Chapter 2
Seismic Reflection Principles: Basics

Abstract Seismic reflection events are caused by the impedance contrasts at layer interfaces having a minimum width (Fresnel Zone). Seismic studies to represent reliably the subsurface geology, require quality data, which depend on signal-to-noise ratio and resolution, the latter being the ability to image thin geologic features separately. This calls for a seismic broad-bandwidth source consisting of both low and high frequencies that can improve resolution limits to layer thicknesses.

Seismic reflections record attributes such as amplitude, phase, polarity, arrival time and velocity that can be measured or estimated. The attributes define the shape and arrival time of reflection waveforms which depend on rock properties. Estimation of rock properties from seismic waveforms and their vertical and lateral changes in time and space is the essence of seismic interpretation.

Appropriate choice of seismic display modes and plotting scales are also important.

When a seismic wave, generated artificially on surface propagates through the earth and meets interfaces between different kinds of rocks, creates phenomena like reflections, refractions, scattering and diffraction. Of these, the reflection is by far the most significant phenomenon, as it forms the basis of the potent seismic reflection method deployed to image the subsurface for finding hydrocarbons. A compressional wave (P-wave) when incident normal to an interface, causes reflection and transmission also normal to it, but when incident at an angle (inclined), it produces two sets of waves, P-reflected and P-transmitted (refracted) and S-reflected and S-transmitted (Fig. 2.1). We shall limit the discussion to the principles of relatively simpler P-wave reflections, used extensively for measuring rock and fluid properties.

A seismic reflection event to be generated needs necessarily two things, an impedance contrast at the interface of two rock types and a minimum width (Fresnel Zone) of the interface. The reflection amplitude and its continuity depend on the degree of contrast across the interface and its extent and nature. The effectiveness of the reflections to reliably represent the subsurface geology is conditional on the quality of seismic reflection signal, which depends on, (1) the amount of noise recorded in the data and (2) the ability of the seismic wavelet to image the different interfaces separately. The reflection signal quality is thus adjudged by the two

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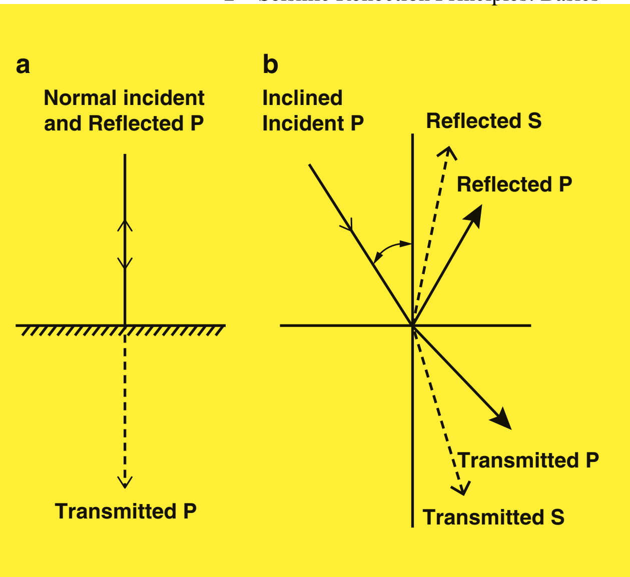

Fig. 2.1 (**a**) A normal incident P-wave on an interface produces one set of waves normal to the interface, the P-reflected and the P-transmitted. (**b**) An inclined incident P-wave, however, produces two sets of waves P-reflected and transmitted and S-reflected and transmitted (refracted)

important factors, the signal-to-noise ratio and the resolving power of the seismic wavelet, briefly discussed below.

Signal-to-Noise Ratio (S/N)

Noise may be defined as all undesired energy, other than the primary reflections from the subsurface strata. It is an inherent part of the seismic recording and processing system present due to ambient (within earth), geological (natural propagation) or geophysical (artifacts during recording and processing) causes. This noise cannot be wished away, but can be effectively reduced by conscious efforts during data acquisition and processing. Noise, though usually unwanted, can be occasionally helpful in interpretation. For example, remnant diffraction noises despite processing may indicate clues to presence of sharp edges, such as faults and other subtle stratigraphic objects. The presence of scattering noise may give an idea about the order of heterogeneity of the reflector, leading to indication of highly tectonised zones, crushed with faults and fractures. Processing of recorded noise as scatters from fractures and fractured zones can also be used as a technique for delineating naturally fractured carbonate and basement fractured reservoirs.

