Encyclopedia of Marine Geosciences
DOI 10.1007/978-94-007-6644-0_128-1

Reflection/Refraction Seismology

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Synonyms

Controlled-source seismology; Multichannel reflection seismics; Wide-angle reflection/refraction profiling (WARRP)

Definitions

Methods to image and to physically parameterize the subsurface geologic structures and conditions by means of artificially generated shock waves that travel through the subsurface and return to the surface.

Overview

Controlled-source seismology comprises a variety of geophysical methods to image and to physically parameterize the subsurface geologic structures and conditions. All these methods base upon the principle that artificially generated shock waves travel through the subsurface and that the returned signal can be analyzed regarding the properties of the subsurface. During the last decades the discrepancies between marine seismic equipment as used by the academic marine research community and that used by the hydrocarbon (HC) exploration industry increased significantly, caused by different research targets and the simple fact that gear commonly used for HC exploration is much too costly. In this chapter we will focus on those systems which are typical for academic marine research.

In principle, seismic data acquisition requires an energy source, a receiver, and a recording system. The two most important seismic methods are reflection and refraction seismology (Fig. 1).

Reflection seismologists deal mainly with steep angle reflections, which means that the source to receiver distance is small compared to the target depth. This method utilizes the fact that a small part of the down-going energy is reflected on geological layer boundaries. The main fraction of the energy is transmitted and travels deeper where reflections occur at the next layer boundary and so on. This method results in a good vertical and horizontal structural resolution of the subsurface. Earth scientists benefit from the technical and methodical developments of the exploration industry which uses reflection seismology for the detection of oil and gas in depths of up to several kilometers below the seafloor.

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DOI 10.1007/978-94-007-6644-0_128-1

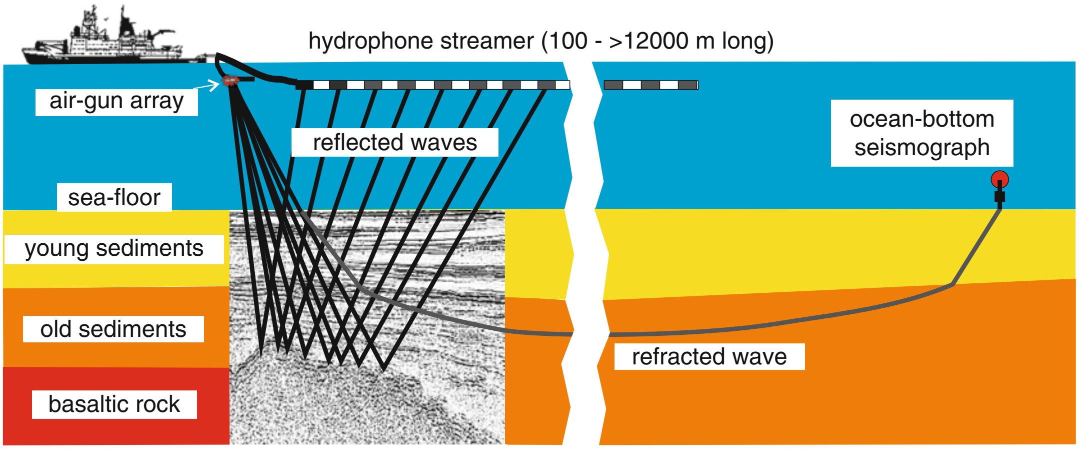

Fig. 1 Basic principles of reflection and refraction seismology. Reflection seismologists deal mainly with steep angle reflections, which means that the source to receiver distance is small compared to the target depth. Refracted waves propagate along layer boundaries or as arcuate "diving waves" mainly horizontally. This method is either used in engineering geology for near-surface investigations or (the other extreme) to analyze deep crustal structures, the earth crust–mantle boundary and the upper mantle

In refraction seismology, seismic waves are recorded that propagate along layer boundaries or as arcuate "diving waves" mainly subhorizontally. This method is either used in engineering geology for near-surface investigations or (the other extreme) to analyze deep crustal structures, the crust–mantle boundary and the upper mantle. Wide-angle reflections recorded at large distances between source and receivers are part of this data analysis scheme. Geophysicists often use the abbreviation WARRP (wide-angle reflection/refraction profiling) for these techniques. The main advantage of WARRP is that the inversion procedure directly results in crustal depth sections; its major disadvantage is the relatively low structural resolution.

History of Refraction and Reflection Seismology

One of the founders of the seismic refraction method was German scientist Ludger Mintrop (1880–1956) who received a patent in 1917 for a so-called portable field seismograph and a method to locate artificial shock sources. In fact, he used this method in World War I to locate the position of Allied heavy artillery pieces. After the war he reversed this method: He released an explosive blast in a known distance to the seismograph and used the underground travel time of the shock wave to calculate the depth of geological features. In 1919 the seismic refraction method was successfully used to constrain the location of a salt dome in northern Germany.

Marine reflection seismology evolved from work by Reginald Fessenden who developed a sonic sounder to find icebergs (after the sinking of the *Titanic*) (Roden, 2005). The first reported usage of seismic reflections for subsurface studies was in 1921 when a small team of geophysicist and geologists performed a historical experiment in Oklahoma (Dragoset, 2005). The team analyzed the return time of reflected waves generated by small dynamite charges and detected the boundary between two subsurface geological layers. The success of this so-called Vines Branch experiment stimulated a boom in seismic exploration when the oil price rose in 1929.

