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AN OVERVIEW OF SEISMIC ATTRIBUTES

Seismic attributes play a vital role in the interpretation of subsurface geological features such as faults, fractures, folds, channels, diapirs and reefs, and in inferring dynamic and static properties of subsurface reservoirs. Hence, understanding of attributes and their extraction from surface seismic data are crucial for the illumination of subsurface structures and properties. This chapter provides an overview of seismic attributes, their historical evolution, and fundamental characteristics or properties that can differentiate objects and their subsurface disposition.

1.1. Introduction

Seismic attributes have been used over the past few decades to infer subsurface properties and geologic features from reflection seismic data. These attributes illuminated geologic features, revealed structural architecture, and quantified specific physical properties. The analysis of seismic attributes plays a pivotal role in petroleum exploration through the delineation and interpretation of subsurface faults, fractures, folds, channels, diapirs, reefs (Figure 1.1), etc. These subsurface features act as traps for hydrocarbon accumulation and help in predicting dynamic and static characteristics of subsurface reservoirs (Chopra & Marfurt, 2007). Since inception, a large number of attributes have been generated from seismic data, which have been efficiently utilized to describe and delimit different geologic targets of interests.

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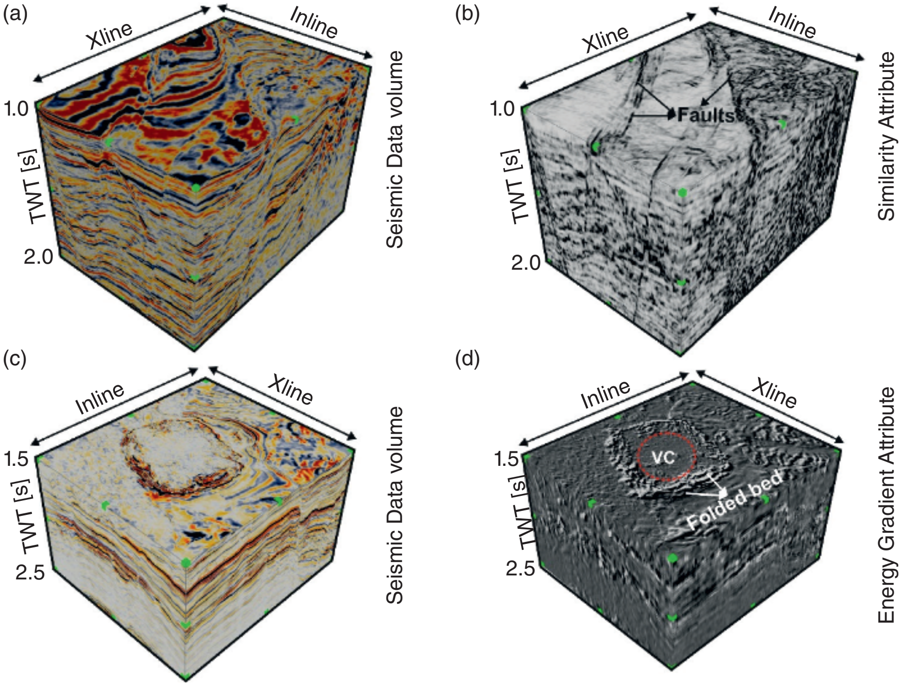


Figure 1.1 Volumetric display of seismic cube and corresponding seismic attributes (a–b and c–d), demonstrating their efficiency in describing different subsurface geological features (after Kumar and Sain, 2018; Kumar et al., 2019; VC: Volcanic Core).

Seismic attributes are used to extract information from the pre-stack or post-stack data i.e., gathers or volumes. Pre-stack attributes treat seismic data as records of seismic reflections that are associated with the P- and S-impedances, P- and S- wave velocities, amplitude variation with offset (AVO), attenuation, anisotropy, AVO intercept, and gradients. However, post-stack attributes consider seismic data to be a representation of Earth's subsurface image that includes a large family of attributes, e.g., complex trace attributes, interval attributes, horizon-based attributes, time-frequency attributes, and waveforms (Barnes, 2016; Al-Shuhail et al., 2017). The attributes, as a whole, follow a unified characteristic, based on which maximum information about a target can be extracted and subsurface architecture of a geologic body can be inferred from data. Thus, they act as filters, designed in such a way as to illuminate the properties of interest by setting aside those which are of no interest. Though both domains divide the family of seismic attributes by assigning different means of usage, attribute analysis has received the utmost attention in image processing and enhancement, which aims to extract valuable subsurface information from surface data.