Since noise severely affects seismic clarity in portraying the subsurface image, it is desirable to record good and clean signals with minimum noise. It is a common practice to benchmark the quality of data in terms of a measure of a ratio between signals and noise (S/N). Improved data acquisition techniques including meticulous survey layout plans, field experimentations and strict on-field execution ensure good quality of data. In this context, the common depth point (CDP) seismic data acquisition is a unique technique. A standard technique practiced all over the world, it achieves signal enhancement at the cost of noise, via a summation process of several traces reflected from the same subsurface depth point but with different offsets known as CDP folds. Though summation of higher number of traces in a fixed offset range generally provides better S/N ratio, there may be a limit beyond which it may not be desirable, as adding additional traces (folds) may cost more money without improvement in the seismic images. Also, summation is an integration process, which affects resolution, especially in cases where large far offset traces are included for summing. In areas where the geology promotes good quality seismic reflections, the interpreter may still prefer to look at less-fold CDP data which is likely to offer better resolution and at a lower cost. It may also be noted that data with high S/N ratio does not necessarily assure higher resolution, as the resolution depends on other factors such as source signal frequency, sampling interval and subsurface wave propagation effects, besides noise.

makes the Nyquist frequency to be 250 Hz. This means that with this Nyquist value, no aliasing effect is expected since the maximum frequency (signal cut-off frequency) is expected to be far below (250 Hz). However, all recording systems are equipped with the anti-aliasing filter that can be applied when it is required. The anti-aliasing filter is normally applied whenever re-sampling of the data is carried out. Very often, in seismic data processing, the recorded digital data is re-sampled from 2 to 4 ms sampling period for economic motives.

8.6 Signal Resolution and Resolution Power

Resolution is defined as the ability of distinguishing individual objects gathered to gather in one group, or the details of shape changes of an irregularly shaped object. In the field of seismic exploration, the seismic resolution is the ability of recognizing two adjacent seismic events as distinct two events and not as one blurred event.

Resolution power can be measured by the minimum separation distance between two seismic events that can be resolved as two distinct features on the seismic section. Obviously the sharper the reflection wavelet, and higher signal-to-noise ratio, the better the resolution power will be. The term (resolution power) is used to imply ability of detecting and bringing to vision a certain seismic event

In seismic work, we are concerned with two types of resolutions of seismic reflection events: vertical resolution and horizontal resolution (explained here-below).

8.6.1 Vertical Resolution of Seismic Signals

Vertical resolution of seismic reflection events, is defined as the minimum vertical distance between two interfaces that give two distict reflection events on a seismic section. It is basically governed by the wavelength of the seismic signal. The shorter the wavelength (i.e. the higher the frequency) the greater the vertical resolution.

In addition to the frequency factor, depth and reflector spacing have significant effects on the resolution. The vertical resolution is governed by the ratio of the depth separation-distance of the reflectors (**Δz**) to the wavelength (**λ**) of the incident seismic signal. The lowest limit (resolution limit) of this ratio; (**Δz/ λ**) is found to be (1/4) (Sheriff and Geldart 1995, p. 174). This means that the reflector separation must be more than quarter of the wavelength (**Δz > λ/4**). This also means that the image separation (events separation measured on a seismic stack section) should be more than half a period (**Δt > τ/2**) in order to be distinctly resolved (Fig. 8.21).

Adoption of the (**λ/4**) criterion for the resolution limit, implies that the two events reflected from two neighboring interfaces are separated by a half cycle, which means that depth separation (**Δz**) between two neighboring interfaces greater than (**λ/4**) will lead to minimum destructive

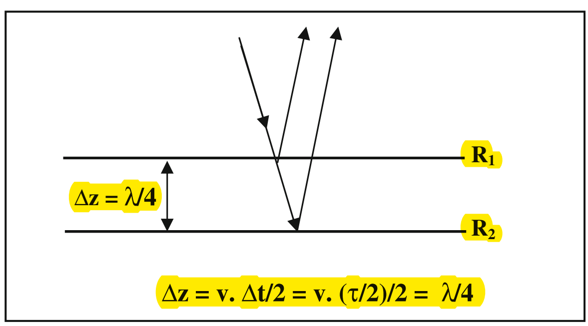

Fig. 8.21 The seismic vertical resolution. Minimum reflector separation (Δz) is equal to ($\lambda/4$)

interference between the reflected waves from the two interfaces, causing resolution deterioration.

(i) **Factors Affecting Resolution**

In general the higher the frequency content of the seismic trace the better is the resolution power. Well logs (wireline logs) have greater resolution power than seismic traces since well logs are generated by high frequency sources. These logs can resolve beds on centimeter-meter scale while seismic reflection records cannot resolve so-much detailed variations. Reflection survey data can resolve reflectors at depth-separation of about 10 m at its best.

The main factors affecting resolution are reflector spacing, reflector depth, and reflection signal frequency. Closely spaced reflectors cause interferences of reflected waves which lead to loss of resolution. The resolution-power is generally decreasing with depth for the following reasons:

- Earth filter which is cutting high frequencies, that is cutting short wavelengths. Thus for depth of 800 m, say, velocity of 1000 m/s, and frequency of 100 Hz, the wavelength will be 10 m and the resolution becomes only 2.5 m. However, when depth is 3000 m, velocity of 4000 m/s and frequency of 25 Hz, the wavelength will be 160 m and the resolution becomes 40 m. In general resolution gets less (poorer resolution) with increasing depth due to the effect of the earth high-cut filter.
- Increase of velocity due to compaction and decrease of frequency due to the earth high-cut filter with depth, both are leading to increase of the wavelength and hence decreases the resolution power.
- Application of high-cut filters (as application of the anti-aliasing filter), which lead to attenuation of the high frequencies of the signal and hence result in lowering the resolution power.