During the first decades each subsurface point was imaged by a single set of source and receiver. Multichannel seismics became more common in the 1950s. This method allowed for significant noise reduction and for computing of layer velocities, enabling the conversion of travel times

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to depth. The advent of the digital technology in the 1960s represented a giant step forward because digital post-processing opened a wide variety of possibility to enhance seismic data and image quality. Several technical developments in the 1980s such as plotters for wiggle trace display or color maps as well as methodical progress including seismic stratigraphy or seismic attribute analysis became available for earth scientists and stimulated academic frontier research.

The hydrocarbon industry benefited largely from the introduction of the 3D seismic method which enhanced understanding of petroleum reservoirs and reduced exploration risks. However, the earth science community has had quite limited access to these data, also because 3D seismic experiments for nonprofit-oriented research are generally too costly.

Seismic Energy Sources

The theoretical optimum seismic source produces a Dirac delta function like signal (called wavelet) which is infinitesimal short in time by having a maximum spectral bandwidth. In the real world, a "good" seismic source creates a high energy and temporally short signal with repeatable characteristics in terms of wavelet signature and frequency content.

Marine seismic sources are subdivided into exploders and imploders. Exploders create the wavelet by an expanding volume (solid material or gas/air). Imploders generate the signal by the collapse of a volume, created for instance by cavitation. We can further distinguish between chemical, mechanical, electrical, and pneumatic/hydraulic sources (Parkes and Hatton, 1986). Chemical sources comprise various explosives. Explosives can create very strong signals; however, the shot interval is relatively low and the signal characteristics are reproducible to a limited amount due to surface waves and explosion depth. Mechanical sources, such as a boomer or piezoelectric transducers, rely on physical vibration to transmit seismic waves into the water. Sparkers are electrical sources that discharge large electrical charges into the water. The steam bubble that vaporizes along the spark collapses, thus producing the desired signal. Pneumatic/hydraulic sources dispel gas (usually air) or fluid (usually water) under high pressure into the water. For instance, a water-ejecting water gun produces a cavitation and its subsequent collapse generates a seismic wave-field. The water is accelerated in the water gun by a piston, whereas the driving pressure consists usually of compressed air.

The pneumatic so-called air gun is nowadays the most common source in marine seismics (Dragoset, 1990). Compressed air of usually 140–210 bar is released into the water every few seconds. The rapid expansion creates the highly reproducible primary signal (Fig. 2a). The reflection at the sea surface creates a similar strong but phase-reversed signal, the so-called ghost. Signal strength is described either as the peak amplitude pk (level A in Fig. 2a) or as pk-pk amplitude which includes the amplitude of the ghost arrival (A–B in Fig. 2a), both traditionally expressed in bar-meter (bar-m). If the peak amplitude is 1.5 bar-m as in Fig. 2a, a hydrophone located in a distance of 1 m to the source would measure peak amplitude of 1.5 bar, in 3 m distance 0.5 bar. A second important source characteristic is the spectral bandwidth (Fig. 2b). Amplitude spectra are usually shown on a logarithmic scale. A reasonable parameter for the bandwidth is the range between the −3db (71 % of maximum) or −6db (50 % of maximum) points. The frequency notch in the spectra results from the destructive interference between the primary and the surface (ghost) reflection. It is a function of the source towing depth and can be easily calculated by $f_{Notch} = V_{H_2O}/(2 * \text{towing depth})$. V_{H_2O} is the seismic wave speed in water which amounts to ca. 1,500 m/s.

The bubble signal is an undesired effect which results from an oscillation of the air bubble. Consequently, an important characteristic of a single air gun or an array of air guns is the peak to

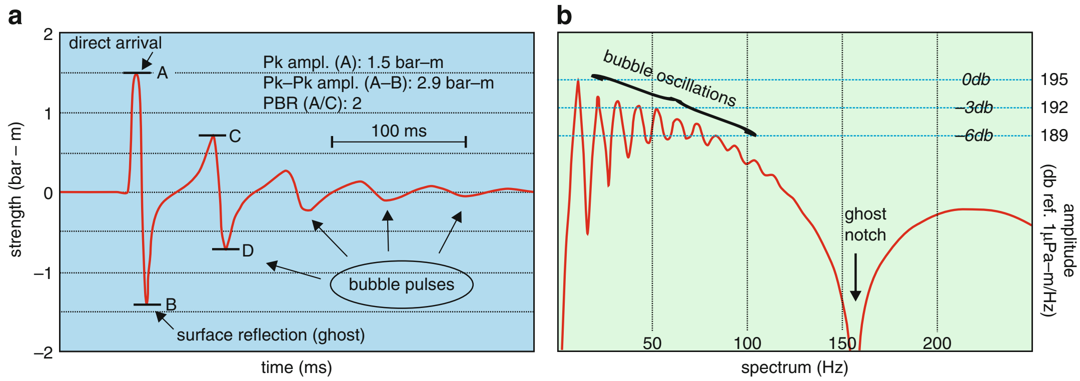

Fig. 2 (**a**) Definitions of time-domain air gun specifications (After Dragoset, 1990, 2005). The signal is composed of the primary signal, the phase-reversed sea surface reflection (ghost), and the bubble signal, caused by oscillations of the air bulb. Signal strength is measured in bar-m. Values are either given for the strength of the peak amplitude of the primary signal (pk amplitude. Marked by an "A") or the ghost amplitude marked by a "B" is included (pk-pk amplitude). (**b**) The spectral bandwidth is usually shown on a logarithmic scale. A reasonable parameter to characterize the bandwidth is the range between the −3db (71 % of maximum; ca. 10–52 Hz) and −6db (50 % of maximum; 8–80 Hz) points. The bubble oscillations are visible in the low-frequency domain. The ghost signal forms a notch at a frequency depending on the source depth due to destructive interferences

