes were (obviously) run on volumes. However, if one wants to evaluate alternative parameters (say, the size of a coherence analysis window) one quickly accumulates five to ten 20 Gbyte volumes. At least one software vendor has directly addressed this issue in commercially available software. If the user wishes to evaluate the appearance of a given vertical inline, vertical crossline, or horizon slice, the software is intelligent enough to read in just those seismic data bricks needed to compute the desired view. In this manner, the interpreter calculates and examines a suite of five to ten slices, not volumes. If the slices or parameters are changed, the appropriate calculations for the new view are performed and the results are displayed. Once the desired parameters are found, the entire volume can then be computed by another click of a button.

Limiting the computation and output to the displayed slices requires programming, but it is not an overly difficult task. Computing output (say 50 spectral components) along a map (or along a fault surface) is somewhat more computationally intensive, but should arrive soon in the interpretation workstation market.

Others are linking programs to (almost interactively) look at that subset of data that can be displayed on the screen of view. Their first objective is interactive AVO analysis, where the interpreter modifies the NMO velocity with a slider bar to better flatten a given gather. This action is linked to update the AVO calculation that is displayed on a map. Other commercial vendors have linked interactive microseismic event pick modification and updating of the event location. Bellman (2014) has taken this approach to an extreme, by linking software to show the impact of a change of 5% in the background shear velocity estimate, carried through to prestack inversion, then through a rock physics based brittleness template to visualize the sensitivity of a brittleness prediction based on a parameter chosen several programs back in the workflow.

The linkage to cluster analysis should now be clear. I predict that an interpreter will be able to interactively add and subtract attribute volumes to determine which combination of attributes differentiate a given facies of interest, e.g., diagenetically altered chert from the encompassing tight limestone.

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Statistically correlating attributes to completion and production results

The biggest change that the geophysical community has seen in the past five to ten years, at least in North America, is the advent of resource plays. Many companies define resource plays as targets where the depth and location of the reservoir are both widespread and relatively well mapped. The reservoir is assumed to be fairly uniform but expresses both sweet and sour spots, and where success is determine by economic drilling and completion. Most, if not all resource plays are "unconventional" and require hydraulic fracturing, acidation, or some other completion process to be economic. One critical difference between these resource plays and conventional plays is in the number of wells drilled. As an example, the 60 mi^2 survey in the Barnett Shale shown in Figure 2 has over 400 wells completed within the target zone (Zhang et al., 2013). There are several dozen seismic surveys of comparable size that cover the Fort Worth Basin. Such dense drilling provides the control for significantly more advanced statistical analysis. Rather than mapping one or two "X"s on a map to indicate the best drilling locations, in resource plays our goal is to improve the percentage of economically completed wells from say 80% to 90%. One challenge is to make these correlations convincing enough that it will convince our drilling partners to modify their original plans.

Furthermore, the success of completion goes beyond the obvious geomechanical estimates of P-impedance, S-impedance, density, and azimuthal anisotropy. Layering is also critical, with favorable interbedding of brittle and ductile layers leading to better completion (Stephens et al., 2011). While engineers are quite comfortable with geomechanical estimates, in both the Woodford and Barnett Shales there is a depositional imprint, with higher TOC and higher concentration of radiolarians (forming brittle chert) in the deeper parts of the basins and less on the shelf (Gupta et al., 2013). These locally deeper parts of the basin have their own seismic stratigraphic expression, such that one can "infer" areas that may be more productive using "softer" attributes like spectral components that are sensitive to vertical variability.

Since multiple wells will be drilled and completed in a given field, resource plays often justify the acquisition of "specialty" logs. Microseismic experiments (six lie within the survey of Figure 2) and image logs run in horizontal wells are quite common (several in the same survey), while production logs are rather rare (though there are four in the survey of Figure 2). Electron capture spectroscopy logs provide a measure of mineralogy, and with an appropriate model, an estimate of brittleness. The challenges here are difficult, but they are also exciting. While we can visually correlate curvature to fractures seen in image logs, we do not have a quantitative way to do so. Likewise, while we can visually recognize that microseismic events tend to occur in more brittle rock, we do not know how to establish quantitatively a brittleness threshold where this might happen. Finally, how do we best correlate production measured at the surface with the attributes measured within this diffuse zone? Do we assume a completed well has stimulated a cigar-shaped zone around the well bore? We know the relationship to be nonlinear, with cutoffs and thresholds playing a role. Such nonlinearity will require new developments in statistical analysis.

Conclusions

The attribute road ahead will have turns and detours but will continue to climb. A great deal of basic science needs to be done. Often, we see features on seismic data that are rarely, if ever seen in outcrop. Education, training, experience, and ultimately documentation is critical. Specifically, how do we link multiple attributes that delineate specific components that fall within the limits of seismic resolution into a unified geologic picture that helps us infer features that are either fall below seismic resolution, or are so subtle that they are easily overlooked?

Through improved software linkage, interpreters will modify base-line processing parameters such as velocity and horizon picks, limit azimuth and incident angle ranges, and even modify deconvolution filters to analyze the impact on the attribute expression of a given geologic feature. "Object" extraction will grow beyond extracting planes, autopicking horizons, and encapsulating channels. The linkage of cluster analysis and level sets to geobody tools promises to be able to extract the discrete interlocking channels such as seen in Figure 1a.