(ii) **The problem of Thin Beds**

A special case, related to the subject of resolution which brought appreciable attention by geophysicists, is the problem of resolving thin beds. Two reflectors spaced by less than quarter of a wavelength, have reflection responses depending on the layering model. A layer is regarded as a thin layer when its thickness is less than a quarter of the dominant wavelength (Sheriff 2002, p. 353).

Consider a thin bed of thickness of (**λ/4**) and of velocity ($\mathbf{V_2}$), sandwiched between two layers of velocities ($\mathbf{V_1}$ and $\mathbf{V_3}$) where ($\mathbf{V_1 = V_3 < V_2}$), the wave reflected from its top and that from its base will interfere constructively producing a high-amplitude reflection, forming what is normally referred to as the thin-bed effect or tuning effect. If, on the other hand, the thin-bed of velocity ($\mathbf{V_2}$) found between two layers of velocities ($\mathbf{V_1}$ and $\mathbf{V_3}$) where ($\mathbf{V_1 < V_2 < V_3}$), destructive interference will result (Sheriff and Geldart 1995, p. 174). These two models are shown in Fig. 8.22.

Vertical resolution is always improved with higher seismic frequencies. But, due to the earth filtering effect, frequencies get lower with increase of reflector depth.

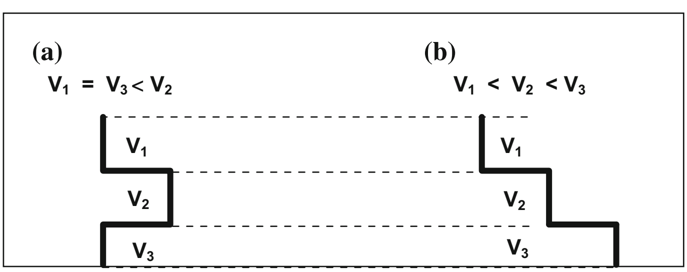

Fig. 8.22 Two models of a thin bed, having interval velocity (V_2). Model A ($V_1 = V_3 < V_2$) and model B ($V_1 < V_2 < V_3$)

Table 8.4 Estimates of the minimum depth interval resolved, corresponding to thre values of sampling period

Sampling period (ms)	Highest frequency (Hz)	Wavelength (λ) (m)	Min. depth-Interval (Δz = λ/4) (m)
1	500	5	1.25
2	250	10	2.50
4	125	20	5.00

Consequently, vertical resolution gets poorer with increasing depth.

Decrease of frequency (that is increase of wavelength) is leading to decrease of the ratio (**Δz/λ**) below the limiting value of (1/4). For example, an incident wave of (velocity = 1200 m/s, frequency = 40 Hz, wavelength = 30 m), the minimum depth interval between two reflectors to be resolved will be 7.5 m and for a second case of (velocity = 3000 m/s, frequency = 10 Hz, wavelength = 300 m), the minimum depth interval between two reflectors to be resolved will be 75 m.

(iii) **Role of the Sampling Period in Vertical Resolution**

Use of a sampling period (Δt) which gives a Nyquist frequency (1/2 · Δt) higher than the cut-off frequency of the highest frequency component of the seismic signal, will avoid aliasing effect. Examples of minimum depth interval (Δ**z**) for a layer having velocity of 2500 m/s is presented in Table 8.4.

This table shows that the resolution is reasonably good even if the sampling period is as large as 4-ms value. This is adequate for the shallow layers where the velocity is normally less than 2500 m/s. and frequency is less than 125 Hz.

8.6.2 Horizontal Resolution of Seismic Signals

Horizontal resolution concerns the ability of recognizing two neighboring reflecting points (on a horizontal reflector) as two distinct points and not one point. The minimum separation distance for two horizontally-adjacent features, is used as measure for the horizontal resolution. Alongside with other methods, the first Fresnel zone is often taken as a measure of horizontal resolution power on un-migrated seismic data (Sheriff and Geldart 1995, p.177). The radius of the first Fresnel zone is found to be function of frequency, velocity, and travel-time of the seismic reflection wave.

8.6.3 Fresnel Zone Formula

The Fresnel Zone concept was originally developed in connection with the physics of Light. According to this concept, a beam of light, incident on a reflector will illuminate a limited area of its surface, and reflection will take place from the area of that surface and not from a point. In the same way an incident seismic wave-front would be reflected from a surface-area of the reflector. Thus, the incident seismic energy is reflected from a defined area of the reflector surface, rather than from a point (Sherrif 1977).

Fresnel Zone concept is based on the assumption that all of the reflected energy contained in the positive half of the incident wave-front, is contributing in illuminating of the reflection area, which is circular in shape in case of vertical incidence. The reflected energy comes from the area that is affected by the positive half of the cycle of the incident wave. The incident energy will be reflected from the part of the reflector which is within the half cycle following the reflection onset (Sheriff 1980). The energy reflected from this zone is constructively interfering to make up the reflection event. In terms of wavelengths, this occurs for all of the energy reflected within quarter wavelength of the incident wave (Fig. 8.23).