bubble (amplitude) ratio (PBR) (Fig. 2a). There are several possibilities to enhance the PBR. As the bubble period depends on the same parameters as the primary signal, the bubble can be suppressed by simultaneously firing several air guns with different bubble frequencies. The PBR can be further enhanced if the separation distance between the air guns is small enough that the air bubbles interact (Strandenes and Vaage, 1992), which is the so-called cluster effect. Many modern air gun arrays consist of several pairs of clustered air guns. A high-end system frequently used by geophysicists is the so-called GI-Gun (by Sercel), which consists of two air gun chambers built into a single housing. The first chamber, called generator, releases highly compressed air. The air bubble expands, and just before it starts to oscillate, an additional volume is injected by the second air gun chamber (the injector), thus stabilizing the air volume in order to prevent oscillations.

Amplitude and spectral bandwidth (Fig. 2b) can be adjusted by air pressure, air chamber volume, towing depth, and geometry of discharge ports. Air chamber volumes may vary between 32 l to less than 1 l. Large air chambers are used for low-frequency, high-amplitude sources which are desirable for deep crustal refraction and wide-angle reflection seismics. Small air guns of up to a few liters chamber volumes are used for high-resolution shallow reflection seismics.

Data Acquisition and Processing: Reflection Seismology

A seismic recording system comprises a sensor or receiver that converts the seismic wave into an electrical signal, an analog–digital converter and a recorder. The most common sensors in marine seismics are hydrophones, which are piezoelectric elements that produce an electric potential difference caused by the pressure pulses of the seismic wave. Usually groups of hydrophones are used to eliminate translational accelerations and to enlarge the signal-to-noise ratio by signal summation (Telford et al., 1990).

Encyclopedia of Marine Geosciences
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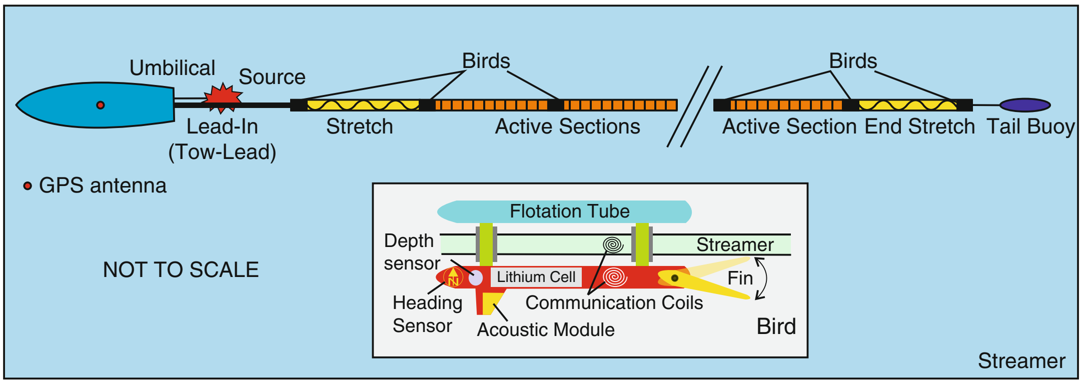

Fig. 3 A marine seismic streamer typically used for academic 2D reflection seismic surveys comprises a lead-in cable, a stretch section that mechanically decouples ship movements from the active sections, an end stretch, and a tail buoy. The streamer is depth controlled by cable levelers also called birds (insert)

Seismic Streamers

The standard device for marine reflection seismics is the streamer (also towed array, seismic cable) which comprises hydrophone groups (so-called channels) or single hydrophones (Fig. 1). There is a huge variety in the length and number of channels. A streamer geometry quite common for systems operated by academic research institutes comprises a lead-in cable (also tow-lead) which is a heavy, steel mash protected cable with negative buoyancy which connects the streamer with the streamer winch (Fig. 3). The next part of the streamer is the elastic stretch section (also passive or compliant section) which mechanically decouples irregular ship accelerations from the active sections, consisting of the hydrophone channels. Another stretch section decouples the streamer from the tail buoy.

The length of the individual sections may vary. Typical values for systems operated by academic institutions are front stretch 50–200 m, active length 300–3,000 m, and end stretch 50–100 m. Depth levelers, so-called birds, are connected every 100–200 m.

Typical hydrophone group distances are integer multiples of 6.25 m. This number results from times when no satellite positioning was available. A good trade-off between water current-induced noise and progress is a ship speed of about 5 kn (5 nautical miles per hour). This speed corresponds to 2.5 m/s. A shot interval of 5 s results in 12.5 m shot distance, an interval of 10 s in 25 m. With those figures the geometry of the multichannel data could be easily calculated (see below). The number of hydrophones within and the total length of a hydrophone group control its spatial response characteristic (Hübscher and Spieß, 1997).

