Seismic Reflection Principles—Basics

Abstract

Seismic reflection events are caused by impedance contrasts at interface of two layers and with a requisite minimum width (Fresnel Zone). The reflection images are required to be of utmost quality to represent reliably the subsurface geology. The quality of an image depends on signal-to-noise ratio and its resolving power, the ability to show details of individual geologic features, vertically and laterally. This requires an efficient energy source to generate seismic waves with broad-bandwidth, consisting of both low and high frequencies that can penetrate deeper to detect and define stratal layers and their properties.

A seismic reflection trace provides attributes such as amplitude, phase, polarity, arrival time and a record comprising of multitraces the velocity which can be measured or estimated. The polarity information is important for calibration of seismic with well and for identifying lithologies and correlating strata. Reflection polarity is crucial particularly for authenticating high amplitude seismic anomalies for direct detection of hydrocarbon and its role is emphasized in the chapter along with the other attributes. The reflected wave-form and its arrival time depends on rock properties of a strata and its depth and carries these crucial geologic information, contained in the seismic attributes of the waveform. Estimating the rock properties from seismic waveforms and their vertical and lateral changes in time and space is the essence of seismic interpretation.

Display of data plays a major role in visualizing seismic images and appropriate choice of seismic display modes and plotting scales are important for optimal geologic perception of seismic image and is stressed with example.

Seismic wave, generated artificially on surface when propagates downwards through the earth, it meets several interfaces between different kinds of rocks having diverse properties. This causes phenomena such as 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 technology, deployed to portray the subsurface to find 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. 1). We shall limit the discussions for the present to the principles of relatively simple P-wave reflections, used extensively for measuring rock and fluid properties. The S-waves reflections, their properties and utilities are discussed in Chapter "Shear Wave Seismic, AVO and Vp/Vs Analysis".

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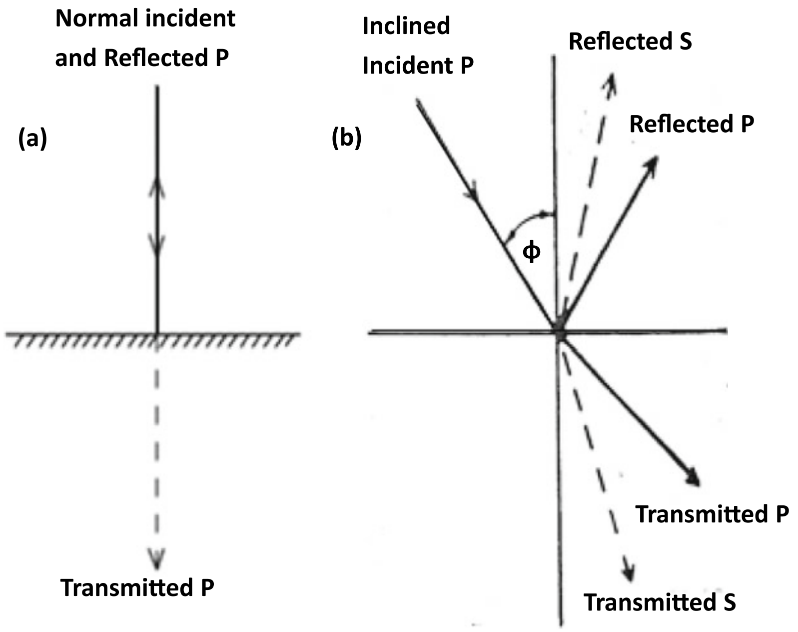

Fig. 1 Seismic wave propagation phenomenon at an interface of two different rocks. (**a**) normal incident P-wave produces single set of waves normal to the interface, the P-reflected and the P-transmitted, whereas (**b**) inclined incident produces two sets of waves, P-reflected and P-transmitted and S-reflected and S-transmitted (refracted)

Seismic reflection event herein is considered as a correlatable event over an area conveying a geologic feature. Generation of a seismic reflection event needs primarily two things, (a) an impedance (product of velocity and density) contrast at the interface of two rock types and (b) a minimum width (Fresnel Zone) of the interface. The reflection amplitude and its continuity depend on the degree of contrast across the interface, its type and geometry and lateral extent. Effectiveness of reflection events to reliably portray the subsurface geology is, however, conditional to the quality of seismic reflection signal, which is influenced by (i) the amount of noise recorded in the data and (ii) the ability of the seismic wavelet to image the different interfaces separately and distinctly. The seismic reflection quality is thus adjudged by the two seminal factors, the signal-to-noise ratio(S/N) and the resolving power of the seismic wavelet, briefly described below.

Signal-to-Noise Ratio (S/N)

Noise may be defined as all types of undesired energy, other than the primary reflections from the subsurface strata that are recorded. Noise is an inherent part of the seismic data acquisition and processing system, created by intrinsic ambient (within earth) noise, geological (natural propagation hurdles in the subsurface) and geophysical (artifacts during recording and processing) processes. Noise cannot be wished away, but can be effectively reduced by conscious efforts during data acquisition and processing. Ironically though, noise usually considered unwanted, can be occasionally helpful in interpretation in some cases. For example, remnant diffraction noises despite processing may indicate clues to presence of sharp edges, such as faults and other subtle stratigraphic objects, particularly in 2D data. Scattering is another kind of noise which may give an idea about the order of heterogeneity of the reflector, leading to indication of highly tectonized zones with complicated structures and associated faults and fractures.

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 requires meticulous planning of survey layout plans, field experimentations and optimal parametrization followed by strict on-field execution to ensure data quality with good S/N ratio. The unique common depth point (CDP) technique for seismic data acquisition in the context is by far the most valuable gift to reflection seismic technology. It is a standard technique practiced all over the world with many possible variations in lay outs, according to suitability of the geologic objectives. It achieves signal enhancement at the cost of noise, via a summation process of several traces reflected from the near-same common depth point with different offsets after correcting for the offset geometry, known as CDP fold stack. In reality it is not exactly the same depth point because of the dipping layers in the subsurface and is more precisely termed as common md point (CMP) stack. What the summation does is it amplifies the signals which are similar and cancels the noise which are random. 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 more traces (folds) cost extra money for acquisition without commensurate improvement in the seismic images. Also summation is an integration process, which affects resolution due to loss of high frequency, 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.

Seismic Resolution

Resolution may be defined as the ability to separate two closely spaced features in depth (time) as well as in space. The resolution we refer to in seismic is of two types, vertical and horizontal. Vertical (temporal) resolution is the minimum separation in time between two reflections arriving at the surface for recording that enables to detect each reflector separately. Lateral (or spatial) resolution is the minimum lateral distance between two closely spaced geologic objects in space that permits each one to be imaged separately. It is important to keep in mind that detection of an event is not the same as resolution which defines the detected object clearly.

Resolution depends on the seismic wavelength with which the subsurface feature is measured. Wavelength is a fundamental property of a wave which is the distance between successive points of its equal phase (e.g., crest to crest), completing one cycle. It is usually denoted by the symbol λ and is defined by the equation $\lambda = v/n$, where 'v' and 'n' stand for the velocity and frequency of the wave passing through a medium. Smaller wavelengths provide better resolution whereas wave lengths, too large compared to the dimensions of the object, fail even to detect it. Since wavelength is a direct function of velocity and inverse of frequency, seismic resolution happens to be better at shallow depths where higher frequencies are dominant and the seismic wavelength is smaller due to relatively lower velocity. On the other hand, because of increasing velocity and lowering of frequency with depths, the seismic resolution deteriorates with depth.