Lateral resolution is determined by the radius (**R**) of the first Fresnel zone, which is related to the signal's frequency (**f**), reflection time (**T**) and propagation velocity (**v**) by an expression derived by (Sheriff and Geldart 1995, pp. 152–155):

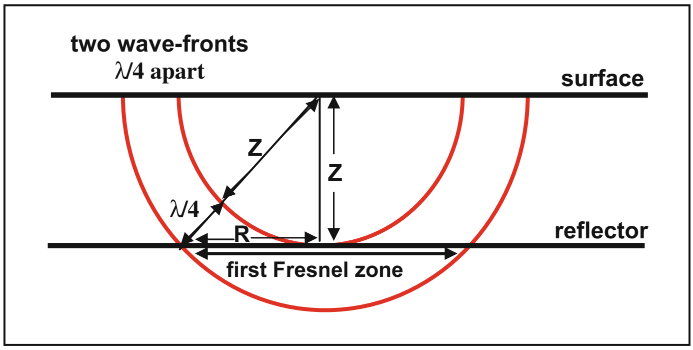

Fig. 8.23 Fresnel zone for a spherical wave. Two wave-fronts separated by quarter wavelength ($\lambda/4$). R, Fresnel-zone radius

$$\mathbf{R} = \mathbf{v}(\mathbf{T}/4\mathbf{f})^{1/2} \quad \textbf{for incident spherical wave}$$

and

$$\mathbf{R} = \mathbf{v}(\mathbf{T}/2\mathbf{f})^{1/2} \quad \textbf{for incident plane wave}$$

These functions show clearly that the radius of the first Fresnel zone (**R**) is function of the propagation velocity, reflection time, and frequency. The variation is direct with velocity (**v**) and square root of reflection time (**T**), and inverse with square root of frequency. The functions also show that the area of the zone is inversely proportional to frequency (**f**). Thus, Fresnel Zone is larger for low frequency components than for high frequencies.

It is important to note that Fresnel Zone radius cannot be used as a measure for horizontal resolution on migrated seismic sections. This is understandable since migration has the effect of collapsing Fresnel Zones. For this reason, use of Fresnel Zones in the study of horizontal resolution, is applicable only on unmigrated data.

8.7 The Common Numbering Systems

To express a sequence of entities, a certain counting system is used in which special symbols have been adopted. These symbols differ with different languages. The familiar system we are normally using is the decimal numbering system, in which we use ten different symbols (**0, 1, 2, 3, 4, 5, 6, 7, 8, 9**). To continue numbering beyond the number (**9**), certain combinations of these symbols are used. Examples of numbering systems are presented in Table 8.5.

Table 8.5 Numbering systems. The decimal and binary are the most commonly used numbering systems

0, 1, 2, 3, 4, 5, 6, 7, 8, 9	Radix = 10 (decimal system)
0, 1, 2, 3, 4, 5, 6, 7, 8	Radix = 9
0, 1, 2, 3, 4, 5, 6, 7	Radix = 8 (octal system)
0, 1, 2, 3, 4, 5, 6	Radix = 7
0, 1, 2, 3, 4, 5	Radix = 6
0, 1, 2, 3, 4	Radix = 5
0, 1, 2, 3	Radix = 4
0, 1, 2	Radix = 3
0, 1	Radix = 2 (binary system)
0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A	Radix = 11
0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B	Radix = 12
…	…
…	…
0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F	Radix = 16 (hexa-decimal system)

is desirable even for data with flat geologic strata. Typically, the Fresnel zone widths, of hundreds of meters in unmigrated data, can be considerably reduced to about 10 m or so by migration. For an effective migration, however, knowledge of proper overburden velocity field and an adequate number of surrounding traces *(aperture)* at the object level is necessary for stacked data. An aperture is the spatial width over which all traces around are considered for migration, and choosing an appropriate aperture is crucial to its effectiveness. Generally, an aperture of twice the Fresnel zone width at the reflection object is adequate (Sun and Bancroft 2001). The migration results suffer gravely near the end of seismic lines as there are no traces recorded and the interpreter should be cautious to consider data in this part.

For better resolution of lateral reflectivity changes of small dimensions, migration may require finer spatial sampling on ground like the temporal sampling used for improving vertical resolution. Take for instance the issue of imaging a small channel of 20 m width, an important geologic object for exploration. Obviously, the channel cannot be resolved with insufficient trace sampling of 25 m though the image with this trace spacing may detect it. The river geometry and more importantly its associated reservoir facies like channel, levee and point bar sands need to be imaged and resolved properly to characterize the reservoir and may necessitate closer trace spacing (subsurface) of no more than 10 m.

