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First order seismic attributes for clastic seismic facies interpretation: Examples from the East China Sea

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A B S T R A C T

Seismic attributes for the interpreting explorationist are numerous. Some are useful, some duplicative, and some less useful. However, with respect to optimizing a systematic basin analysis approach which relies upon heavily upon integrating seismic facies, there are eight particularly useful attributes which have clear geophysical meaning, strong underlying geological rock-fluid implications, and which for clastic depositional environments greatly assist in determining seismic facies, associated paleoenvironments, and lessening the number of interpretive possibilities. They are: Amplitude Envelope, Chaos, Cosine of Phase, Dip Deviation, Instantaneous Frequency, Q, Relative Acoustic Impedance, and Variance. A systematic application of these first order attributes for the East China Sea in particular, and for other clastic environments in general, allows a first pass assessment of a basin's exploration potential through seismic reconnaissance, an interpretive reconnaissance whose accuracy is limited only by the seismic fidelity of the lines and logic of the assumed geology employed.

1. Introduction: Problem definition

To augment conventional reflection seismic amplitude sections, for the interpreter there are almost an overwhelming variety of seismic attributes available (Barnes, 2006). Some are useful, some less so, many are duplicates, and some have questionable practical significance. There are a variety of useful publications which can assist in the understanding of the calculation and use of seismic attributes, for example the seminal classic by Taner et al. (1979), its update (Taner, 2000), and the Petrel work by Schlumberger (2007). Perhaps the most recent compendium is that of Chopra and Marfut (2007) which describes case-history and theoretical applications to the prestack, to the stack, to the signal, and even to distinguishing the noise (acquisition footprints, etc.). Table 1 lists as an example 50 of the most widely used seismic attributes used at present.

It is in light of the practical geological aspects of seismic facies analysis used most often in the practice of seismic stratigraphy (e.g. Vail et al., 1977; Roksandić, 1978; Uttarathiyang and Pigott, 2008) that this paper makes its focus, paying particular attention to those facies within the signal that contribute to a basin's petroleum system analysis (Metwalli and Pigott, 2005) and thus its optimized hydrocarbon exploration. Therefore, in order to systematically characterize the seismic facies (geophysical aspects of the geology) of the operational seismic sequences (that is, the pragmatic interpretation of parasequence sets) and subdivided parasequences (see Pigott and Radivojevic, 2010), we shall describe those seismic attributes best suited to augment classic amplitude sections. The examples are drawn exclusively from marine 2D reflection seismic profiles from the East China Sea from some 11,000 km of 2D seismic (Fig. 1).

The East China Sea is a particularly underexplored basin with a complicated tectonic and depositional history. In brief, physiographically the East China Sea is composed of two major sedimentary basins: The East China Sea Shelf Basin and the Okinawa Trough Basin. These two basins are separated by the Taiwan-Sinzi Fold Belt which trends NE–SW. Geologically, in the East China Sea Shelf Basin, most of the sediments were deposited during the Late Cretaceous to the middle Miocene (Oshima et al., 1988; Zhou et al., 1989). In the Okinawa Trough, however, the middle to late Miocene and Pliocene sediments were deposited upon Paleozoic basement (Kimura, 1985; Sibuet et al., 1987). The East China Sea shelf basin can also be subdivided into a series of sub-basins, which are mainly composed of alluvial and fluvio-lacustrine deposits (Lao and Zhou, 1995; Ren et al., 2002) separated by basement highs or rises such as the Hupijiao, Haijiao, and Yushan rises (Yang, 1992; Zhou et al., 1989). Initial rifting and extension in the proto-East China Sea began in the late Cretaceous and continued until the Paleocene/Eocene, terminating at the onset of regional uplift and folding (Zhou et al., 1989; Yang et al., 2004). Rifting resumed in

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Table 1
Fifty commonly used seismic attributes.

Apparent Polarity[c]	Isofrequency (Spectral Decomposition)[c]	Quadrature Amplitude[c]
Average Amplitude (Energy, Magnitude, etc.)[c]	Instantaneous (Phase) Dip[a]	Rate of Change of Envelope[a]
Chaos[b]	Instantaneous Acceleration[a]	Relative Acoustic Impedance[a]
Coherency[c]	Instantaneous Band Width[a]	RMS Amplitude
Cosine of Instantaneous Phase[c]	Instantaneous Dominant Frequency[a]	Second Derivative of Envelope[a]
Dip of Maximum Lateral Semblance[a]	Instantaneous Frequency[a]	Signal Shape (Loop area, duration, etc.)[c]
Dip Deviation[c]	Instantaneous Lateral Continuity[a]	Smoothed Maximum Lateral Semblance[a]
Dip Histogram[b]	Instantaneous Phase[a]	Structural Smoothing[c]
Dip Variance (Local Dip versus average Dip)[a]	Instantaneous Quality Factor[a]	Sweetness[d]
Divergence[b]	Intensity Varying Phase Display[a]	3D Curvature[d]
Dominant Frequency[c]	Lateral Continuity[a]	Trace Gradient[c]
Envelope[a] (Reflection Strength)	Local Structure (Azimuth, Dip, Flatness, etc.)[c]	$t*$ Attenuation[c]
Event Continuity[a]	Maximum Lateral Semblance and corresponding Dips as Lateral Continuity[a] Attributes	Variance[a]
Flatness[b]	Normalized Amplitude Trace[a]	Volume Reflection Spectral Decomposition[b]
Gabor Filter[b]	Number zero crossings (negative, positive, etc.) [c]	Wavelet Attributes[a]
Gaussian Dip Guided Filter[b]	Orientation Tuned Chaos[b]	Weighted Mean Frequency[a]
Gradient Magnitude[c]	Projected Principal Gradient[b]	