Vertical Resolution

A short-width sharp zero phase wavelet (high frequency bandwidth) ideally provides the best resolution. Zero phase wavelet is symmetrical with maximum amplitude at time zero, chosen as the origin and has small and even side lobes (Fig. 2). Because of short duration (in time) and the nature of the wavelet, reflection arrival times correspond to exact depth of the geologic features without time delay and thus facilitates beds to be imaged individually without overlaps and at appropriate time with respect to depth. In contrast, minimum phase wavelets are asymmetrical, front-loaded energy wavelet with uneven side lobes which impede resolution (Fig. 2). A zero phase wavelet is therefore an interpreter's desired wavelet though the commonly used seismic sources like dynamite on land and air-guns in marine surveys produce minimum phase wavelets. However, Vibroseis source used on land, generates a zero-phase wavelet, known as *Klauder* wavelet that makes it a preferred choice. However, Vibroseis trucks are not accessible in many terrains and also provides relatively less energy compared to dynamite source. More about the zero and minimum phase wavelets and their nature is described under subhead polarity.

The seismic short source wavelet, an impulse, however, while traveling within the earth suffers loss of high frequencies due to absorption and gets changed with passage of time to a long and cyclic ('leggy') wavelet which becomes a mixed phase wavelet. The large and leggy nature of the wavelet does not permit enough separation between the arrival times of reflections coming from closely spaced beds. This results in overlapping of the individual events and losing the ability to resolve the beds separately (Fig. 3). It has been demonstrated by Widess (1973) by modelling a wedge that $\lambda/8$ is generally the limit of bed thickness as the vertical resolution, below which thinner beds cannot be seen as resolved. Widess's wedge model envisages impedance contrasts as same at the top and bottom of the wedge and with the signage reversed (Fig. 4). However, in many geologic situations the impedance contrasts at top and bottom are likely to be different in values and are also of same signage as top and bottom, in which case, the Widess model of thin bed resolution limit may be different. Nonetheless, practical experience shows that in real-earth situations, where some amount of noise is always present in the data, $\lambda/4$ may be considered a reasonable wavelength as the vertical resolution limit for resolving beds. Vertical (temporal) resolution worsens with depth and generally varies from 10 to 15 m at shallow depths to 20–30 m at greater depths.

Exploration objectives (reservoirs) are often thin and require improved vertical resolution for proper delineation. Resolution can be enhanced during acquisition by deploying a broad-band wavelet as a source (dynamite) and by recording

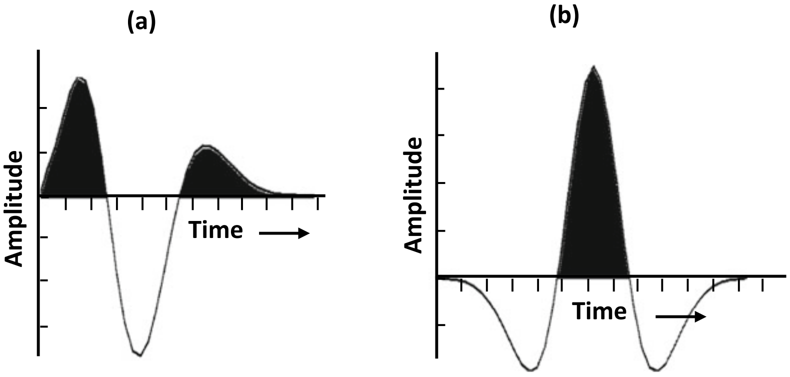

Fig. 2 Showing types of seismic source wavelet types (**a**) minimum phase wavelet, generated by dynamite on land and air-gun in offshore and (**b**) zero phase wavelet generated by Vibroseis in land data acquisition. Zero phase wavelet is symmetrical with even side lobes and the amplitude maxima occurs at time corresponding to exact depth of the strata without time delay. Note the minimum phase wavelet (**a**) is asymmetrical with energy loaded in front and the maxima occurs at a delayed time

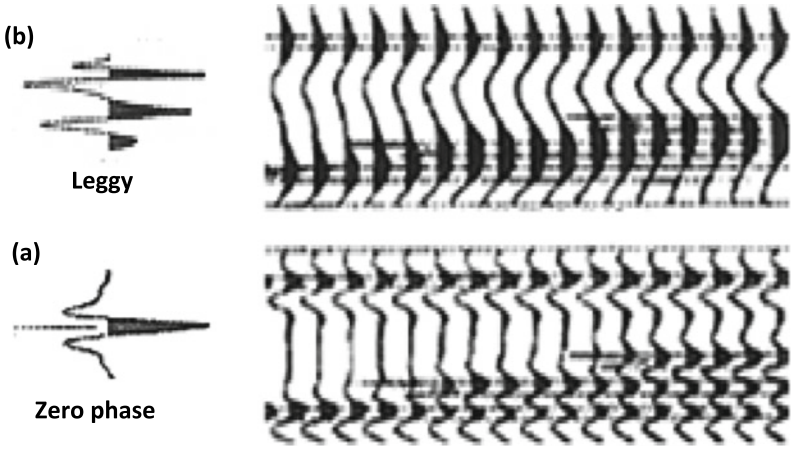

Fig. 3 Example showing resolving power of (**a**) zero phase wavelet and (**b**) leggy (cyclic) wavelet. Note the excellent vertical resolution of thin beds by zero-phase wavelet whereas, (**b**) the leggy mixed phase wavelet impedes resolution by causing overlapping of reflections from thin beds. Zero phase, short wavelet, shows maximum amplitude at zero time without delay and with small side lobes promotes better resolution (after Vail et al. 1977)

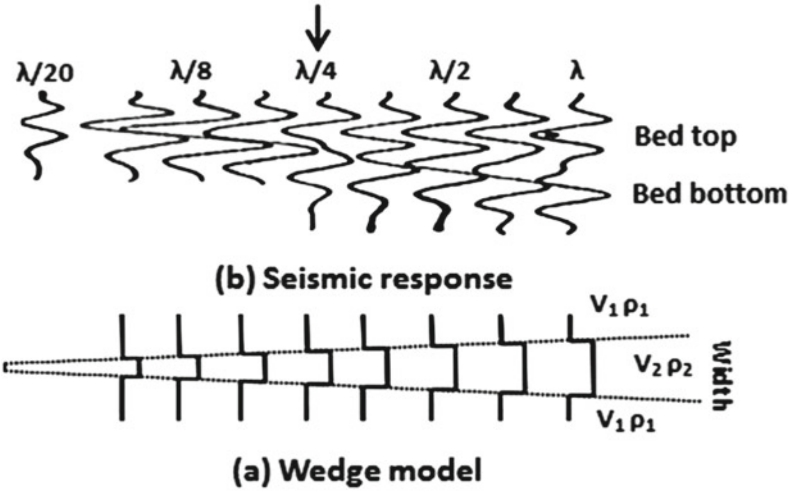

Fig. 4 Schematic illustrating Widess wedge model for vertical resolution limits. (**a**) The Widess wedge model and (**b**) seismic response for varying bed thickness. For a bed thickness greater or equal to the wave length (λ), the top and bottom reflections are clearly resolvable and are so till quarter wave length (λ/4). For beds thinner than λ/4 the top and bottom reflections are not distinct (arrow marked), limiting the vertical resolution to quarter wave length (after Widess 1973)

with smaller sample intervals (temporal, ∼ 2 ms). In addition to the data acquisition efforts, care is taken to retrieve the signals and improve resolution by boosting the higher frequencies during data processing, a technique known as deconvolution. The recorded seismic trace is a convolution, a mathematical process of conjoining two signals (likened to ∼ product), of the source wavelet with the earth's reflectivity series (array of impedance contrasts in the subsurface). If the source wavelet can be removed from the recorded trace through data processing, the impedance contrasts representing geologic rock discontinuities will be left behind which is the sole aim of seismic investigation. Deconvolution and zero-phase wavelet are processing steps to increase vertical resolution by suppressing multiples and by compression of the wavelet (shortening) that is achieved by increasing effective bandwidth and eliminating the effects of side lobes.