Temporal and spatial resolution may be considered somewhat similar in nature and are decided by the wavelength, which is dependent on velocity and frequency of the seismic wave. Both the resolutions depend on velocity but it must be stressed that temporal resolution depends on interval velocity while the spatial resolution is dependent on overburden velocity. As an example, take a limestone bed with an interval velocity of 3200 m/s and an overburden velocity of 2400 m/s for calculating the resolution limits. The vertical and lateral resolution limits for a dominant frequency of 40 Hz, are 20 and 15 m, considering quarter wavelength as the realistic limits of resolution. It is useful for the interpreter to have some idea about resolution limits beforehand; otherwise, he or she may be looking for things that are beyond the capability of the data to offer. It is also interesting to note that the two resolution effects are inter-reliant and improving one tends to better the other (Lindsey 1989).

Interference of Closely Spaced Reflections: Types of Reflectors

We have seen earlier that for beds with thickness, larger than quarter seismic wavelength, reflections from their top and bottom appear as distinct and separate. However, most commonly beds are closely spaced in the subsurface and reflections involving several beds arrive within a time spacing that is less than the length of the seismic pulse. This leads to superposition of the reflections (Fig. 2.6). The ensuing interference can be either constructive or destructive and the resultant composite reflections depend on: (a) number and thickness of the beds (b) magnitude and sign (polarity) of the reflection coefficients and (c) the order of positioning of the individual impedance contrasts. We may consider the behavior of three types of

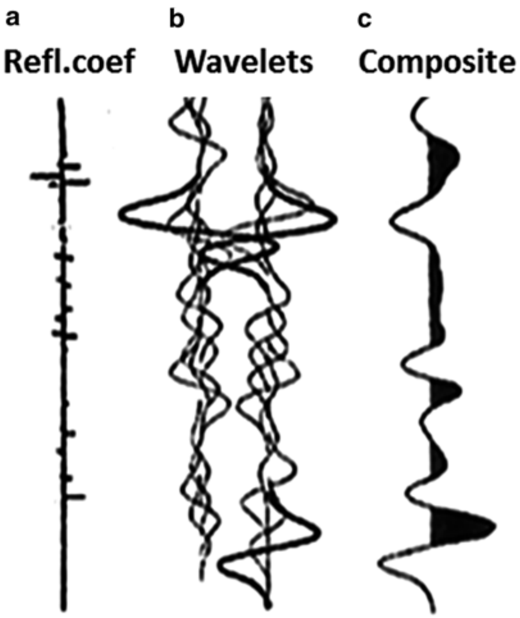

Fig. 2.6 The interference of reflections from closely spaced interfaces. (**a**) Subsurface reflection coefficient series, (**b**) wavelet reflections from the individual beds, and (**c**) the composite reflection caused by superposition of individual reflections from thin beds (Modified after Vail et al. 1977)

reflectors, namely *discrete, transitional* and *complex,* that an interpreter routinely comes across during interpretation (Fig. 2.7).

Discrete Reflectors

Top and bottom of thick beds with sharp impedance contrasts create distinct separate reflections to be recorded and are termed discrete reflectors. The reflections from top and bottom appear well separated with amplitude proportional to reflection coefficients. The onset of the reflection from the interface, either a peak or trough, appears at the right time on record with respect to its subsurface position without any delay.

Transitional Reflectors

A reflector may be termed transitional if there is a gradual gradation of impedance contrasts of one sign, either positive or negative, as in a fining upward channel or coarsening upward bar sand (Anstey 1977). The interference of a succession of reflections of the same signage (polarity) results in a composite reflection of an

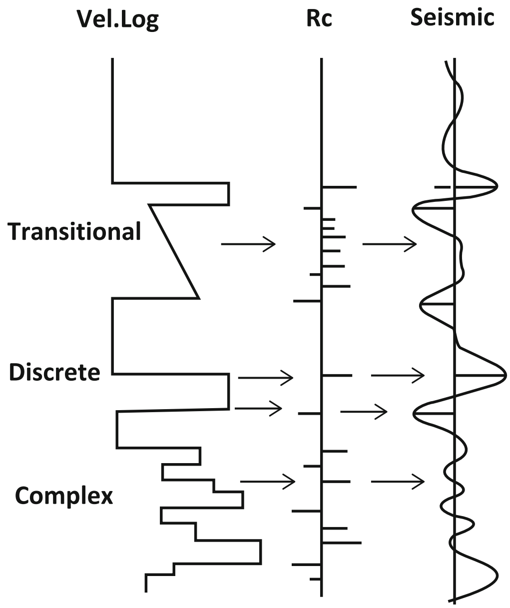

Fig. 2.7 A schematic to show the different types of reflectors. The discrete reflector has thickness that causes top and bottom reflections to be resolvable and with distinctive polarity and exact arrival time. 'Transitional' and 'complex' reflectors are composite events of several closely spaced beds with one or mixed signage respectively. They create reflections with uncertain polarity and delayed arrival time (Modified after Clement 1977)

integrated wave shape. The reflection is generally weak with a low frequency appearance and the event onset is time delayed with respect to the top of the formation.

Complex Reflectors

A complex reflector is a pack of reflectors, spaced closely but with varying magnitudes and polarities of impedance contrasts, which produce a complex reflection. The strength, phase and onset of the reflection are difficult to gauge. Forward seismic modeling may be used as a solution to get an insight to the pattern of a complex reflection.