Attribute cluster and statistical analysis will grow the fastest, with attributes linked directly linked to risk analysis to high grade drilling decisions.

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EDITED REFERENCES

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REFERENCES

Bahorich, M. S., and S. L. Farmer, 1995, 3-D seismic coherency for faults and stratigraphic features: The coherence cube: The Leading Edge, **14**, 1053–1058, http://dx.doi.org/10.1190/1.1437077.

Bahorich, M. S., and P. van Bemmel, 1994, Stratigraphic interpretation of seismic data on the workstation: 64th Annual International Meeting, SEG, Expanded Abstracts, 481–484.

Balch, A. H., 1971, Color sonograms: A new dimension in seismic data interpretation: Geophysics, **36**, 1074–1098, http://dx.doi.org/10.1190/1.1440233.

Barnes, 2007, Redundant and useless seismic attributes: Geophysics, **72**, no. 3, P33–P38.

Bellman, L. W., and J. Leslie-Panek, 2014, The evolution of interpretation: CSEG Symposium, Canadian Society of Exploration Geophysicists, Abstracts, http://cseg.ca/symposium/docs/2014-Abstract_L_Bellman_CSEG_Symposium.pdf.

Bueno, J. F., B. C. A. Honório, M. C. Kuroda, A. C. Vidal, and E. P. Leite, 2014, Structural and stratigraphic feature delineation and facies distribution using seismic attributes and well log analysis applied to a Brazilian carbonate field: Interpretation, **2**, no. 1, SA83–SA92.

Gao, D., 2012, Implications of the Fresnel-zone texture for seismic amplitude interpretation: Geophysics, **77**, no. 4, O35–O44, http://dx.doi.org/10.1190/geo2012-0023.1.

Gupta, N., S. Sarkar, and K. J. Marfurt, 2013, Seismic attribute driven integrated characterization of the Woodford Shale in west-central Oklahoma: Interpretation, **1**, no. 2, SB85–SB96, http://dx.doi.org/10.1190/INT-2013-0033.1.

Kozlov, E., N. Brasky, and E. Korolev, 2004, Imaging scattering objects masked by specular reflections: 74th Annual International Meeting, SEG, Expanded Abstracts, 1131–1134.

Liao, Z., Z. Reches, K. J. Marfurt, and N. Gupta, 2013, Characterizing a fault-zone and associated fractures using lab experiments and attribute-based seismic analysis: An example from Woodford Shale, Anadarko Basin, Oklahoma: 83rd Annual International Meeting, SEG, Expanded Abstracts, 1416–1420.

Lynn, H. B., 2004a, The winds of change: Anisotropic rocks — Their preferred direction of fluid flow and their associated seismic signatures — Part 1: The Leading Edge, **23**, 1156–1162.

Lynn, H. B., 2004b, The winds of change: Anisotropic rocks — Their preferred direction of fluid flow and their associated seismic signatures — Part 2: The Leading Edge, **23**, 1258–1268.

McArdle, N., D. Iacopini, M. A. KunleDare, and G. S. Paton, 2014, The use of geologic expression workflows for basin scale reconnaissance: A case study from the Exmouth Subbasin, north Carnarvon Basin, northwestern Australia: Interpretation, **2**, no. 1, SA163–SA177, http://dx.doi.org/10.1190/INT-2013-0112.1.

Rijks, E. J. H., and J. E. E. M. Jauffred, 1991, Attribute extraction: An important application in any detailed 3-D seismic interpretation: The Leading Edge, **10**, 11–19, http://dx.doi.org/10.1190/1.1436837.

Roberts, A., 2001, Curvature attributes and their application to 3D interpreted horizons: First Break, **19**, no. 2, 85–100, http://dx.doi.org/10.1046/j.0263-5046.2001.00142.x.

Stephens, A., R. Meek, and P. Clarke, 2011, Mining Eagle Ford rock properties data from 3D seismic in south Texas using prestack inversion and neural net technology: Presented at the 17th Annual 3D Seismic Symposium, Rocky Mountain Association of Geologists.

Taner, M. T., F. Koehler, and R. E. Sheriff, 1979, Complex seismic trace analysis: Geophysics, **44**, 1041–1063, http://dx.doi.org/10.1190/1.1440994.

Trumbo, A., and J. P. Rich, 2013, Azimuthal variations in attributes for induced fracture detection in the Barnett Shale: Interpretation, **1**, no. 2, SB51–SB59, http://dx.doi.org/10.1190/INT-2013-0027.1.

Wallet, B. C., M. C. de Matos, J. T. Kwiatkowski, and Y. Suarez, 2009, Latent space modeling of seismic data: An overview: The Leading Edge, **28**, 1454–1459, http://dx.doi.org/10.1190/1.3272700.

Zhang, K., Y. Guo, B. Zhang, A. M. Trumbo, and K. J. Marfurt, 2013, Seismic azimuthal anisotropy analysis after hydraulic fracturing: Interpretation, **1**, no. 2, SB27–SB36, http://dx.doi.org/10.1190/INT-2013-0013.1.