Lateral (Spatial) Resolution and Fresnel Zone, Migration

Huygens' Principle stipulates that reflection from a surface consists of a number of diffractions occurring from each point on it and does not come from a single point. Where the reflecting surface is uniform and planar, the diffractions from all points add constructively to provide a reflection event. If, however, the surface is curved or has limited small continuity, the diffractions may not add effectively resulting in poor reflection. Seismic waves that originate from a point source are spherical in nature, and when incident on a plane reflector, they sweep through it by producing a succession of contact zones. Nonetheless, the limited planar area, which 'effectively' comes into contact at the interface and collectively contributes to produce a coherent reflection event is called the (first) Fresnel zone (Fig. 5a). The seismic wave is a band-limited signal comprising a range of frequencies, and when incident on an interface, each frequency creates its individual area of contact with the interface to cause a reflection. However, the reflections recorded are considered to be from the first Fresnel zone formed by the dominant frequency. Fresnel zone is considered to serve as a yard stick for defining the lateral resolution, smaller the width of zone, better is the resolution. It is important to visualize the phenomenon of reflection as an 'area' concept in two dimensions and as 'volume' concept in three dimensions instead of a single 'point' notion that can have enormous significance in data interpretation and evaluation.

Reflectivity of widths less than a Fresnel zone tend to deteriorate the reflection quality. Modeling has demonstrated that interfaces having width less than $\lambda/4$ cannot be viewed clearly and thus defines the limit for spatial resolution (Fig. 5b). The Fresnel zone may be considered as a spatial requirement, complimentary to the vertical impedance contrast, responsible for causing reflection event. Similar to thickness of the bed which determines the temporal resolution, the Fresnel zone width can be considered to serve as a yard stick for defining the lateral resolution.

The quality of a reflection depends not only on the area defined by Fresnel zone but also on the geometry and type of its reflecting surface. Warped surfaces behave as curved reflectors and depending on whether the reflector is concave or convex upwards, it exhibits focusing and defocusing effects. Consequently tight synclines are well imaged due to convergence of reflected ray paths while tight anticlines are poorly imaged because of divergence of rays (Fig. 6a, b). In extreme cases, acute synclines at greater depths with very high curvatures generate reflections converging from the concave reflector and cross one another before being recorded at the surface. This is known as a 'buried focus' effect and exhibits a familiar reflection pattern known as "bow-tie" (Fig. 6c). The bow tie apparently looks like antiform which in reality is a tight synform. Rougosity of reflectors such as erosional unconformity and highly heterogeneous and anisotropic rocks are other factors that cause large amount of scatter and impede image quality. Scattering is considered a noise and is usually not handled in routine data processing though recent advances in migration techniques can process efficiently the scatters in 3D data by reconstructing the energy from where it originated from.

Poor/no reflections at times, associated with fault edges, sharp facies changes, small reefal mounds and erosional unconformities may be examples of poor imaging linked to inadequate Fresnel's zone width. However, a small discontinuity in the reflecting surface, for instance, a hole cut in the Fresnel zone, will hardly affect the quality of the averaged reflection due to phenomenon known as 'wave front healing', a process by which the waves are diffracted around the

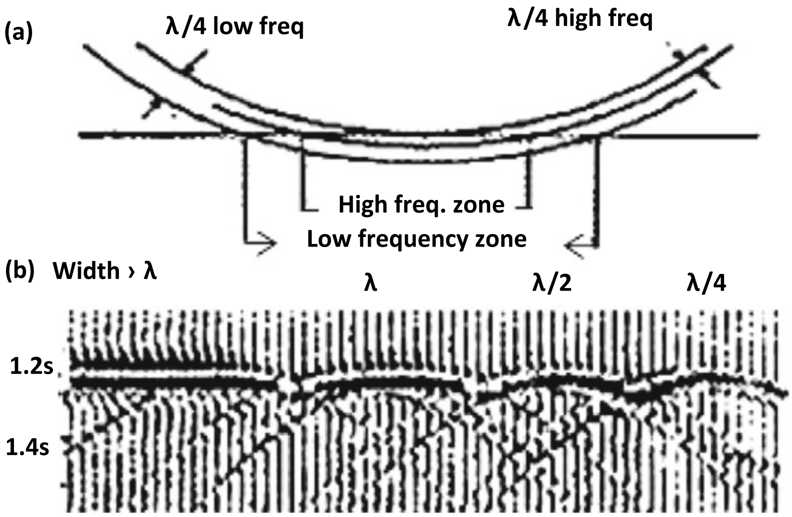

Fig. 5 Schematic illustrating phenomenon of reflection and the Fresnel's zone. (**a**) Spherical wave front incident on plane surface forms contact zones of different widths for each of the frequencies in the bandwidth. However, the contact area for the dominant frequency mainly influences creating reflection events and is known as the (first) Fresnel zone and is a measure of lateral resolution. Smaller the zone-width better is the resolution. The width of Fresnel zone at a depth is dependent on frequency, being larger for low frequency than for high frequency. (**b**) Synthetic reflection events computed with variable source wavelength. Notice the start of deterioration in reflection at λ/4, which sets this as the limit of spatial resolution (after Meckel and Nath 1977)

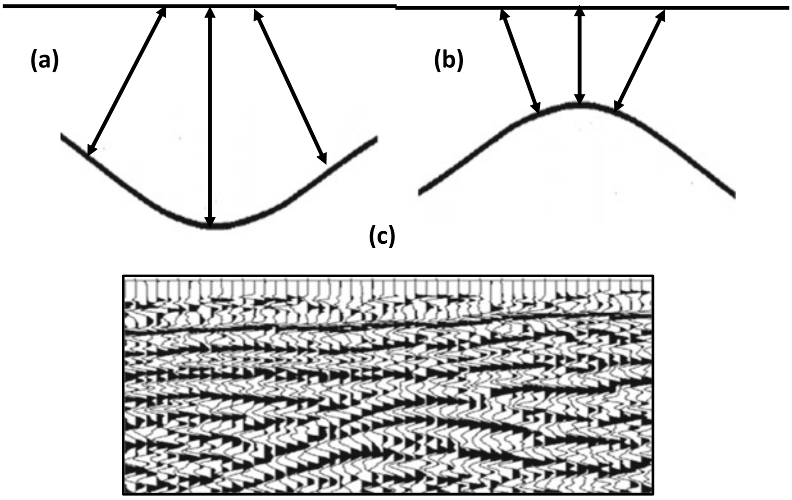

Fig. 6 Effects of curved surfaces on reflection. (**a**) rays reflected from concave reflector (synform) converge while (**b**) they diverge from convex reflector (antiform). Note the rays converging would cross one another before reaching the ground, if it is too far up. (**c**) This can happen for tight synforms at large depth and the effect is known as 'buried focus' and is manifested in unmigrated seismic as a 'bow tie', an artefact showing spurious antiform

anomaly (Fig. 7). This can have important geological implications, the open fractures and cracks present in rocks may be difficult to be imaged directly by seismic. Furthermore, Fresnel zones in the subsurface are often not planar but consist of curved surfaces, which is yet another factor that affects quality of reflections particularly in 2D data. In perspective of Fresnel's zone

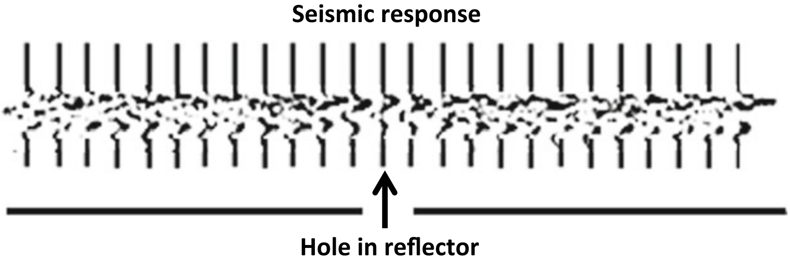

Fig. 7 Sketch illustrating 'wave front healing' effect. A small discontinuity in the Fresnel zone, in the shape of a small hole in the reflector, has little effect on seismic reflection because the diffracted waves go around it, and is known as 'wave front healing' (After Sheriff 1977)

width, for anticlines the contact area of the wave with the reflector is small amounting to lower amplitudes, whereas for concave surfaces (synclines), the contact area being more, provides strong amplitudes. This phenomenon is similar to focusing and defocusing effects of an optical lens as stated earlier. However, most of the effects discussed such as bow-tie, imaging of curved surfaces, focusing and defocusing and diffraction noise are usually not evinced in present day data as they are removed by powerful migration techniques during data processing. Nonetheless, interpreters may be mindful of these artefacts as in many cases 2D data of old vintage are only available for interpretation. Furthermore, hints of such features on seismic can be an indicator about the quality of processed data, being ineffectual and under migrated.