Innate Attributes of a Reflection Signal

A seismic trace is a log measure of disturbances (particle velocity/ acoustic pressure) of waves reflected from subsurface with time. It records in a waveform the intrinsic attributes of a reflection signal amplitude, phase, frequency, polarity, arrival

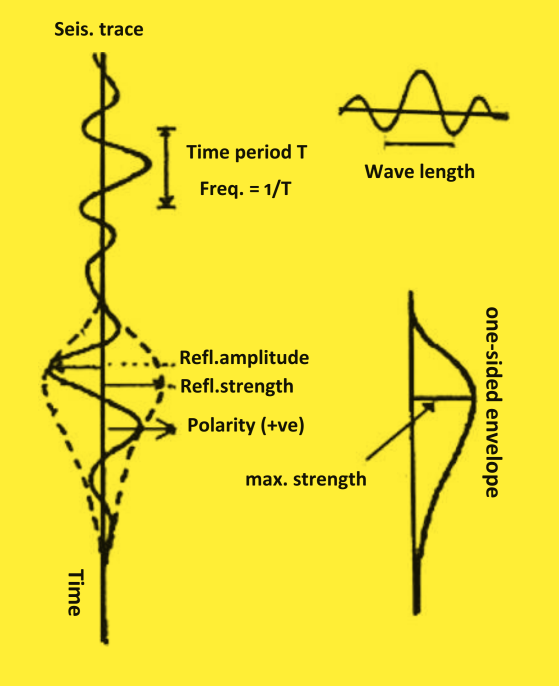

Fig. 2.8 The seismic attributes measurable on a trace, namely the time period, wavelength, reflection amplitude, reflection strength and polarity. Reflection strength is the maximum amplitude of the envelope of a composite reflection, independent of phase (After Anstey 1977)

time and velocity, all of which can be measured or estimated. The reflection attributes (Fig. 2.8) define the shape and arrival time of reflections depending on properties of the rocks. Thus the waveforms carry important geologic information encrypted in them. Estimates of these rock properties from seismic waveforms and their vertical and lateral changes in time and space is the essence of seismic interpretation, which predicts the subsurface structures and stratigraphy required for petroleum exploration. The basic seismic attributes are introduced here; their measurement and application is described in Chap. 10.

Amplitude and Strength

As stated earlier, a seismic wave incident normal to an interface with an impedance contrast produces two waves normal to interface, one reflected back and the other transmitted onward. The amplitude of the reflected wave with respect to that of the incident wave is termed the reflection coefficient (*Rc*) or the reflectivity. Reflectivity depends on the degree of contrast between the impedances on either side and the angle of incidence of the wave. For a normally incident wave, reflectivity *(Rc)* is expressed by the founding equation of seismic reflection method, $Rc = V_2\rho_2 - V_1\rho_1/V_2\rho_2 + V_1\rho_1$, where V_1, ρ_1 and V_2, ρ_2 are the velocities and densities of the upper and lower layers respectively. For non-normal (oblique) incidence, there will be, however, two pairs of *'P'*and *'S'* waves (see Fig. 2.1) and the above equation for the normal reflection coefficient gets relatively complicated and assumes a more general form as in Zoeppritz's equations, discussed in Chap. 10.

Amplitudes are measures of particle velocities or pressures and in an ideal case, the maximum value at peak/trough of a pulse wavelet represents the reflection coefficient of an isolated reflector. Where the wavelet is leggy (lengthy and cyclic) and the reflection is of composite nature, as is often the case in nature, it is difficult to choose the appropriate peak/trough for calculation of amplitude to represent reflectivity. In such cases, it is convenient to make use of the reflection strength, which is specified by the maximum amplitude of one side of a symmetrical envelope, centered about the reflection event (Fig. 2.8). Reflection strength is more meaningful as it is independent of phase and relatively less sensitive to the factors affecting amplitude. Reflection strength may have a maximum at a phase other than at peak/trough and may indicate the nature of the composite reflection. Reflection amplitude and its variations are vital clues to predict lithology of formations and their lateral changes, porosities and sometimes pore fluids as in the case of gas reservoirs. However, a crucial limitation of amplitude is its proneness to wide variance due to several other factors that may not be linked to geology.

Phase

Phase may be expressed simply as the time delay with respect to the instant of start of a reflection. Phase is independent of amplitude, indicates the continuity of an event and provides another useful criterion to interpret reflections. In areas of poor reflectivity, where reflection amplitudes are too weak to be manifested and correlated, phase is likely to be helpful in mapping the continuity of the reflection (reflector). Phase mapping is especially sensitive to detection of discontinuities like pinch outs, faults, fractures and angularities as well as unconformities based on 'out of phase' events.