The towing depth of the streamer should be a quarter of the wavelength ($\lambda/4$) of the expected seismic signal in order to prevent destructive interferences within the frequency range of the source. Buoyancy of a streamer is controlled both by the average density of the stretch and active sections and by cable levelers. For several decades, the sections have been filled by kerosene and later by Isopar. These fluids have a density less than that of seawater. The volume of the oil is calculated in a way that the average density of the section containing hydrophones and towing and data cables is close to that of seawater to yield neutral buoyancy. So-called solid streamers filled with polyurethane and similar solid materials have replaced more and more the conventional oil-filled ones, because they have proven to be more robust. Birds allow for an active control of the streamer depth (insert Fig. 3). The bird is attached to the streamer by bird collars and can rotate freely around. Depth sensors determine the actual depth. Inductive communication coils within birds and streamer allow data transmitting to the shipboard controller system where depth values are averaged depending on

DOI 10.1007/978-94-007-6644-0_128-1

the swell. If depth correction is necessary, the controller sends a signal to the birds, which turns the fins accordingly, and the streamer segment is dragged up or down. Heading sensors (fluxgate magnetometers or mechanical compass) allow for geometric corrections if the streamer drifts off the track by currents. On the opposite side of the bird, a flotation tube is also attached to the collars. The flotation tube eliminates the negative buoyancy of the bird and keeps the bird always beneath the streamer and, consequently, the fins parallel to the sea surface. For 3D applications the precise position of each streamer segment with respect to the air guns is determined by acoustic triangulation. This requires acoustic senders (so-called pingers), e.g., close to the air guns, and acoustic modules (Fig. 3) in the birds which receive the pings and send travel times to a control PC.

Seismographs

The term "analog acquisition" refers to a receiver–recorder system where the electrical signal is digitized by a seismic recording unit, which is a data recorder specially designed for seismic data recording, located in the vessel. The seismic recorder fulfills several tasks. Prior to analog–digital conversion, data is usually preamplified and low-pass filtered in order to avoid spectral aliasing. Since the suppression of frequencies becomes significant at about 60–70 % of the Nyquist frequency, the A/D conversion frequency should be about three times the maximum signal frequency. High-pass filtering can be wise to apply in order to suppress high-amplitude ship propeller noise. After A/D conversion, data are normally formatted to standard formats developed by the Society of Exploration Geophysicists (SEG), e.g., the SEG-D or SEG-Y formats. Analog data transfer via cables results in some loss in data quality, e.g., due to the antenna effects. This disadvantage is overcome by digital systems which digitize the electric signal representing the incoming seismic wave inside the streamer. More expensive digital receivers are standard in exploration geophysics, while the scientific community still operates many analog systems. The disadvantage is less significant for the often near-surface applications.

Acquisition Schemes

The classical acquisition scheme for academic marine reflection seismic surveys is the 2D geometry. The first dimension is the 1D acquisition geometry and the second one the travel time of the seismic waves. This acquisition scheme is designed for common midpoint (CMP)-based processing (Fig. 4). If a shot is released, the seismic signal travels from the shot point down to the seafloor. Assuming a horizontal seafloor, the reflection points have a distance half of the hydrophone group spacing $\Delta H/2$ (Fig. 4). Let us focus on the reflection point of the ray traveling from the shot point down to the seafloor and up to the nearest hydrophone group (Fig. 4a). If the shot spacing is also $\Delta H/2$, the same reflection point on the seafloor is covered by the ray between the second shot point and the second channel (Fig. 4b), but the travel time is longer and so is the travel time of the wavelet between shot 3 and channel 3 (Fig. 4c). The effect that travel time increases with offset is called normal move-out (NMO). During data processing, the individual shot records are sorted to CMP gathers which comprise all those records which have the common midpoint between shot and receiver coordinates (Fig. 4d). Analysis of the offset-dependent travel time discrepancies allow – if offset is not much less than reflector depth – calculating interval velocities and reflector depth. During data processing (see below), recordings of each CMP gather (Fig. 4e) are NMO corrected and stacked (summed to one single trace) which results in a constructive superposition of primary information (reflections) and destructive superposition of (incoherent) noise (Fig. 4f). Displaying of all CMP traces along a profile (Fig. 4g) gives an image of subsurface strata.

In the exploration industry, 2.5D, 3D, and 4D data acquisition schemes are more common. Sequential acquisition of parallel and fairly narrow-spaced 2D lines results in a 3D subsurface