[a] Taner (2000).
[b] Randen and Sonneland (2005).
[c] Schlumberger (2007).
[d] Schlumberger (2009).

the early Oligocene, until a second phase of uplift in the early Miocene terminated the rifting process (Lee et al., 2006). The post-rift phase is characterized by regional subsidence, resulting in the formation of a broad continental shelf through the tectonic inversion during the middle Miocene (Zhou et al., 1989; Yang et al., 2004; Lee et al., 2006). Although the timing of uplifts is unclear, uplifting associated with the development of the rise likely was active prior to late Miocene because erosional surfaces of early Miocene strata developed on top of the eroded basement (Lee et al., 2006; Han et al., 2008). These tectonic elements and the complicated basin evolutionary history have provided a variety of structural and depositional styles which in turn provide a wide spectrum of seismic facies particularly amendable to seismic attribute analysis.

2. Approach

The definition of seismic attributes is somewhat general, referring to any feature which describes "either by direct measurements or by logical or experience-based reasoning" (see Sheriff, 1992) a seismically observed character. Attributes are generated in a variety of ways. Some are based solely upon the real part of the complex seismic trace, others upon complex trace analysis (quadrature traces generated by the Hilbert transform: Taner et al., 1979), and still others using a variety of mathematical formulas or algorithms that describe their pre-stack or post-stack variations and even geometries (Taner, 2000; Schlumberger, 2007). The mathematics which underlie these attributes have been extensively described and cited elsewhere and are not repeated here, but let us compress this definition and yet modify it to include a pragmatic emphasis and state that "*Practical seismic attributes are quantitative or qualitative aspects which describe a seismic response with an assumed underlying geological reality*".

There are two approaches to attribute analysis with respect to hydrocarbon exploration. One is a stochastic approach and the other is a deterministic approach. The stochastic approach represents one which in a sense throws as many attributes as one has available at the volume and see which ones stick and clump statistically with respect to various geologically hypotheses which are generated. The second approach is to employ attributes systematically in a petroleum system analysis either during or following the sequence stratigraphic framework construction. While the first approach is quick, demands less understanding, and can satisfy short deadlines, the end result can suffer from falsely interpreting the non-unique and multiple geological possibilities which may result. The second approach, on the other hand, requires a greater understanding both geologically and geophysically, and is a purposefully systematic application of very specific seismic attributes that have a clear geological grounding. The second approach can then be, if the interpreter desires, be followed by seeing what additional attributes might check early hypotheses. It is the deterministic approach which we now describe and illustrate.

Though there are many ways that one could classify attributes: prestack, stack, based upon mathematical derivations, etc. (see Chopra and Marfut, 2007), for this paper we suggest a simple threefold classification. We term the standard amplitude display *Zeroth order* as it is the most fundamental. *First order* are those basic geophysical attributes which deal with illuminating one or more of the basic geological properties. *Second order* are all those additional attributes (most of the attributes in Table 1) which duplicate, supplement, or corroborate these fundamental attributes with varying degrees of illumination or detection.

While first order attributes can provide a firm foundation for subsequent input into a petroleum system analysis, there is a very important caveat. It must be pointed out that while some attributes directly indicate facies aspects while others indirectly illuminate facies aspects, the attribute chosen for interpretation is only as good as the geophysical fidelity of the seismic, and the resulting interpretation is only as good as the geological logic constrained by the borehole.

Importantly, a seismic image does not have a unique interpretation of its paleoenvironment. A prograding geometry could be representative of an alluvial fan, reef talus, delta, submarine fan, etc. However, if one links several facies together, the number of possible interpretations decrease. For example, if one could link a prograding facies to those of an upstream meandering river, an attached swamp, an adjacent shallow nearshore bay, and deeper downdip marine shale, the porgrading geometry would be highly suggestive of a delta front of alternating sands and silts. It is for this reason, that seismic attributes if they have geologic meaning can greatly assist the seismic interpreter in making seismic facies anal-