It is important to comprehend the Fresnel zone curvatures and the widths which in reality vary greatly contingent to several factors making it an intricate three-dimensional problem. In a two dimensional case, at a particular depth it is approximated by a simplified form as product of seismic wavelength and depth as $R \approx (\lambda \text{ x } z/2)^{1/2}$, where R, λ and z represent the Fresnel zone radius, seismic wavelength and depth respectively. The Fresnel zone width varies with depth, is small of about ten to fifteen meters at shallow depths (small wave length and distance from source) and increases to the order of hundreds of meters at depths. Since the Fresnel zone width sets the spatial resolution limit, it is important that the zone be reduced to a minimum to improve spatial resolution so as to resolve small geologic objects clearly separated from each other. This is achieved by sampling the profile with closer geophones on ground during acquisition and to a large extent in data processing by a technique called migration. Migration enhances horizontal resolution, a role similar to that of deconvolution which augments vertical resolution.

Migration

Migration technique works on mathematically continuing downward the wave field, virtually amounting to lowering of the surface geophones down up to the reflector. This reduces the distance and consequently the Fresnel zone for improved resolution. The process of migration achieves primarily (i) restoration of dipping seismic reflection events to their true geological subsurface positions and (ii) collapsing of diffractions to improve images and their continuity. Migration puts the reflected energy back where it originated from (Etris et al. 2002) and provides a reconstructed version of the true geometry of the subsurface. A schematic illustration of two dimensional migration restoring the exact disposition of a subsurface dipping segment by shifting it laterally and updip is shown in Fig. 8. It shows that the true length of the segment is smaller and the dip higher compared to its apparent location mapped in an unmigrated section. For the same reason, unmigrated or under migrated seismic sections show larger areas for anticlines and smaller for synclines. The geologic significance is that the reserves estimated for anticlines on poorly or

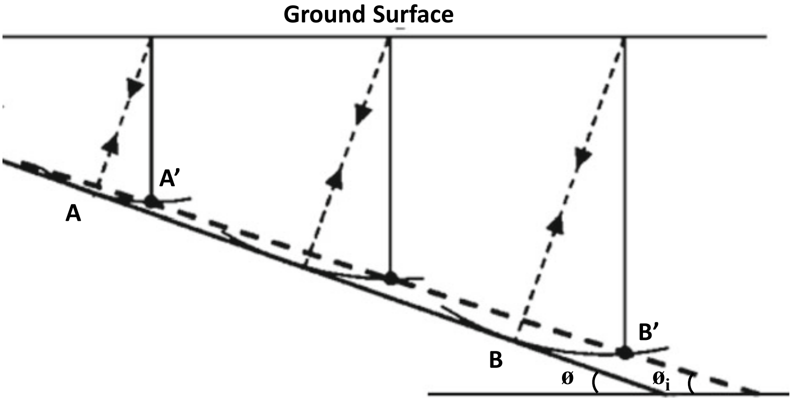

Fig. 8 Schematic illustrating seismic migration in restoring exact position of the subsurface reflector with true dip. The thick line AB represents the real subsurface reflector segment while the dashed line is its apparent position A'B' as seen in unmigrated seismic. This is because the normally reflected ray paths (arrowed dashed lines) from the real reflector are deemed arriving from vertically below the shot points and are plotted accordingly. Note the difference between the true and apparent dips and length of the reflector segment. The true dip is more and the length is shorter with the segment laterally shifted to be positioned updip to represent its proper subsurface position

unmigrated 2D data are likely to be inflated than actual. Fresnel's zone being a three dimensional phenomenon, two dimensional migrations carried out on 2D data is never perfect as it narrows the Fresnel zone in that plane only. Restoration of true disposition of subsurface features essentially require 3D migration for optimum resolution of three dimensional geologic features.

Migrated sections also preserve true reflection amplitude, creates a more accurate image of the subsurface and more importantly, enhances spatial resolution. For these reasons, migration of data is desirable even for data with flat geologic strata. Typically, the Fresnel zone widths, which are 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 traces around the object, referred as aperture, is necessary for migration stack. 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. However, the migration results suffer gravely near the end of seismic lines due to lack of traces recorded and the interpreter should be cautious to consider data in this part during interpretation.

For better resolution, lateral changes in reflectivity of small dimensions, migration requires finer spatial sampling on ground mentioned earlier, similar to temporal sampling used for improving vertical resolution. Take for instance the issue of imaging a small channel of 20 m width, which is often the exploration objective. Obviously, the object cannot be resolved with insufficient trace sampling of 25 m though the image with this trace spacing may be able to detect it. The channel 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 with one exception, the temporal resolution depends on interval velocity while the spatial resolution is dependent on overburden velocity. As an example, consider a limestone bed with an interval velocity of 3200 m/s and an overburden velocity of 2400 m/s for calculating the resolution limits. Given the dominant frequency as 40 Hz, the vertical and spatial resolution limits are 20 and 15 m respectively, considering quarter wavelength as the realistic limits of resolution. It is useful for the interpreter to have some idea about resolution limits beforehand; otherwise, one may be looking for things that are beyond the capability of the recorded data to offer. It is also interesting to note that the two resolution effects are co-linked and improving one tends to better the other (Lindsey 1989). For instance, if two thin beds placed vertically or sidewise are not resolvable, a blurred image of envelop of the entwined beds would be created, whereas resolved either vertically or laterally, each of the beds can be clearly defined.

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, in nature beds are commonly closely spaced in the subsurface and reflections from several beds arrive within a time spacing that is less than the length of the seismic wavelet. This leads to superposition of the reflections (Fig. 9). The ensuing interference can be either constructive or destructive and the resultant composite reflections depend on a) number and thickness of the thin 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 reflectors, namely *discrete, transitional* and *complex*, that an interpreter routinely comes across during interpretation (Fig. 10).

Discrete Reflectors

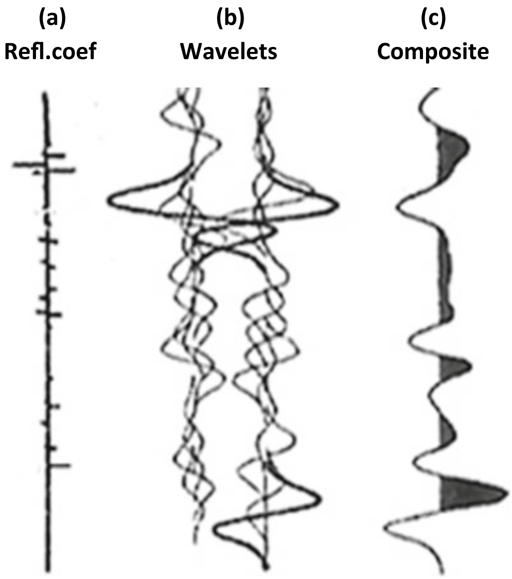

Fig. 9 Interference of reflections from closely spaced interfaces. (**a**) subsurface reflection coefficient series. (**b**) reflected wave let from the individual beds and (**c**) the composite reflection caused by superposition of individual reflections from the thin beds which are unresolved (modified after Vail et al. 1977)

Top and bottom of thick beds with sharp impedance contrasts create distinct separate reflections with reverse signage for recording and are termed discrete reflectors. The reflections from top and bottom appear well separated with amplitude proportional to reflection coefficients. For a zero phase wavelet, the onset of the reflection from the interface, either a peak or trough (polarity), appears at the correct time on record with respect to its subsurface depth without any time delay.