DOI 10.1007/978-94-007-6644-0_128-1

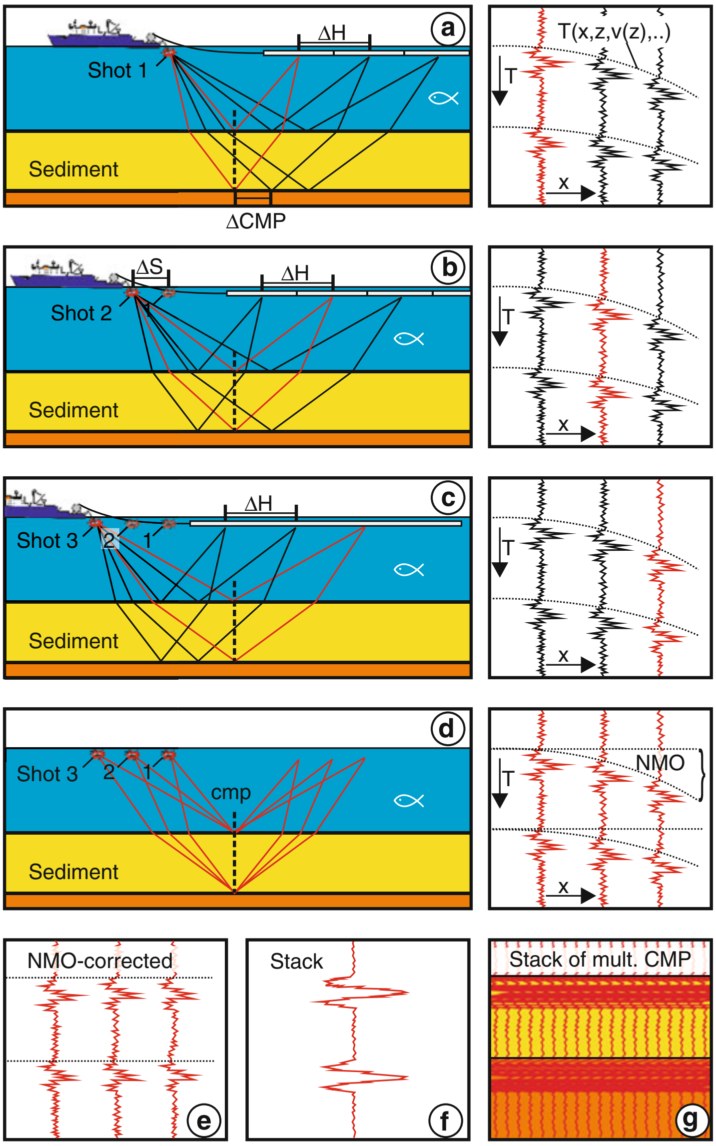

Fig. 4 CMP-based 2D multichannel seismic acquisition scheme (After Mutter, 1987). See text for detailed description

model. However, this is called 2.5D seismics because azimuth-dependent factors are not considered. In a strict sense, the term 3D seismics refers to acquisition geometry only if seismic waves are recorded by a 2D pattern of receivers; thus, the seismic waves are measured with different azimuth angles. Repeated measurements within the same area with a 3D geometry are called time-lapse monitoring or 4D seismics, enabling the interpreter concluding on subseafloor fluid dynamics. Recently a highly mobile 3D seismic system has been introduced which allows imaging the upper 1–2 km with high lateral and vertical resolution. A bundle of 12 short streamers containing 8–16 channels is towed behind the survey vessel (e.g., Berndt et al., 2012).

Data Processing

Seismic data processing comprises a vast of different methods for the analysis of recorded seismic signals to reduce or eliminate unwanted components (noise), to create an image of the subsurface to enable geological interpretation, and eventually to obtain an estimate of the distribution of physical

DOI 10.1007/978-94-007-6644-0_128-1

material properties in the subsurface (inversion) (Chowdhury, 2011). Processing is a science by its own and it is impossible to give a complete overview here (for a comprehensive text book, see Yilmaz, 2008).

One of the primary goals is the enhancement of the seismic *signal* and the suppression of *noise*. The term signal refers commonly to primary reflections, which is seismic energy reflected only once during its path from source to receiver. Everything else can be considered as noise; it comprises random and coherent noise (Kumar and Ahmed, 2011). Random noise does not correlate with neighboring channels. Coherent noise includes multiple reflected energy, side wipes (out-of-plane reflections), and energy from previous shots or processing artifacts. Ambient noise means noise resulting from other sources such as waves, swell, ship propeller, or marine animals. Noise suppression is easy if its frequency lies outside the signal frequency range; otherwise more sophisticated methods have to be applied.

A fundamental parameter which is crucial to know for several processing steps is the distribution of the seismic wave speed, called "velocity." For example, the velocity controls the propagation of the seismic wave, its reflection, refraction, and diffraction as well as the geometrical spreading of the wave front and the related amplitude loss (spherical divergence). Vice versa, seismic velocities are crucial to correct for amplitude losses, travel time differences within a CMP gather, and dislocated reflections and to bring the seismic energy smeared along diffraction hyperbola into focus (called migration). The conversion from a seismic time section to a depth section can be only correct if the velocity distribution is well known. Further, velocity functions can be used to remove multiple reflections. Basically, the velocity distribution can be calculated from the move-out in CMP gathers. The bigger the move-out, the more accurate are the derived velocities. If the reflector depth is much higher than the maximum offset (streamer length), the move-out becomes neglectable and no reliable velocity calculation is possible. For example, if a 600 m streamer is used – a quite typical value for streamers operated by academic institutions – accurate velocities beneath depths of 1,000 m can hardly be derived. The necessary computation of velocity is a relatively easy task if the subsurface is a horizontal layer cake, but geological formations are often not formed in this simple matter. It becomes more difficult if strata are tilted, deformed, disrupted, and anisotropic, all resulting in lateral velocity changes.

The supreme discipline in seismic data processing is seismic migration (Yilmaz, 2008; Gray, 2011). It comprises a set of techniques for transforming reflection seismic data into an image of reflecting boundaries in the subsurface. It brings the seismic energy distributed along a diffraction hyperbola into focus and corrects geometric effects caused by dipping reflectors and velocity effects. If the velocity model is well known, pre-stack migration gives best results; however, it is quite costly in terms of CPU time. Migration can result either in time or depth sections. Pre-stack depth migration (PSDM) is the ultimate goal of seismic data processing.