This chapter shows how the seismic attributes have evolved and are used for enhancing characteristic properties stored within the seismic data. Most of these properties form the basis for designing and formulating seismic attributes for subsurface interpretation from surface data.

1.2. Historical Evolution of Seismic Attributes

The 1920s marked the beginning of field reflection seismic experiments, which mapped subsurface geological structures by identifying reflections and converting the arrival times into corresponding depths. This practice continued through the 1950s until the late 1960s. The advent of Analog-to-Digital (A/D) conversion techniques facilitated seismic data processing on digital computers. However, this digital revolution still did not stream interpretation practices by geophysicists who could correctly map subsurface geology from data. Rummerfeld (1954) was one of those visionaries who could qualitatively use reflection characteristics to interpret subsurface stratigraphy from seismic data. This event triggered the enthusiasm of geophysicists for critically understanding the properties from seismic data for inferring subsurface geological structures. Koefoed (1955) laid down his interpretational insights into signal processing from amplitude variations with offsets (AVO), which led to the interpretation of subsurface lithological properties. Thereafter, several geophysicists (Merlini, 1960; Savit, 1960) documented their pioneering works for the interpretation of seismic reflection data. The digital revolution brought about significant changes in signal processing and quality (Yilmaz, 2001). Slowly, the interpretation of seismic reflections in inferring subsurface stratigraphy became a routine job.

The late 1960s witnessed a significant discovery from such practices. Recognition of “bright spots” from seismic data by Soviet geophysicists opened up a new era in interpretation strategies. These anomalous features aroused interest in the direct detection of hydrocarbons, geared up seismic explorationists, fascinated many seismic contractors, and led to successful exploration cases in the Gulf of Mexico. The bright spot detection through the 1970s captivated the interpretation community, making the first seismic attribute “reflection amplitude.”

Reflection strength (Figure 1.2) is a classic example of amplitude attribute, designed by Anstey (1972).

Today this attribute is considered the most important and powerful of all existing seismic attributes. Once the amplitude phenomena led to the direct search for hydrocarbons, researchers immediately became curious about the frequency characteristic of the signal. When seismic waves propagated through a gas

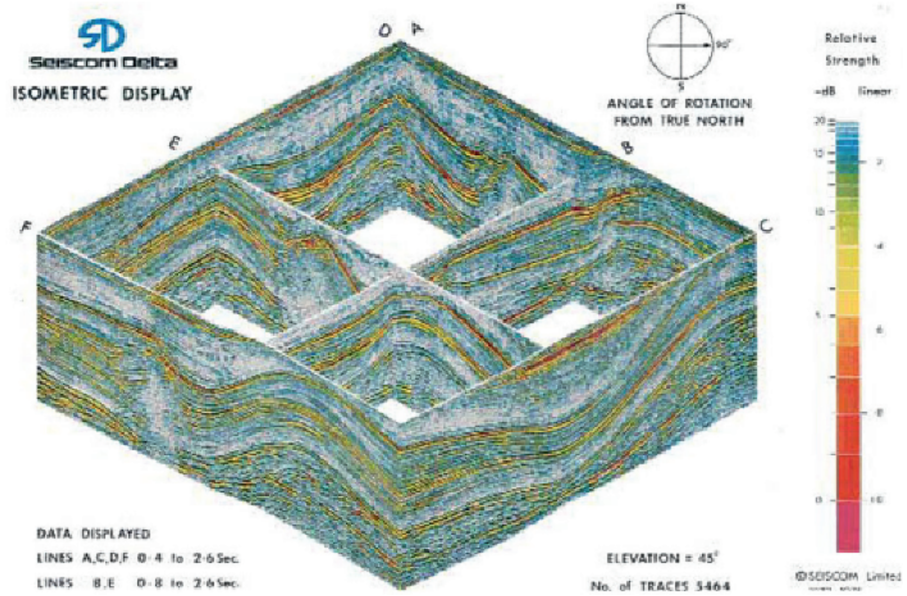


Figure 1.2 Isometric display of reflection strength attribute (after Anstey, 1972).