Transitional Reflectors

A transitional reflector has a gradual gradation of impedance contrasts of one signage, either positive or negative (Anstey 1977), as in a fining upward channel or coarsening upward bar sand. The interference of a succession of reflections of the same signage of impedance contrast results in a composite reflection creating a combined average wave shape. The reflection amplitude is generally weak with a low frequency appearance, the onset time is delayed with respect to the top of the formation and with unclear peak or trough to represent the contrast of beds

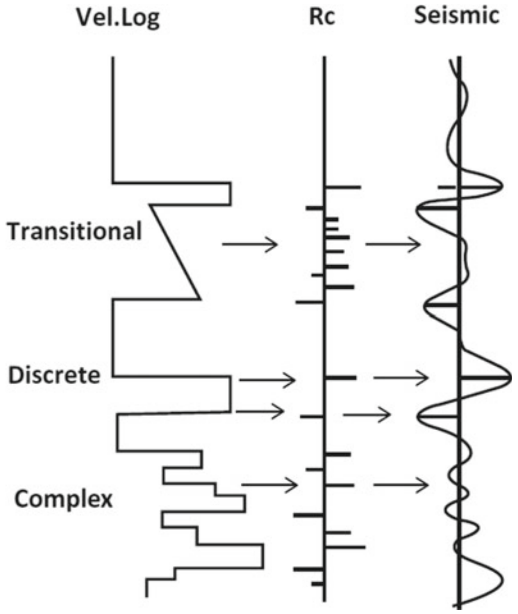

Fig. 10 Schematic showing the different types of reflectors. A ‘discrete’ reflector causes top and bottom reflections, resolvable with distinctive polarity and exact arrival time. The ‘transitional’ and ‘complex’ reflectors are composite events of several closely spaced beds with uncertain signage of polarity and delayed arrival time (modified after Clement 1977)

Complex Reflectors

Complex reflector is a pack of reflectors, spaced closely but with varying magnitudes and signage of impedance contrasts (polarity), which produce a complex wave form of the reflection event. The strength, onset time of the reflection and the signage of impedance contrast 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 which are the amplitude, phase, frequency, and polarity, arrival time (velocity), all of which can be measured or estimated. The attributes of the reflection signal carry important geologic information encrypted in them and provide the arrival times of the geologic strata. Estimates of these rock properties from seismic waveforms and their vertical and lateral changes in time and space is the essence of seismic interpretation to predict subsurface structures and stratigraphy for petroleum exploration. The basic elements of reflected seismic wave which is the signal, are introduced here; their measurement and application are described in Chapter “Analysing Seismic Attributes”. The schematic diagram Fig. 11 illustrates the attributes of a reflected wave.

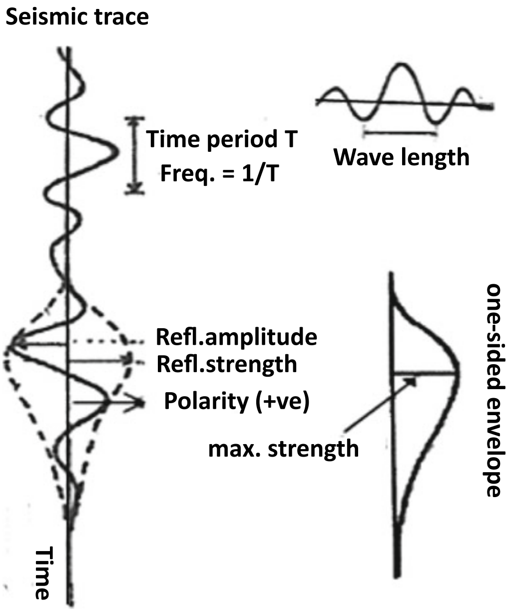

Fig. 11 The seismic signal attributes measurable from a trace, namely the time period, wavelength, reflection amplitude, reflection strength and polarity. Reflection strength is the maximum amplitude of the envelope of a composite reflection, independent of phase. Note the reflection amplitude maxima is different from the reflection strength maxima (after Anstey 1977)

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 upward and the other transmitted downward. 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 also on 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 (refer Fig. 1) and the above equation for the normal reflection coefficient gets complicated and is guided by Zoeppritz's equations, discussed in Chapter "Shear Wave Seismic, AVO and Vp/Vs Analysis".

Amplitudes are measures of particle velocities or pressures and in an ideal case, for zero-phase wavelet, the maximum value at peak/trough of the wavelet pulse represents the reflection coefficient of a discrete 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 may be convenient to use reflection strength, which is the maximum amplitude of one side of a symmetrical envelope, centered about the reflection event. 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 (Fig. 11) Reflection amplitude and its variations are useful tools 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 influence of 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 change can be visually seen as a change in continuity of a reflection horizon manifested by a shift in the peak/trough correlated. Phase is independent of amplitude and indicates the continuity of an event which 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. However, phase correlation needs processing of data for transforming the signal from time domain to frequency domain (Chapter "Analysing Seismic Attributes").

Frequency (Bandwidth)

A seismic wavelet, usually of one to one-and-a-half cycles duration 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 becomes wider with depth during propagation indicating lowering of frequencies caused by 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 of a wavelet decides the duration time (width) of the changing wavelet corresponding to depth intervals, reliant on the velocity and defines the vertical and co-linked lateral seismic resolution. A broad bandwidth consisting of both low and high frequencies is thus essential to provide quality seismic images. Ironically, the frequency ranges behave in contrasting manner. The lower frequencies in the spectrum help in deeper penetration of energy but have poor resolution power whereas the higher frequencies have poor depth penetration but provide higher resolution to delineate thin beds. 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, frequency variance can provide valuable geologic information. Generally reflections dominant with high frequency looks indicate thin layers of strata at shallower depths whereas relatively low- frequency dominated reflections indicate older and harder rocks (i.e. Pre-Tertiary) at deeper depths. The differences in frequencies of groups of reflections evinced on data can sometimes be strikingly clear to suggest unconformities. Experienced seismic interpreters are familiar with such clearly discernible decrease in frequency 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 in Chapter "Analysing Seismic Attributes".

Polarity

Polarity is an attribute which represents signage of reflectivity and is different from phase which is an intrinsic property of a wave. Polarity of a reflection signal is crucial in seismic-well ties for correlating reflection horizons. It helps identify lithologies and is the mainstay for analysis of high amplitude seismic anomalies (DHI) for detection and validation of hydrocarbon in reservoirs and fluid contacts. Hydrocarbon bearing DHI anomalies, 'bright', 'dim' and 'flat spots' are essentially characterized by the signage of reflection polarity (Chapter "Direct Hydrocarbon Indicators (DHI)") and it is important the seismic analyst is mindful of the polarity displayed in the seismic data before interpreting DHI anomalies. Polarity expresses reflectivity of a bed interface and 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.

Polarity Display Conventions, Acquisition Source Wavelet

In processed seismic data, polarity can be displayed in different ways depending on the conventions followed by individual companies or/and the interpreter's preferred choice. There are basically two standard display conventions mostly followed, the SEG in USA and other countries and the Europa, in European countries. The display conventions are essentially based on the type of source wavelet used in seismic data acquisition. In processed data, the SEG normal polarity display for minimum phase source wavelets, generated by dynamite and air-gun sources, compression (+ve Rc) is represented by trough (white/red) and rarefaction (−ve Rc) by peak (black/blue). However, the SEG normal polarity convention for zero-phase wavelet generated by Vibroseis source is opposite; the compression (+ve Rc) is represented by peak (black/blue) and the rarefaction (−ve Rc) by trough (white/red). The European normal polarity convention is just the opposite of SEG normal polarity for both type of source wavelets, i.e., for minimum-phase, compression is denoted by peak (black/blue) and rarefaction by trough (white/red) and conversely, compression by trough and rarefaction by peak for zero-phase source wavelet. The SEG and Europa polarity display conventions are shown in (Fig. 12). However, display option of reverse polarity exits in both SEG and Europa for interpreters, which is just the opposite of normal polarity. Thus, there can be eight display options for polarity, namely the SEG and the European normal and their reverse, for each of the two types of source wavelet, the minimum and zero phase. This