Frequency (Bandwidth)

A seismic wavelet, usually of one to one-and-a-half cycles in the beginning, changes shape progressively during propagation and becomes long and cyclic (leggy) with passage of time. The pulse width of a wavelet on the seismic record in time (time period) provides an estimate of its dominant lowest frequency, and it grows larger with depth during propagation, indicating lowering of frequencies caused due to attenuation. The bandwidth is a measure of the width of a range of frequencies in the wavelet, measured in hertz and is the key to quality of reflection. Bandwidth decides the time duration of the changing wavelet corresponding to depth intervals, reliant on the velocity and controls vertical and lateral seismic resolution. A broad bandwidth consisting of both low and high frequencies is thus considered essential to provide quality seismic images. The lower frequencies in the spectrum help in deeper penetration of energy where as the higher frequencies direct the thin bed resolution. Unfortunately, during propagation of the wave, the earth attenuates the high frequencies and hampers desired resolution at depths.

Because frequency is affected by propagation phenomena like absorption and transmission in the subsurface, its variance can provide at times valuable information on geologic strata and its geometry. Layered beds at shallower depths generally evince reflections with high frequency contents whereas older and harder rocks (for example, Pre-Tertiary rocks) at deeper depths show relatively low- frequency reflections. The experienced seismic interpreter is familiar with the clearly discernible decrease in bandwidth of reflections from the top to bottom of a typical seismic section. Bandwidth, amplitude and phase create the shape and form of a signal, and the individual components can only be measured and analyzed by detailed spectral analysis, discussed later in Chap. 10.

Polarity

The polarity expresses the sign of a reflection coefficient. It is considered positive if the impedance of the rock below is positive (a hard rock underlying a soft rock) and negative, the other way round. Conventionally, on normal processed data (SEG normal polarity convention), peaks and troughs of reflection events represent positive (black) and negative reflection coefficients (white), though an option for plotting reflections with reverse polarity remains with the interpreter. It is important to define the polarity convention clearly in the processed data so as to avoid making basic mistakes in interpreting the geology. Picking of reflection polarity is simple and straight forward in case of discrete reflectors, but is difficult in transitional and complex reflectors where superposition of reflectors leads to distortion of events and provides a composite reflection. Noise in data also acts as a deterrent for clear determination of polarity. Deconvolution and zero phase processing help to some extent in estimating polarity of composite reflection events. Accurate picking of polarity, wherever possible, helps in locating the disposition and nature of the strata in the subsurface.

Arrival Time

Reflections arriving at different times on a record for discrete reflectors indicate the temporal position of rock boundaries encountered in the subsurface. Since the events are recorded in time, accurate velocity function is required to convert the arrival times and determine the depths of the causative reflectors. Despite deploying true velocity, there can still be inexactness in some cases in matching the actual subsurface depth with depth converted from time. For transitional and complex reflectors, the precise time of onset of a reflection is usually recorded as delayed and can pose a problem, *prima facie*. The system of recording and processing of data also behaves like filters and introduces time lags. If the induced delay is not properly taken care of, it may add to the overall delay, which may vary from a few to several milliseconds, depending on type of seismic data (2D/3D). Seismic analysts often find such time shifts in tying a particular reflection phase in different vintages of seismic, especially in 2D data, due to varying recording and processing parameters used and one must be careful before picking and mapping geologic horizons.

Velocity

Velocity is an important seismic attribute, not only to estimate depths of formations, but also to provide vital information on subsurface rock and fluid properties. Basically, velocities are of two kinds, the *overburden* or vertical average velocity, and the *interval* or formation velocity. Vertical velocity is used for conversion of reflection times to depth and the interval velocity for estimating lithology and other rock properties like porosity and fluid contents. The two velocity functions are interrelated; knowledge of one can lead to calculation of the other. The seismic CDP technique permits the calculation of an apparent overburden velocity from multi-trace data processing and is known as the normal move out (NMO) or stack velocity. Stacking velocity is so named, as it is computed mathematically from the normal move out equation which maximizes the effect of summation of traces in a CDP gather. It is a velocity along the direction of the geophones and is affected by factors such as dips of strata and recording spread lengths. Stacking velocities are usually higher (by about 6–10 %) than true vertical average velocity, which can be measured only in a well. Stacking velocities are also referred to as RMS (root mean square) velocities. Where well velocity is not available, the RMS velocity after appropriate correction is used to predict top, bottom and thickness of geologic formations. The lithology and other rock properties can be also inferred from interval velocities (formation velocity) calculated from stack (RMS) velocities.

The velocity used for migration of seismic data, a process that moves the subsurface reflecting points to their true spatial position below the shot point is known as the migration velocity. It is an overburden velocity and applied appropriately, produces relatively clean and accurate seismic images that help predict rock properties better. Generally, it is lower than stack velocity but tends to equal true overburden velocity where migration of data is perfect to provide reliable depth conversions.

Seismic Display

The visualization of seismic data is an integral part of interpretation and as such, it is important that the processed seismic data be displayed in suitable graphic modes and scales. Nonetheless, it depends to a large extent on the objectivity of the interpretation and the perception and creativity of an individual interpreter. Generally, data are displayed in any one of these modes, wiggle trace, variable area, and variable density or in a combination (Fig. 2.9).