reservoir, it was observed that the signal suffered from higher frequency being washed out, leaving behind the lower frequency, thereby causing a shadow. Sheriff (1975) called this "Frequency Shadow Effect", which directly indicates the presence of a gas reservoir. Dobrin & Savit (1960) documented that such attenuation could be used for the quantification of rock quality factor. Anstey (1977, 2001, 2005) developed a novel procedure for attribute analysis, in which he demonstrated the use of color displays for analyzing seismic attributes. The "Complex Trace Analysis" made its first appearance in the 1976 annual meeting of the Society of Exploration Geophysicists (SEG) in the form of seminar papers by Taner, Sheriff and his group, which later on became the first masterpiece of work. Based on this concept, Taner & Sheriff (1977) and Taner et al. (1979) developed five attributes: instantaneous amplitude, instantaneous phase, instantaneous polarity, instantaneous frequency, and weighted average frequency. While these developments were gaining pace, Peter Vail and his group formulated the principles of seismic stratigraphy. Being inspired by the pioneering works of Taner and his group, the complex trace attributes found their place in explaining the seismic properties related to the stratigraphy. Several other attributes, e.g., root mean square amplitude, zero-crossing frequency, and cosine of phase, which were observed in early 1980s, were also regarded to be more comprehensible substitutes for complex trace seismic attributes. On the advent of 3D seismic data and the use of computer systems during the mid-80s, attribute maps and their analysis came to light. The first attribute maps were the simple attributes extracted from seismic amplitude volume (Denham & Nelson, 1986), horizon attributes, and horizon-guided interval attributes (Bahorich and Bridges, 1992; Dalley et al., 1989; Hoetz & Waters, 1992; Rijks & Jauffred, 1991). Bahorich & Farmer (1995) further developed 3D discontinuity attributes, which, when displayed through time and horizon slices, distinctly revealed faults, salt domes, and meandering channels. This caused curiosity among interpreters and led to the revitalization of seismic attribute analysis. This development opened an avenue for assessing other 3D properties such as dips, azimuths, curvatures, parallelism, etc. (Marfurt et al., 1999; Oliveros & Radovich, 1997; Randen et al., 2000; Taner, 2001). Mapping of thin beds and channel deposits from seismic data led to the development of spectral decomposition, which also made a breakthrough in seismic attribute analysis (Gridley & Partyka, 1997). Such an approach, coupled with tuning thickness analysis, led to a step forward for the quantitative application of seismic attributes.

Multi-attribute analysis gained importance and found a place in routine applications for seismic data interpretation. It is notable that the supervised methods were more preferred, as these methods could be trained to produce results of geological importance (Aminzadeh & de Groot, 2004; Hampson et al., 2001; Meldahl et al., 2002; Nikravesh et al., 2003). However, extraction of meaningful geology through unsupervised methods remained challenging. To date, a plethora of seismic attributes have been developed to capture the responses from subsurface geologic features for meaningful interpretation. Seismic attributes and their evolution have been very important in quenching the thirst of interpreters.

1.3. Characteristics of Seismic Attributes

Seismic attributes possess interesting characteristics that make them unique tools for the interpretation of subsurface geology.

They operate as filter: Seismic attributes act as filters in which they have the ability to highlight the desired component of data by removing the unwanted elements.

They perform qualitative and quantitative operations: Attributes can be used to divulge geological complexities, such as the structural and stratigraphic architecture of the subsurface, and to quantify reservoir properties, such as porosity, saturation, and permeability.

They convey geological or geophysical implications: For example, the discontinuity attribute signifies high dissimilarity or low continuity in a geophysical sense, which is associated with the faults or fractures in geological terms.