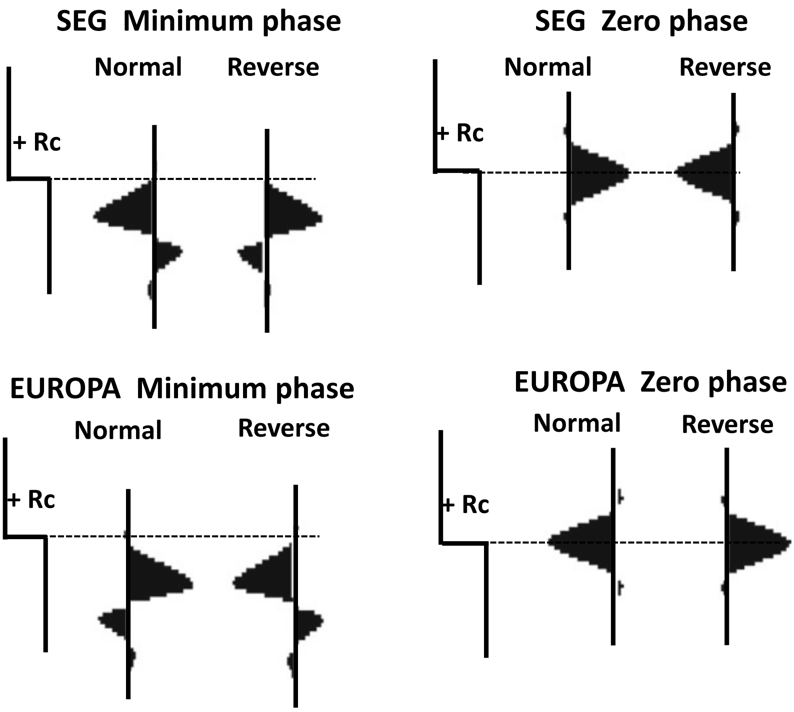

Fig. 12 Display of different polarity conventions for minimum and zero phase source wavelets in SEG and Europa, Normal and Reverse. Note the opposite polarity conventions for minimum and zero phase wavelets in both SEG and Europa. The Europa convention is opposite to corresponding SEG convention

could be indeed confusing unless the polarity display in seismic sections are clearly indicated to link the signage of the reflection, for example, stating that positive *Rc* (+ve) represents peak/trough along with the color code (black/red).

But how and why is the polarity display convention tied to the type of source wavelet used in seismic data acquisition? The reasons for opposite polarity display for the minimum and zero phase wavelet for SEG normal polarity is explained and illustrated (Fig. 13). The inherent presumption is that the minimum phase source wavelet is a '*causal*' wavelet which causes the wave motion to begin after the onset of the wavelet (Fig. 13a). This causes the reflection to appear at the start of the first displacement and with a time lag. However, it is different for zero-phase wavelet, generated by Vibroseis source in acquisition. The zero phase wavelet known as the *Klauder wavelet* is different as it is embedded in the source wavelet and no longer represents the observed physical quantities such as the geophone amplitude as in explosive or air-gun sources. The zero phase *Klauder wavelet* is considered '*acausal*' (non-causal) wavelet which means the wave motion begins before the onset of the wave and the maximum displacement located at zero-lag (Fig. 13b). Universally, compression (positive reflectivity) is recorded as a negative number on tape during acquisition for minimum phase source wavelet and is retained as a trough in processed data without change (Fig. 13c). But for zero phase wavelet the compression is recorded as a positive number on tape during acquisition and is retained as a peak (Fig. 13d) which is opposite to polarity displayed for minimum phase data.

Accurate picking of polarity is important for locating the disposition and nature of the strata in the subsurface. 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 create composite reflection events leading to obfuscation of individual reflection events and loss of polarity information. Noise in data also acts as a deterrent for clear

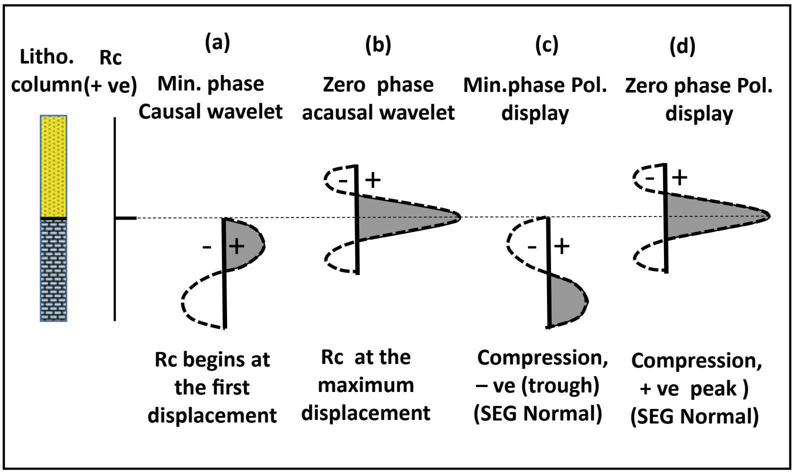

Fig. 13 Illustrating minimum (*causal*) and zero phase (*acausal*) wavelets and their link to polarity display convention in SEG (Normal). Note (**a**) the onset of reflection maxima delayed as reflection starts at the first displacement for minimum phase 'causal' wavelet and (**b**) the amplitude maxima without delay for zero phase 'acausal' wavelet. (**c**) compression conventionally recorded on tape as a negative number (trough) and is displayed as trough in processed data whereas (**d**) for zero phase wavelet, it is recorded positive and displayed as peak (courtesy: Satinder Chopra, Calgary)

identification of polarity. Processing techniques such as deconvolution and zero phase processing can help to some extent in estimating appropriate polarity of composite reflection events.

Arrival Time (Onset of Reflection)

It is therefore desirable the seismic interpreter is aware of the source used in data acquisition and the polarity convention displayed by the processing centre, prior to interpretation of data. A simple but important consequence of polarity information is the issue of picking the correct arrival times of reflected events which in many cases are not discrete but are of complex nature. The concern often is about which phase of a reflection is to be picked on seismic time sections, the peak, the inflection point (zero crossing) or the trough. This is crucial as the phase is important for well calibration and correlation while its arrival time is vital for depth estimation in interpretation. For instance, for minimum phase source wavelet used in offshore (air-guns) and on land (dynamites) in most cases, the reflection beginning at the leading edge displays the maximum amplitude of peak/trough, which happens to be delayed in time corresponding to the true depth of the object. Despite identifying the proper polarity, the picked time would therefore warrant appropriate time corrections for accurate depth prediction. For zero-phase wavelets, however, since the displacement maxima corresponds exactly to the depth of interface without time delay no such problem exists. Interpreters therefore prefer to work on zero-phase data which can be achieved in processing by phase shifts to minimum phase recorded data.

However, in offshore data a simple observation can provide clue to the polarity information. The sea bottom is generally a strong reflector with positive reflectivity (+*Rc*), being the interface between water and sediments. The energy source is known to be air-gun which generates a minimum phase wavelet. The polarity display of the sea bottom reflection therefore provides the clue to polarity display - if it is a trough, it is normal SEG polarity (Fig. 14). A peak would indicate otherwise, that the data is either zero-phased or reversed in polarity at the processing centre. However, there is also a catch, often the first strong signal recorded from the sea bed

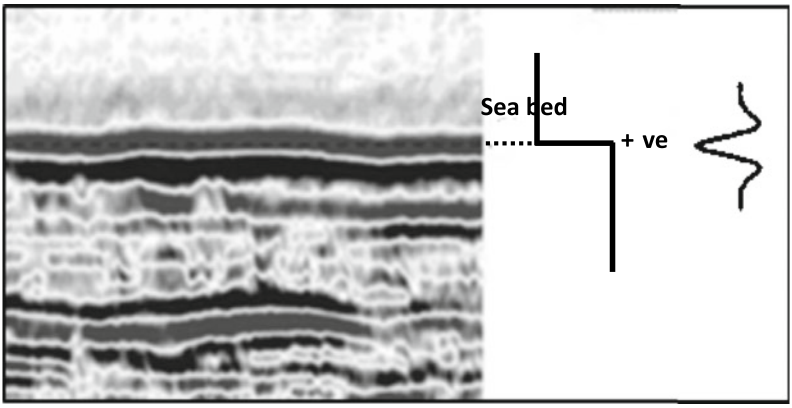

Fig. 14 Illustrating identification of polarity convention from seabed reflection in offshore data The sea bed reflector between water and sediments has positive Rc and shows strong reflections. The air-gun source is minimum phase and by SEG Normal convention it would show negative amplitude (trough, red). If the polarity is seen as peak, the data is processed zero-phased or with SEG reverse polarity (image courtesy, ONGC, India)

reflection are muted during processing which makes it difficult to determine exactly the polarity of the sea bottom reflection.