A basic processing sequence for marine seismic data includes the following steps:

- Preprocessing: Set amplitudes of bad traces to zero, correct misfires, assign geometry (CMP numbers) to traces. Suppress noise outside signal frequencies by band-pass filtering.
- Pre-stack processing I: Mute direct wave; balance energy between individual channels.
- Velocity analysis: Sort shot gathers to CMP gathers; calculate velocity model.
- Pre-stack processing II (based on velocity model): Correct amplitudes for spherical spreading, absorption, and energy partitioning at interfaces; suppress multiples with the help of velocity model.
- Pre-stack time or depth migration (optional).

Encyclopedia of Marine Geosciences
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- Stacking: Flatten reflection events by NMO correction using velocity model within CMP gather; stack all traces.
- Post-stack time or depth migration (optional).

Data Acquisition: Refraction Seismology

Modern ocean-bottom seismometers (OBS) or hydrophones (OBH) are autonomous receiver and recording systems which are deployed on the seafloor where they remain for days or even several months and where they record seismic profiles during this time. The decoupling between seismic source and receiver allows for great distances which is necessary to receive refracted waves from the deep crust and upper mantle. These systems consist of a data logger, batteries, a three-component seismometer and/or a hydrophone, a radio beacon, a xenon flashlight, and a flag. These components are either mounted on a steel frame, which is kept afloat by syntactic foam bodies, or are installed within and on top of a floatable glass sphere. Either system type is connected to an anchor frame via an acoustic releaser. On hydroacoustic signaling, the releaser opens a hook to release the OBS/OBH system from its anchor and the system ascends to the sea surface. Recording parameters such as sample rate (e.g., 200 Hz) and gain are set before deployment, and data are retrieved from the data logger after recovery. Most commonly the data logger is programmed such that it records continuously.

Data Processing and Signal Enhancement

Data processing of standard seismic refraction records is – compared to that of the seismic reflection technique – relatively straightforward. As a major component of the record analysis and modeling is focused on extracting seismic velocities from the relationship of seismic travel times to source-receiver offsets, the accurate determination of source and receiver coordinates is of great importance. While this is a trivial problem to be solved in land surveys, the exact location of an ocean-bottom seismometer, which may have drifted on its sinking path to the seafloor, can in most cases only be estimated by using the direct acoustic water wave phase in the record. After this so-called re-localization process of each OBS, the remaining data processing includes mainly band-pass filtering for enhancement of the signals which have their largest amplitudes between 5 and 12 Hz in deep crustal seismics. Deconvolution filters can be applied in some instances to improve the identification of the time onset of particular refraction phases. Some workers use coherence filters in order to enhance seismic phases of a particular dip range or to suppress the so-called wrap-around, which is the direct acoustic wave-field through the water emitted from the previous shot. As this direct wave travel with only 1.5 km/s water velocity, it is still recorded at large offsets and is sometimes superposed on reflected or refracted phases from the deep crust or upper mantle. Most commonly, seismic refraction records are displayed with travel times reduced (Fig. 5) in order to include all refraction and wide-angle reflection phases of interest into a reasonably sized display window and to provide the viewer with a visual impression of the velocities of the main refraction phases. For instance, a record displayed with travel time T reduced with a velocity V_{red} of 8.0 km/s ($T_{red} = T - X/V_{red}$, where X is offset) shows refractions with an apparent P-wave velocity of 8.0 km/s as horizontal phases.

The processing flow is similar for the four components (hydrophone h, vertical z, horizontal x, horizontal y) of an OBS record or the three components of a land instrument record. When searching for S-waves or converted wave phases (P-to-S or S-to-P), records are displayed with the corresponding main reduction velocity applied to travel time.

DOI 10.1007/978-94-007-6644-0_128-1

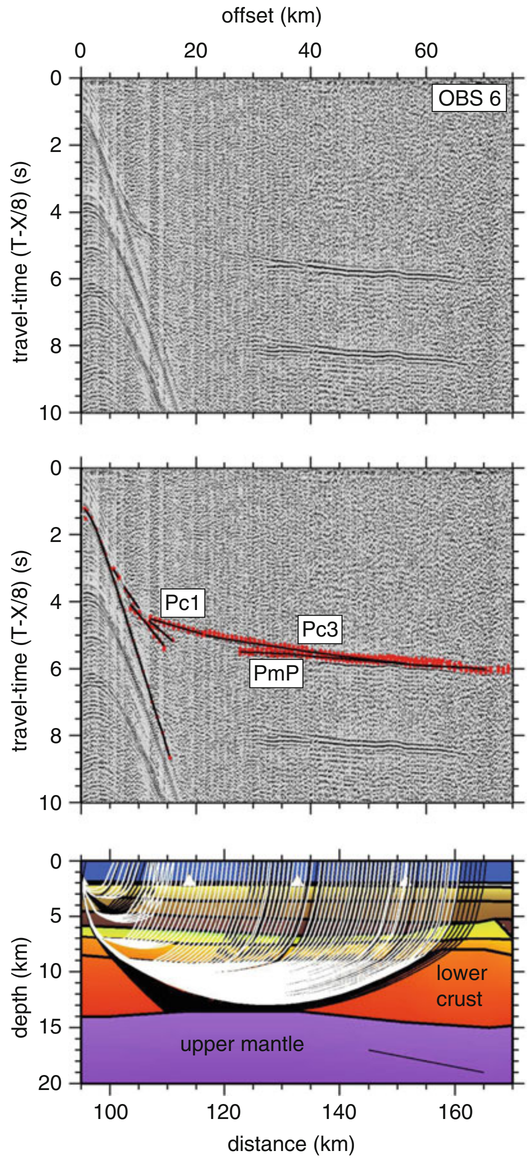

Fig. 5 Example of a seismic refraction OBS record with travel times reduced with 8 km/s (*top*), picked and modeled refraction phases (*middle*), and a crustal cross-section model with traced rays corresponding to the picked refraction phases (*bottom*) (From Suckro et al., 2012). Pc1 and Pc3 are refraction phases from the middle to lower crust, while PmP denotes a wide-angle reflection from the crust–mantle boundary (Moho discontinuity)