1.4. A Glance at Seismic Characteristics

Barnes (2016) defines seismic properties/characteristics as geological, geophysical, or mathematical. Seismic data possess several characteristics and seismic attributes, which are commonly used in describing the geological features. A few seismic attributes are amplitude, phase, frequency, bandwidth, amplitude change, tuning thickness, and waveform. Some important characteristics are dip, azimuth, curvature, discontinuity, and parallelism. Below is a short description of these properties.

1.4.1. Amplitude

The amplitude (Figure 1.3) is the most crucial seismic property and plays an important role in formulating many other attributes.

The amplitude attribute is defined as the magnitude values of a seismic trace or trace envelope. The most commonly used amplitude attributes are the reflection strength, root mean square (RMS) amplitude, average amplitude, maximum amplitude, and trace envelope. The reflection strength is generally computed through complex trace analysis, and is synonymous with trace envelope and instantaneous amplitude.

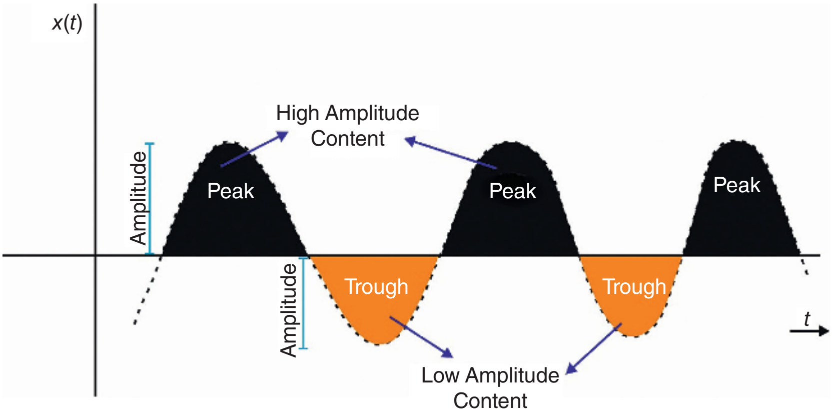
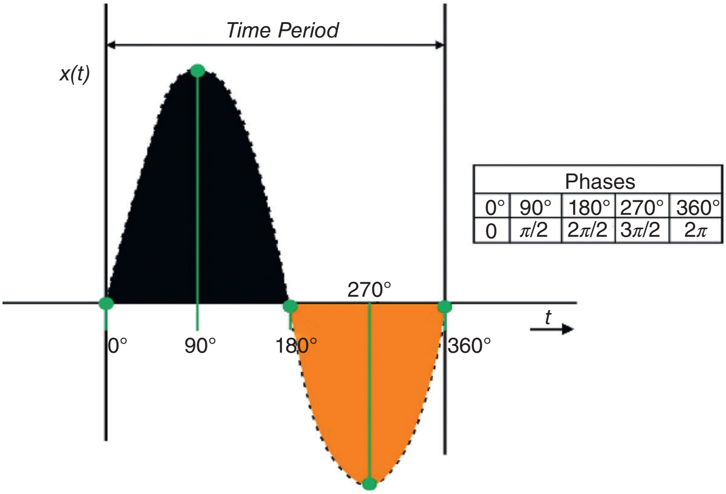


Figure 1.3 Display of seismic amplitude for a sinusoidal wave.



Phases				
0°	90°	180°	270°	360°
0	$\pi/2$	$2\pi/2$	$3\pi/2$	2π

Figure 1.4 Phase measures along a seismic waveform x(t).

1.4.2. Phase

Phase (Figure 1.4) refers to the relative position along a seismic waveform and is independent of amplitude. The common seismic attributes derived from phase are the instantaneous phase, response phase, and apparent polarity (Barnes, 2016).

1.4.3. Frequency

The number of sinusoidal cycles that occur along a seismic waveform within one second of time is called frequency. The common frequency attributes include instantaneous frequency, zero frequency, average spectral frequency, RMS frequency, and tuning frequency. The frequency attribute is most commonly applied in measuring bed thickness and seismic attenuation.

1.4.4. Bandwidth

Bandwidth refers to the breadth of the frequency power spectrum of a waveform. For a given seismic trace, the bandwidth is a function of change in frequency and amplitude along the trace (Barnes, 2016). Bandwidth attributes are used to discriminate stratigraphic features.