Despite correct reflection phase and time picked and velocity used, there can be mismatch between the times converted depth and the actual subsurface depth. This is because the picked reflection time may have been delayed due to acquisition and processing systems that behave as filters and introduce time lags. The induced delays may ultimately range from 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. This may be reconciled by advancing the reflection time by a negative correction though the exact amount would be a best guess process.

Velocity

Velocity is an important seismic property, 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. The two velocities are interrelated, knowing one can lead to compute the other. Other types of velocities, stacking (NMO), root mean square (RMS), migration and instantaneous velocities are also briefly described.

Average Velocity

Average velocity is the true vertical velocity used for conversion of reflection times to depth, and is the most important element in the exploration gamut. The true vertical average velocity, besides used for determining depth to geologic objectives, helps deduce the crucial interval velocities accurately for stratal layers and more importantly for proper prestack depth migration of data.

Stacking Velocity

Stacking velocity, also known as normal move out velocity (NMO) is an overburden velocity computed mathematically during velocity analysis process for normal move out correction of the multi-offset seismic traces used in common depth point (CDP) technique. The NMO corrections are for adjusting the geometrical effect of the varying offsets so that the traces are transformed to normal incident time for stack with maximum amplitudes. Stacking velocity is an apparent velocity recorded along the spread of ground geophones and is affected by factors such as dips of strata and acquisition spread lengths. Stacking velocities are usually higher (by about 6–10%) than true vertical velocity.

RMS Velocity

RMS velocity is root mean square (RMS) velocity and is another way to denote stack velocity. Assuming that the subsurface layers are parallel and horizontal, RMS velocity permits to deduce mathematically the layer interval velocities by a formula known as Dix's formula. In the absence of well velocities the RMS velocity, after appropriate correction, is used to predict top, bottom and thickness of geologic formations and also for migration in data processing. The lithology and other rock properties can be also inferred qualitatively from interval velocities (formation velocity) calculated from RMS (stack) velocities. Unfortunately, the above assumptions about the beds being flat and parallel are never met in nature and consequently the derived interval velocities have the inherent inaccuracies. Grossly speaking the NMO, stack and the RMS velocities genetically belong to a group of velocities almost similar to one another.

Migration Velocity

Migration velocity is the velocity used for time migration of seismic data to accurately locate the true subsurface reflecting points below the shot point. Similar to stacking velocity, migration velocity is an overburden velocity that provides the optimum imaging to produce relatively clean and accurate seismic images that helps predict structural configuration of geologic formations, their depth and rock properties. Migration velocity takes into consideration both the horizontal and vertical components of overburden velocity in contrast to vertical velocity used for depth conversion. Commonly, the migration velocities are stack (RMS) velocities used with some modifications. It is usually lower than stack velocity but tends to equal the average overburden velocity when data is optimally migrated.

Interval Velocity (Vint)

Interval velocity is the velocity of a formation (layer) and is called formation velocity. Interval velocities of a number of formations can be integrated to compute vertical overburden velocity and the other way round, from a given a series of layers with interval velocity the vertical velocity can be calculated. Interval velocities are generally calculated from RMS velocity and are important to predict lithology and rock-fluid properties of the layer, such as porosity and fluid contents. However, interval velocities are highly sensitive to interval of thickness for which they are computed and also to accuracies in velocity picks during seismic velocity analysis in data processing that provides the stack or RMS velocity.

Instantaneous Velocity (V_{inst})

Instantaneous velocity is a velocity at which a seismic wave propagates at a point within the interval of a formation, similar to interval velocity. However, instantaneous velocity is slightly different from interval velocity. Instantaneous velocity within a given interval changes with depth defined by a gradient, whereas the interval velocity remains constant without change in the interval. While interval velocity denotes the average formation velocity, the instantaneous signifies the finer details such as the layer interval velocities within the formation. The instantaneous velocity concept can be best realized as being closest to continuous velocity log (CVL) computed from sonic log by converting the slowness (μs/ft) to velocity (m/s). The change in instantaneous interval velocity with depth, the gradient and the constant interval velocity is illustrated in Fig. 15. Important applications of instantaneous velocity include computing synthetic seismograms wherein the product of sonic log derived instantaneous velocity and the density provides the impedance log as the input. More importantly, the Instantaneous velocities are used in building velocity models for depth conversion and migration and are discussed in Chapter "Seismic Interpretation Methods".

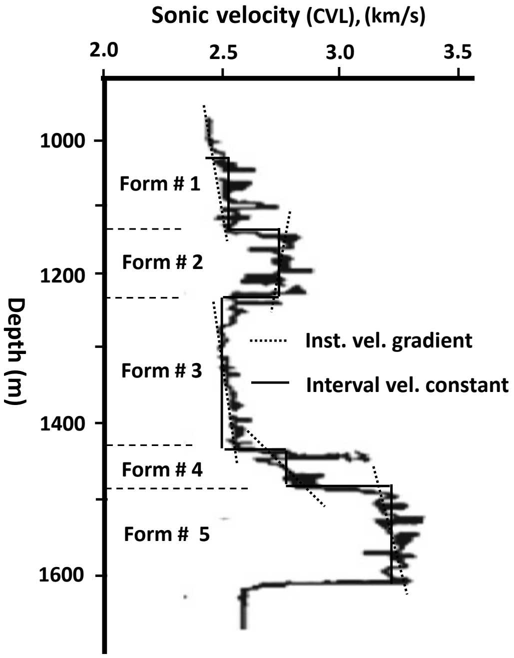

Fig. 15 Shows sonic instantaneous velocity curve (CVL) illustrating instantaneous and Interval velocity. Interval velocity is constant for formation while instantaneous velocity varies within It with a gradient. Interval velocity shows the gross formation velocity while instantaneous denotes the layer velocity with in the formation (courtesy ONGC, India)

Seismic Display

Display Modes

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 combination.

- 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 (Fig. 16a).
- Variable area (VA) and wiggle displays are wiggles shaded with bias, however, make reflection events appear more consistent and convenient for correlation by reflection character, the wiggle shapes providing better geologic information (Fig. 16b).
- Variable density (VD) shows reflection strength, and displayed with color, provides better relative standout and continuity of reflections. VD sections, though more commonly used showing better horizon continuity, do not show the waveform shapes which embed significant geologic information (Fig. 16c).
- Combinations of variable area with wiggles and at times may be a preferred display for interpreting stratigraphic details (Fig. 16d).

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 are conveniently used for extraction of seismic attributes for display (Fig. 16c). But the continuity in correlation can at times be misleading in many geologic settings. For instance, in continental to fluvio-deltaic depositional environments, where fast and frequent facies variations are likely to occur, one would normally expect discontinuous and patchy reflections and not wide-spread continuity of horizons. Seismic reflection horizons with perceived good continuity may in such cases, do not properly represent the subsurface geology and seismic interpretation without the geologic set-up can be highly flawed. Use of seismic display in wiggle with variable area mode may be preferred for correlation of seismic reflections. Horizon correlations guided by wave form characters permit better sensitivity to perceive vertico-lateral variabilities in the wave shapes which carry the subsurface geologic information (Fig. 17). Wiggle with variable area displays are also desirable for calibrating synthetic seismograms/corridor stacks with seismic which can clearly show the quality of matching of events.