Modeling, Inversion, and Tomography

Various modeling strategies are exercised to derive physical properties of the subsurface, the crust and/or the upper mantle from the seismic refraction, and wide-angle reflection records. Deriving the seismic velocity–depth distribution along a surveyed 2D profile or in a 3D area is the most widely desired aim for modeling because of the strength of seismic refraction technique to provide firsthand information on P- and S-wave velocities of the layers penetrated. While basic geometric methods such as the plus-minus method, the intercept-time method, the delay-time concept, and reciprocal methods (e.g., Palmer, 1986) are sufficient to represent simple 2D subsurface geometries, even with irregular interfaces, as often approximated for the shallow subsurface, deep crustal complex layer structures and heterogeneous velocity–depth distributions can only be modeled with more

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sophisticated numerical methods using a ray-geometric or elastic wave-field inversion approaches. A short overview of commonly used modeling schemes is given here.

Forward ray-tracing and travel time inversion: Based on acoustic wave propagation laws, software for ray-tracing in complex multilayered media was first developed in the 1970s (e.g., Cerveny et al., 1977). The method of ray-tracing is performed by an efficient numerical solution of the 2D ray-tracing equations coupled with an automatic determination of ray takeoff angles. The model response is iteratively optimized by approaching a best fit to the observed travel times. This ray-tracing method was further optimized by Zelt and and Smith (1992) who implemented a travel time inversion by a best-fit approximation with a damped least-square algorithm. Due to its nonlinear nature, the inversion process is controlled by strict boundary conditions on travel time picking uncertainties as well as model parameterization and resolution bounds. Due to its efficiency, the open-source software RAYINVR, originally developed by Zelt and and Smith (1992), is still the most widely used 2D ray-tracing scheme in academic research to date (Fig. 5), although different modifications exist, mainly improving model parameterization and visualization and adding more features (Zelt, 1999). The software was further developed to allow modeling in 3D subsurface media (Zelt and and Barton, 1998). Ray-tracing can also be used to calculate synthetic amplitudes that can be compared with the observed ones. However, this has limitations as it does not take into account the full elastic properties of the subsurface layers and interfaces.

Travel time tomography: A 2D and 3D travel time inversion by using an iterative first-arrival seismic tomographic (FAST) algorithm, in which a regularized inversion routine is computed rapidly over a regular grid using finite-difference extrapolation (Vidale, 1990), was developed by Zelt and and Barton (1998). This routine was originally developed for mid- and deep crustal seismic refraction tomography (e.g., Zelt et al., 2004; Stankiewicz et al., 2008) but has been utilized for shallow subsurface imaging by appropriately adjusting model parameters (Deen and and Gohl, 2002). As required for a linearized inversion, an initial model has to be implemented first. From this initial velocity–depth model, a series of iterations improves the model with respect to the picked travel times. Each subsequent iteration of the model is developed using both a finite-difference forward calculation of travel times and ray-paths and a regularized inversion incorporating a combination of smallest, flattest, and smoothest perturbation constraints, the weights of each being allowed to vary with depth. An advanced tomographic inversion based on a Monte Carlo scheme with an implementation of automated model regularization and a polynomial expansion of the probability function has been developed by Korenaga and and Sager (2012).

Wave-field inversion: One of the first widely used wave-field inversion techniques was developed by Pratt et al. (1996) and is based on finite-difference modeling of the wave equation, thus allowing very general wave types to be incorporated and enhancing the resolution when compared to travel time methods. Their method operates in the frequency domain and allows modeling and inverting velocity structure as well as inelastic attenuation factors. The inversion can be iterated to improve the data fit and to take account of some nonlinearity. Some of the nonlinearity can be dealt with by using starting models that have been developed with standard forward ray-tracing. Despite advances in computational speed, full wave-field inversion techniques that incorporate (visco-)elastic and anisotropic wave equations on full crustal model scales still remain in a small user niche as parameterization is cumbersome and computational requirements are not always met. However, it is a matter of time until this method will be taken to the next level of being accepted for more regular use in the academic research and exploration communities.

DOI 10.1007/978-94-007-6644-0_128-1

Seismic Interpretation

As seismic methods can be considered as a way of remote sensing into the earth, all interpretations can be significantly corroborated by ground truthing, meaning to calibrate the interpretation by drilling results, which includes both coring and well logging. The understanding of large-scale crustal structures can be significantly supported by modeling and inversion of gravity and magnetic data.

The interpretation of reflection seismic data consists of two major steps. During the first one data are described by an association-free nomenclature in order to prevent a biased point of view. For example, "disrupted horizons" is descriptive; the denotation "normal fault" is a possible interpretation of this pattern. From that objective description of the data, conclusions are drawn regarding tectonic and sedimentary processes.