- Wiggle trace is a log of reflection amplitudes with time and makes it handy to interpret geologic information from the variability in the waveform shape.
- Variable area (VA) and wiggle displays are wiggles shaded with bias, and make reflection events appear more consistent and convenient for correlation by reflection character.
- Variable density (VD) shows reflection strength, and displayed with color, provides better relative standout and continuity of reflections. VD sections, though more commonly used, do not show the waveform shapes that embed significant geologic information (Fig. 2.10).
- Combinations of variable area and wiggles may be a preferred display for interpreting stratigraphic details.

Though the work stations provide different modes of display, interpreters generally use Variable density sections due to better apparent continuity of reflections and their amplitude stand-outs that can be conveniently used as an attribute display. But

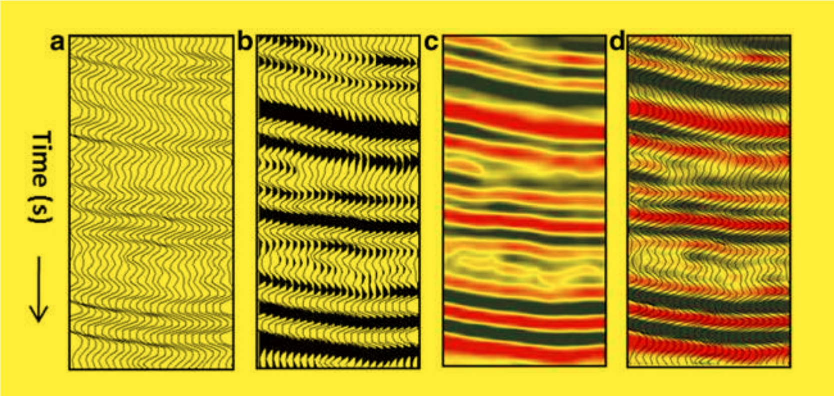

Fig. 2.9 The types of seismic data display modes. (**a**) wiggle, (**b**) wiggle and variable area, (**c**) variable density, (**d**) combination of wiggle and variable density. Note the waveform changes seen clearly in wiggle and variable area display mode (**b**), that carry the crucial geologic information

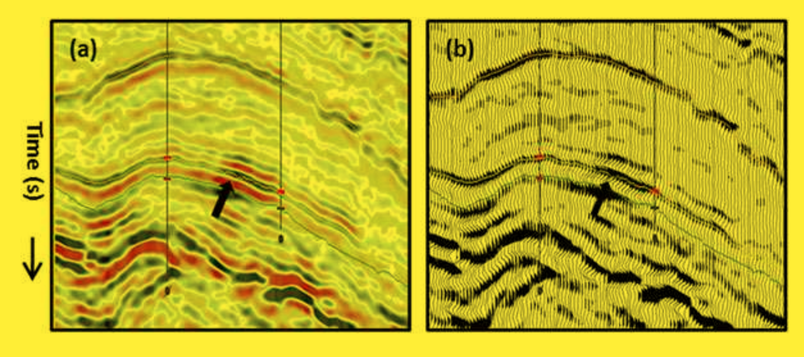

Fig. 2.10 Comparison of seismic (**a**) variable density, and (**b**) wiggle display modes. Reflection stand-outs and continuity seen better in the variable density display, but does not show the changes in waveform that carry important geologic information, whereas wiggle mode clearly shows the variations in waveform shape (trough indicated with an *arrow*) (Image: Courtesy, Hardy Energy, India)

this can be misleading in sedimentary environments of continental to fluvio-deltaic deposits where fast and frequent facies variations are likely to occur causing discontinuous and patchy reflections. Use of Variable density sections for tracking reflection continuity in such cases may be geologically flawed. One may prefer wiggle mode of seismic display that allows inferring geology guided by reflection character relying on the waveform shapes.

Color display is known to increase optical resolution leading to better visual discrimination of features and is used widely. The selection of suitable color and its encoding depends on the artistic attitude of the interpreter but assigning colors in a spectral progression is preferred as it enhances the relative magnitudes well.

Plotting Scales (Vertical and Horizontal)

Plotting scales are extremely important in data display, as reducing or stretching the scales changes visualization of the geologic objectives. The scales are to be suitably chosen depending on the objectivity of the interpretation. Horizontally compressed sections improve perceived continuity of events with gentle dips appearing stronger. Stretched sections, on the other hand, appear to deteriorate reflection continuity with flattening of the dips. Accordingly, faults with small displacement, low dipping progradations, gentle pinch outs and terminations etc., which are subtle but important as exploratory objects, look more conspicuous to be picked on compressed scales. Compressed (squashed) sections are also very useful for interpretation of regional geology for basin evaluation as a long stretch of a profile can be conveniently displayed in one vision frame at a time. Similarly, vertically compressed (half) sections offer the advantage of viewing the entire geological section from the deepest depth to the surface and help in better assessment of geological evolution of a basin. On the other hand, sections stretched in time are often used to magnify details of important targets to be picked for mapping. Each geologic object requires appropriate scales for its clear standout and needs experimenting for choosing the best judicious combination of both the vertical (time) and horizontal (trace) scales along with the mode of display.

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