CHAPTER 2

Seismic Reflection Theory and Seismic Stratigraphic Concept

2.1 Introduction

Seismic reflection profiling can be used to determine sub-surface geological information including stratigraphy, depositional system and geometry of sedimentary sequences and structures (Fagin, 1991). For the past several decades, technological development in seismic interpretation had not been virtually effective until a concept of seismic stratigraphy was introduced to petroleum exploration in early 1970s (Evans *et al.*,1995; Payton, 1977; Dobrin and Savit, 1988). Seismic stratigraphy is basically a geological approach to the stratigraphic interpretation of seismic data. The three-step interpretational procedure consists of seismic sequence analysis, seismic facies analysis and analysis of relative changes of sealevel (Mitchum and Vail, 1977; Vail and Mitchum, 1977).

This chapter briefly reviews the theory of seismic reflection, principle of continuous reflection profile, the technique of shallow marine seismic reflection profiling, and a concept of seismic stratigraphic interpretation as well as an application of the concept to the study of the Quaternary sequences.

2.2 Theory of Seismic Reflection

Seismic waves are elastic disturbances that are propagated through materials as patterns of particle deformation with velocities which depend on their elastic properties and densities (Dobrin and Savit, 1988; Sheriff, 1991).

2.2.1 Elastic Property of Media

Elasticity is the ability of material to return to original shape after removal of a distorting stress and the return of shape is complete and essentially instantaneous rather than gradual. Therefore, seismic waves generally cause a non-permanent deformation of material in which stress and strain are linearly related in accordance with Hook's law (Sheriff, 1991). The deformation consists of alternating compression and dilatation as the particles in the material move closer together and far apart in response to forces associated with the traveling waves (Dobrin and Savit, 1988).

2.2.2 Seismic Waves and Velocity

When elastic waves are generated, they propagate with velocity depending on the elastic property of the medium that they are traveling through. Two types of elastic wave are considered in seismic prospecting. The compressional wave or P-wave is the wave that the particles move in the same direction as wave propagation. In contrast, the shear wave or S-wave is the wave that the particles move perpendicular to the direction of wave propagation (Ensley, 1984; Dobrin and Savit, 1988; Sheriff, 1991; Evans *et al.,* 1995).

The velocity of compressional wave (Vp) is a function of density of media (ρ), bulk modulus (incompressibility) (κ), and shear modulus (rigidity) (μ). The compressional wave velocity is given by the equation;

$$\mathrm{Vp} = \sqrt{\frac{\kappa + 4\mu / 3}{\rho}} \quad \text{.......................................(1)}$$

The velocity of shear wave (Vs) is a function of shear modulus (μ) and density of media (ρ). The shear wave velocity can be expressed as follows;

$$\mathrm{Vs} = \sqrt{\frac{\mu}{\rho}} \quad \text{.......................................(2)}$$

The rigidity of material affects velocity more than the density (Evans *et al.,* 1995). Velocity is very much dependent on the porosity, mineral composition, cementing material and the material filling in the pores (Dobrin and Savit, 1988; Evans *et al.,* 1995).

Fluids cannot support the propagation of shear waves because they have no resistance to shear (Ensley, 1984; Dobrin and Savit, 1988; Evans *et al.,* 1995). Hence, only the compressional wave is very important to marine seismic survey.

The velocity of sound in sea water is between 1.46 to 1.56 km/sec (Evans *et al.,* 1995). It depends on ambient temperature, salinity and pressure (depth). If no precise value is available, normally, an interpretation of seismic profile uses a value of 1.5 km/sec in sea water. The velocity of sound through sediments or rocks increases with decreasing porosity. Velocities of sound in different rock types are shown in Table 2.1.

A knowledge of the velocity of the sequence being considered is essential to convert a seismic profile to depth. This can be done either using a velocity from a nearby area or a calculated velocity where a borehole crosses the profile track. In this study, an average velocity of 1.75 km/sec was assumed through all the sedimentary sequences in the area, as this average velocity used in previous seismic interpretation of the Gulf of Thailand Project gives reliable depth-conversion (Offshore Mineral Exploration in the Gulf of Thailand Project, 1988a, 1988b, 1989a, and 1989b; Lallier, 1988).