The seismic interpreter should start with the evaluation of recording and processing parameters. From this he/she will get a first idea about the reliability of his observations. The description of reflection seismic images should follow the following scheme:

1. Identification and mapping of unconformities and correlated conformities
2. Determination of termination style (e.g., onlap, toplap, downlap, offlap, etc.)
3. Classification of internal reflection pattern (e.g., parallel, wavy, divergent, etc.)
4. Recognition of clinoforms, structural highs and lows
5. Categorization of seismic attributes (interval velocity, instantaneous frequency, etc.)

From the yet described data, the interpreter derives the processes which led to the observed features. Both the inductive and deductive approaches are used. The consensus about earth processes is used for deductive reasoning, which means propositions generally accepted by the scientific community are used for explaining specific observations. New general propositions about earth processes evolve from inductive reasoning by arguing that a specific example is representative for other cases. A "good" interpretation explains a maximum of observations and makes minimum assumptions about unknowns.

In all cases the interpreter should have a sound knowledge about both geology and geophysics. Since a quantitative failure discussion is often not possible, the interpreter needs a sound knowledge and experience to distinguish between imaging or numerical artifacts and geological features.

The primary information content of seismic refraction data consists of P-wave and – if properly recorded – S-wave velocities of the penetrated subsurface layers. As seismic velocities translate to ranges of sediment and rock types, velocity–depth distribution models are used to help interpret shallow subsurface to deep crustal 2D cross-sections or 3D depth-slices, ideally in combination with complimentary seismic reflection and/or potential field (gravity, magnetic) data. Interfaces of first-order impedance discontinuities or layers with strong vertical velocity gradients with respect to wavelength are well recognizable in travel time phases and can be meaningfully modeled. Amplitude analyses of either refracted or wide-angle reflected wave-fields, using ray-geometric or wave-field inversion techniques, are useful for characterizing layer interface properties such as thin lamination or intercalation. For instance, such analyses have revealed a complex formation and composition of the crust–mantle boundary in some regions (e.g., Levander et al., 2005).

DOI 10.1007/978-94-007-6644-0_128-1

Contribution to Earth Science

Classical applications of the reflection and seismic refraction method to earth science are seismic stratigraphy and structural geology. Both approaches are needed to unravel the dynamics of continental and oceanic basins. Structural geology deals with the imaging of 3D distribution of rock units; its interpretation aims on the reconstruction of their deformational histories.

Seismic refraction surveying has largely contributed to the understanding of the architecture and composition of the earth's crust and uppermost mantle. Crustal thicknesses of the ocean and continental lithosphere have been determined largely due to the frequently encountered strong impedance contrasts at the crust–mantle boundary. Intra-crustal reflection interfaces are deciphered from analyses of amplitude characteristics in wide-angle reflection and refraction records. Being a powerful tool in the studies of continent–ocean boundaries, refraction surveying and the resulting velocity–depth models have revealed that these boundaries are often transitional zones of various widths in continental margins of both volcanic and non-volcanic types (e.g., Mjelde et al., 2005; Voss and and Jokat, 2007; Suckro et al., 2012). While the normal-incidence seismic reflection technique largely fails to properly image sub-salt and sub-basalt sedimentary formations and structures, the seismic refraction technique is used as a complimentary tool to provide velocity information from such "hidden" zones.

Sequence stratigraphy is a methodology that provides a framework for the elements of any depositional setting, facilitating paleogeographic reconstructions and the prediction of facies and lithologies away from control points (Catuneanu et al., 2011). Seismic stratigraphy is the approach to conclude on sequence stratigraphy by seismic interpretation. A special discipline of seismic stratigraphy is the analysis of depositional geometries in terms of oceanic currents, which may influence deposition processes forming so-called contourites or contourite drifts (Nielsen et al., 2008). Geophysicist therefore may contribute to paleoceanographic and related paleoclimate studies.

The contribution of the reflection seismic method to chemical processes and the migration of fluids and volatiles, both producing particular characteristics in seismic images, were acknowledged in the 1990s, stimulating research cooperation with biologists and chemists. Further, the transition of free gas to overlying gas hydrate, mainly consisting of methane trapped inside cages of hydrogen-bonded water molecules, gives a strong reflection crosscutting depositional strata, which is easy to detect in seismic data.

The assessment of geohazard potential caused by landslides including their tsunamigenic potential is a fast-developing research field. Owing to the specific internal and external deformation pattern, large submarine landslides are easy to detect in seismic data. The imaging of the internal geometry of volcanoes allows for conclusions on acting volcanism processes and recurrence rates.

The seismic refraction technique is successfully employed in geotechnical and engineering surveys to determine the depth to bedrock. Applications range from the detection of fracture zones in hard rocks in connection with groundwater prospecting, to delineating unconsolidated strata in civil engineering (road and tunnel constructions), to hazardous waste disposal projects.

Conclusion

Seismic reflection and refraction methods are two of the most commonly used geophysical methods in exploring the earth's subsurface for both hydrocarbon exploration and academic research of the buildup of the crust and its sedimentary cover. Both techniques have provided data to constrain the

DOI 10.1007/978-94-007-6644-0_128-1

development of the earth's crust from the sedimentary basins down to the transition to the uppermost mantle of the continents and oceans. Their relatively high structural resolution capacity is one of their greatest advantages. Future developments will see further improvement of 3D imaging and 4D monitoring capabilities from observing resource reservoirs and hydrological systems to geotectonic hazards in regions at risk of earthquake and tsunami.

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