1.4.5. Amplitude Change

Amplitude change is defined as the change in seismic amplitude over an interval in a given direction. Geologic faults or edges of channels undergo a significant change in amplitude (for example, fault zones are associated with amplitude loss). The amplitude change attribute provides detailed information from the data.

1.4.6. Slope, Dip, and Azimuth

The orientations of seismic reflectors are determined by the dip and azimuth of a reflector and serve to formulate the dip and azimuth seismic attributes. The slope is defined as the ratio of the change in depth of reflection over a change in the horizontal distance. The arctangent of the slope outputs the dip, which is defined as the angle in degrees that a seismic reflection makes with the horizontal, and is expressed in microseconds per meter. However, to obtain the values in degrees, the dip must be estimated using a conversion velocity. The slope is considered a geophysical property, whereas the dip is a geological property. Azimuth is the angle measured in the clockwise from the geographic north in the direction of maximum downward dip or slope. Figure 1.5 (a, b) demonstrates the measurement of slope and dip components in 2D and 3D.

1.4.7. Curvature

Curvature is defined as the degree of curvedness of a surface, i.e. how or to what extent a surface bends or curves (Figure 1.6).

The curvature attribute is also defined as the rate of change of dip and azimuth along with a seismic reflection or an identified seismic horizon (Barnes, 2016). Roberts (2001) defines a complicated set of curvature properties, namely the Gaussian curvature, mean curvature, maximum and minimum curvature, most

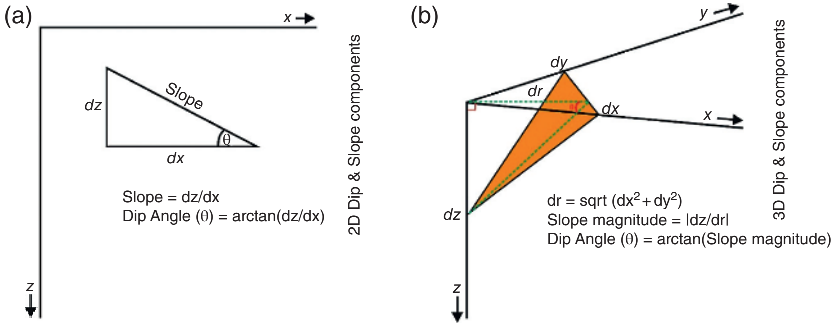


Figure 1.5 Dip and slope in (a) 2D and (b) 3D measurements.

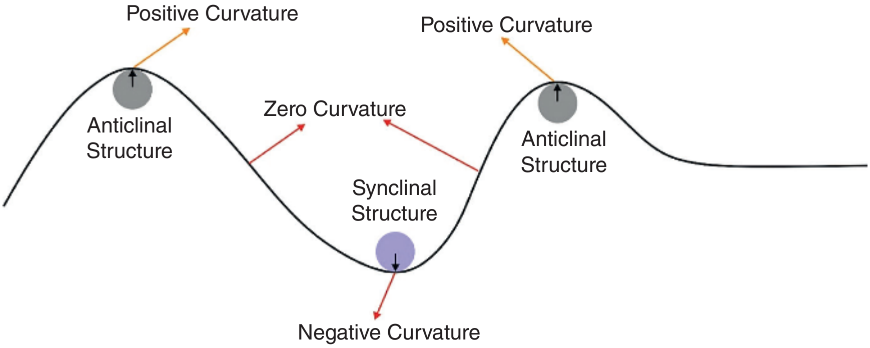


Figure 1.6 Display of curvature measures for different kinds of geologic structures.

positive and most negative curvature, dip curvature, strike curvature, curvedness, and shape index. Most positive and most negative curvature measures demonstrate a wide range of ground applications, e.g., submarine channel interpretation, identifying displaced fault blocks, fracture interpretation, etc. By sign convention, anticlines or reflection bumps are associated with positive curvature, and those of synclines or bowl-shaped features are related to negative curvature (Figure 1.6). The upthrown portion of a formation displaced by a fault has a positive curvature, and the downthrown part is associated with the negative curvature. However, Rich (2008) argued that these set of curvatures cannot measure true curvatures. The curvature measures are very important for fracture delineation (Lisle, 1994), as fractures mostly occur in anticline tops, synclinal bottoms, and at flexures. High curvature values may not indicate fractures but could ascertain fracture-prone areas or where fractures are more likely to form.