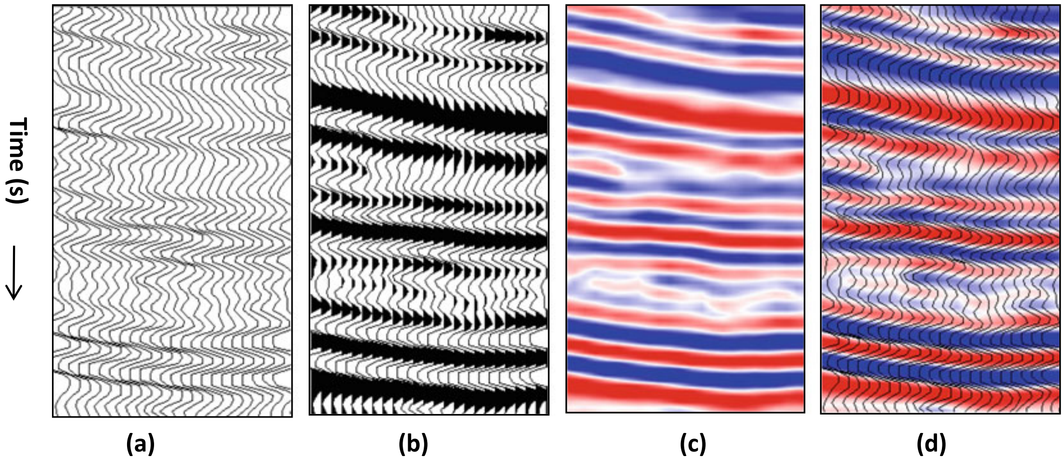

Fig. 16 Seismic segments showing types of display modes. (**a**) wiggle, (**b**) wiggle and variable area, (**c**) variable density, (**d**) combination of wiggle and variable density. Note the lateral changes in wave form seen clearly in wiggle and variable area mode (**b**) but not so clear in (**c**). Lateral variability in wave forms provide valuable geologic information

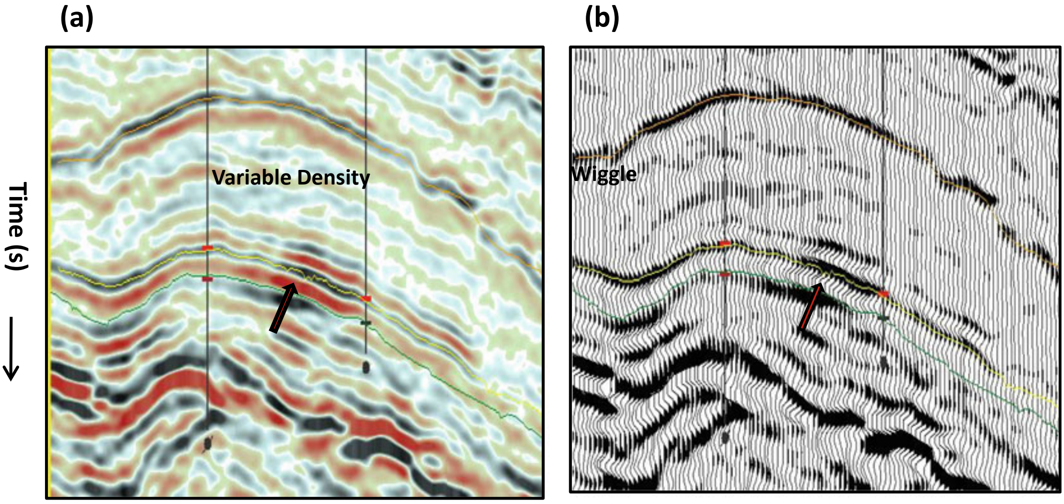

Fig. 17 Seismic image in display modes showing comparison of (**a**) variable density and (**b**) Wiggle with variable area modes. Reflection standouts and continuity are seen better in the variable density, but does not show the changes in wave form and misses the important geologic information they carry. Wiggle and VA mode shows clearly the variations (the trough marked by arrow) and help proper correlation based on reflection character and also offer geologic information from the lateral change of wave forms (image: courtesy, Hardy Energy, India)

Color display is known to increase optical resolution leading to better visual discrimination of features and is widely used. The selection of suitable color and its encoding depends on the artistic attitude and geologic perception of the interpreter so that the seismic vertical sections provide a look close to natural subsurface geology. Assigning colors in a spectral progression is usually preferred as it enhances the relative magnitudes better for visualization.

Plotting Scales (Vertical and Horizontal)

Plotting scales are extremely important in data display, as reducing or stretching the scales impacts visualization of geologic objectives. Visualization of images is important as it is an integral part of mind and the image interpretation depends often on what the mind dictates. For the same reason, the plotting scales are also to be suitably chosen depending on the objectivity of the interpretation. Horizontally compressed sections promote perceiving better continuity of events and the subtle dips appearing stronger. Stretched sections, on the other hand, appear to deteriorate reflection continuity with flattening of the dips. Vertically stretched and horizontally compressed sections improve the dip effect and make minute dips noticeable better. Low angle faults with small displacement, lowly dipping progradations, gentle pinch outs and terminations etc., which are subtle but important as exploratory objects, can be made to look more conspicuous by suitably adjusting the vertical(time) and horizontal display scales to be picked as anomalies (Fig. 18). Horizontally compressed (squashed sections) and vertically reduced (reduced time scale) sections play a very useful role in studying regional basin scale geology, helpful in understanding evolution of basins for evaluating hydrocarbon prospectivity. Choice of scaling depends entirely on the interpreter depending on the length of profile and the depth (time) recorded. Usually squashed sections are plotted every fourth trace with proportionate reduction in time scale so that long segments of profiles can be conveniently viewed in one frame. This offers the advantage of viewing the entire geology, from the deep basement to the surface for assessing the tectono-stratigraphic evolution of the basin. However, vertically stretched sections are at times used to magnify details of important target windows for mapping the objective. Each geologic object thus needs appropriate scales of display for the target to standout clearly and may need experimenting for choosing the best judicious combination of both the vertical (time) and horizontal (trace) scales along with the mode of display.

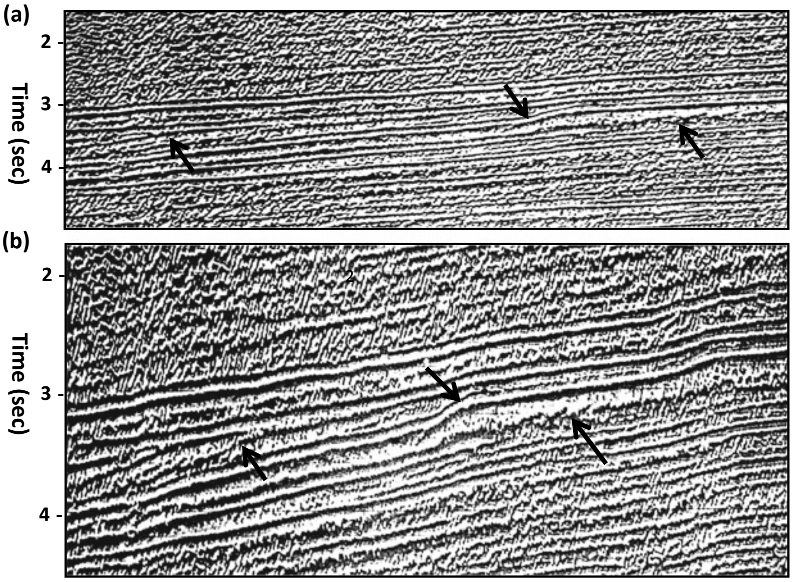

Fig. 18 Seismic segment illustrating visual effects of plotting scales. (**a**) horizontally stretched and vertically compressed and (**b**) horizontally compressed and vertically stretched. Note the subtle dipping features clearly seen in compressed section (**b**) not well discernible in expanded scale (**a**). Arrows point out the anomalies (courtesy, ONGC, India)

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