2.2.3 Acoustic Impedance and Reflection Coefficient

a) Acoustic impedance

Acoustic impedance (Z) is the product of the bulk density (ρ) and compressional wave velocity of the medium (V) and is defined as follows;

$$Z = V\rho \qquad \text{...(3)}$$

b) Reflection coefficient

Reflection coefficient (R) is the ratio of amplitude of the reflected wave to the incident wave. At the normal incidence of acoustic signal, where Z_1 and Z_2 are the acoustic impedances of the upper medium and the lower medium respectively, reflection coefficient is given by

Table 2.1 The acoustic velocity in different lithology
(after Evans et al., 1995)

Lithology	**Acoustic velocity (km/sec)**
High porosity mud and silty sand of Quaternary age	1.46-1.6
Low porosity coarse sand of Quaternary age	~ 1.8
North Sea off UK	
post-Paleocene sand, silt, clay	
-at depth of 1 km	~ 1.8
-at depth of 6 km	~ 2.1
Jurassic- shale, clay and sandstone	2.4-4.0
Hong Kong waters	
young Quaternary sediments	~1.6
old Quaternary sediments	2.0
consolidated sediments	3.0
igneous, evaporite and limestone	3.0-6.0

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad \text{...(4)}$$

Reflection of acoustic wave usually occurs at boundaries between layers of contrasting acoustic impedance. The acoustic impedance contrast between both sides of the reflecting surface affects the strength of reflected waves. Where the contrast between the media is large, the strength of reflected waves will be large too, and vice versa. The contrast at a sediment-sediment interface is normally associated with lithological changes. In a uniform soft mud sequence, it may display continuous, moderate amplitude reflection on the profile (Dobrin and Savit, 1988). This is due to subtle changes in sediment density related to variable consolidation of the sediment column rather than lithology (Evans *et al.,* 1995).

Reflection coefficient (R) is positive when the wave travels from a lower impedance material into a higher one and the phase of reflected signal remains unchanged. This situation occurs in sedimentary sequences when impedance increases with depth of burial (Gregory, 1977; Sheriff, 1977; Dobrin and Savit, 1988; Evans *et al.,* 1995). However, signal inversion of reflection also occurs when the wave travels from the higher acoustic impedance material into the lower acoustic impedance one *e.g.* from a water-filled to a gas-filled sand and from sea water to air. In Quaternary sediments, signal inversion is usually associated with a layer of low velocity peat or a thin gas rich sandy unit (Evans *et al.,* 1995).

2.2.4 Wave Propagation

Generally, an acoustic source produces the signal containing a composite of frequencies. However, dominant frequency which has a maximum energy is a representative frequency of the signal (Dobrin and Savit, 1988). The acoustic signal property can be evaluated from its wavelength (λ) which is defined as;

$$\lambda = \frac{V}{f} \qquad \text{...(5)}$$

where V is the sound velocity in m/sec,

f is the frequency in hertz (cycle per second).

The dominant frequency of signals varies with the acoustic sources used, shown in Figure 2.1.

In general, the reflection process has been considered in term of signal paths, but acoustic signal actually propagates as a wavefront which spreads spherically. The acoustic energy is intensified in a small specific area when wavefront hits an interface or seabed. This area is known as the first Fresnel zone where it is effectively generating reflection. Its size depends on the wavelength of the dominant frequency of the incidence wave and depth of reflector. A lower frequency signal has a larger Fresnel zone than a higher frequency (Figure 2.2) and the size of Fresnel zone also increases with depth (Figure 2.3). Therefore, the first Fresnel zone controls the horizontal resolution of the profile (Sheriff, 1977 and 1991; Dobrin and Savit, 1988; Evans *et al.*,