1.4.8. Seismic Discontinuity

Seismic discontinuity refers to a break in the continuity of seismic reflections. It is often referred to as “coherence” or “similarity” and is widely used for the interpretation of geological features, e.g., faults, diapirs, pinch-outs, channel belts, noise, and artefacts (Figures 1.7 and 1.8).

It is opposite to seismic continuity, where continuity refers to the degree to which seismic reflectors exhibit consistent amplitude and phase. Seismic discontinuity is a structural or geometrical attribute.

1.5. Summary

This chapter has presented a brief overview of seismic attributes from their historical evolution and outlined different characteristics that form the basis for

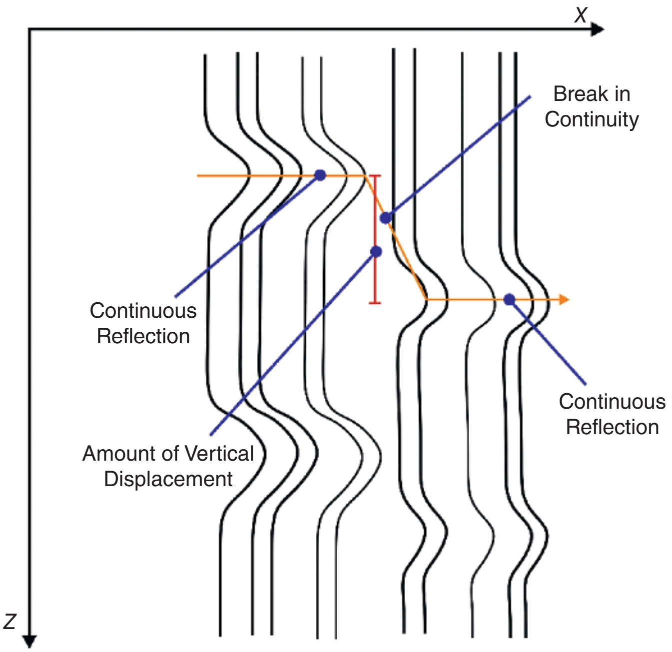


Figure 1.7 Seismic discontinuity, observed within the seismic trace, which is defined as break in seismic reflectors. This is a characteristic property of discontinuous structures used for interpretation from seismic data.

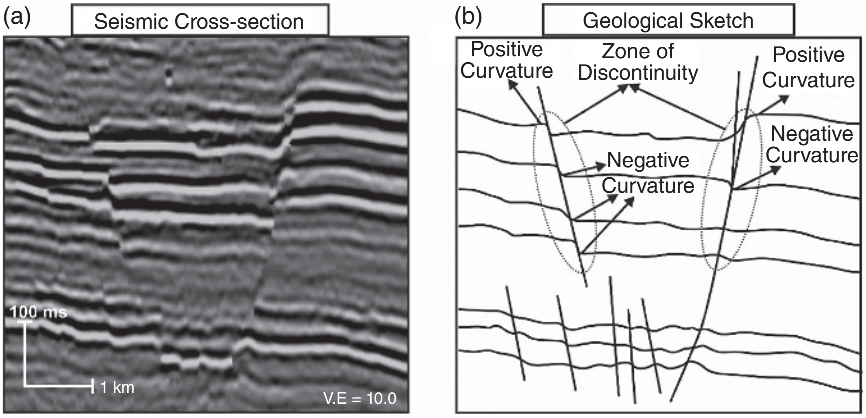


Figure 1.8 (a) Seismic discontinuity and curvature property on seismic amplitude section that has been explained through (b) a sketch for interpretation of geologic faults.

their formulation and computation. Based on these ideas, the next chapter explores different seismic attributes that have been widely used for the interpretation of subsurface geologic features from seismic data.

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