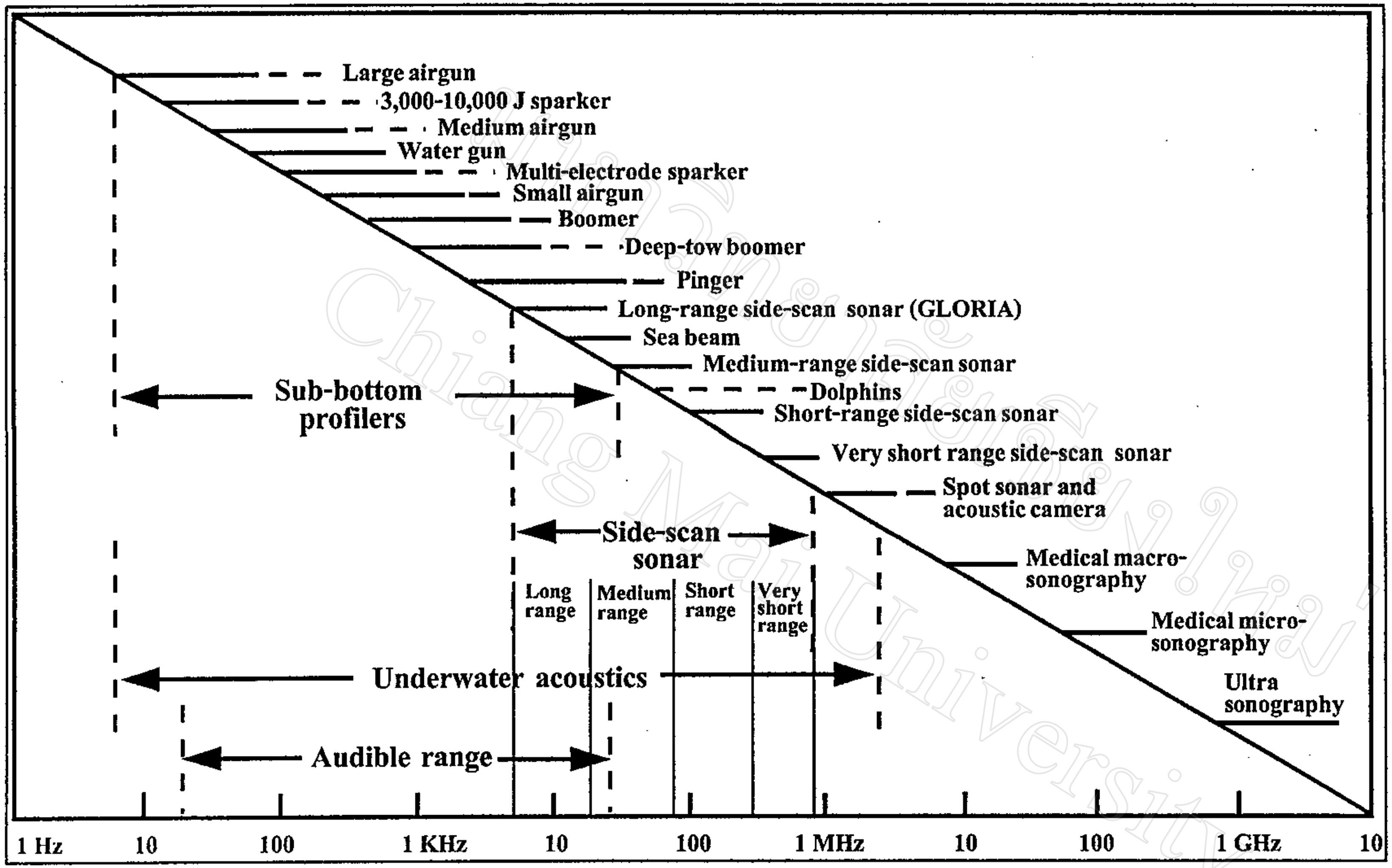
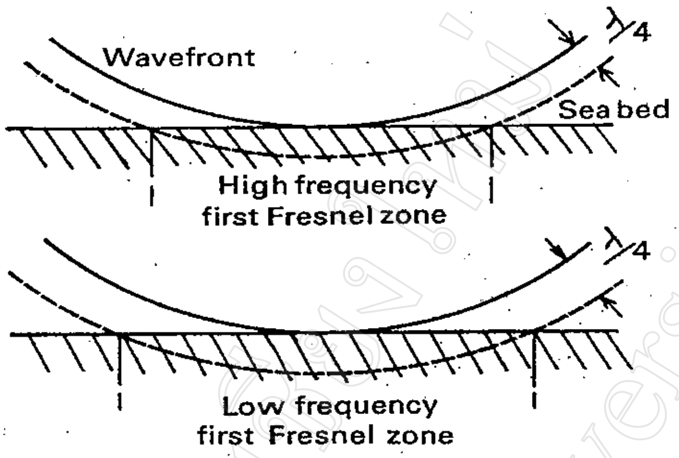


Figure 2.1 Frequency spectra of various acoustic methods (after Flemming, 1982)



The high frequency acoustic signal has a smaller Fresnel zone than the low frequency signal.

Figure 2.2 Diagram showing radius of the first Fresnel zone defining the area involved in the reflection process (after Evans et al., 1995).

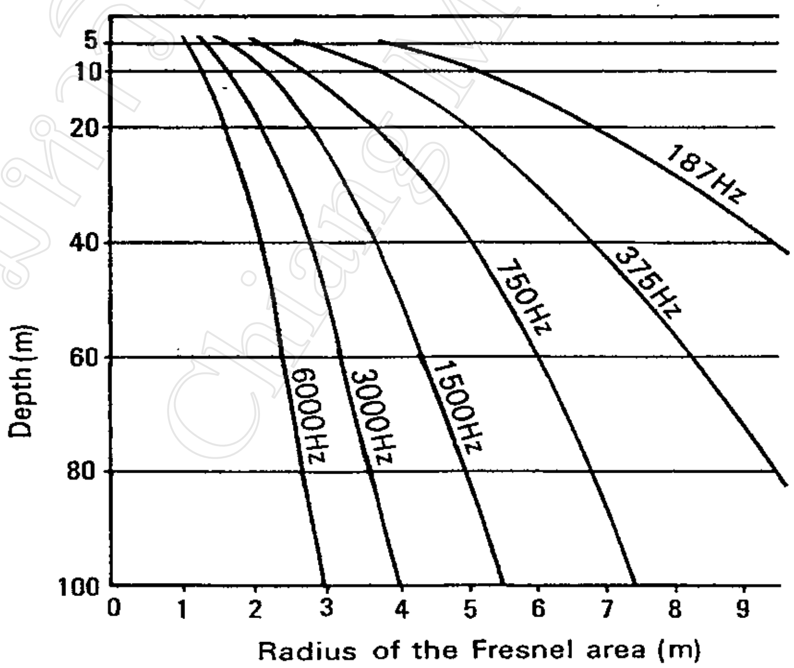


Figure 2.3 Graph showing the radius of the Fresnel zone as a function of the frequency of the acoustic source and depth to a reflecting horizon (modified after Geyer, 1983).

1995). Center and boundary of a circular region are determined by one-quarter wavelength of the signal (Geyer, 1983).

2.2.5 Energy Loss Mechanism

When an acoustic wave travels through a medium, it will experience a reduction in energy content as it propagates outwards. There are three main mechanisms for attenuation.

a) Geometric spreading loss

The energy at the spreading wavefront decreases inversely proportional to the square of the distance that the wave has propagated. As a spherical wave spreads out from its source, the energy must be distributed over the area of the sphere. However, this attenuation does not depend on frequency. In a shallow water survey, the energy loss through geometrical spreading in water column is much less than that in a deep water survey because the source and detector are relatively close to the target reflector.

b) Energy absorption

The loss of energy is due to internal friction between material grains as the wave passes through, resulting in irreversible heat energy. The loss of energy is very small as the wave pass through water, but it is a considerable loss as the wave pass through the sediment. The absorption generally decreases with depth as the porosity of sediment decreases. The energy absorption is greater at higher frequency. Therefore, higher frequency signals are unable to penetrate as deeply as lower frequency signals. Reflections from deeper formations have more dominant low frequency component than those from near the seabed. To improve penetration, high energy, low frequency source is needed. However, low energy, high frequency source is appropriate for improving resolution. Therefore, many studies use a range of seismic sources of different frequencies operating simultaneously.

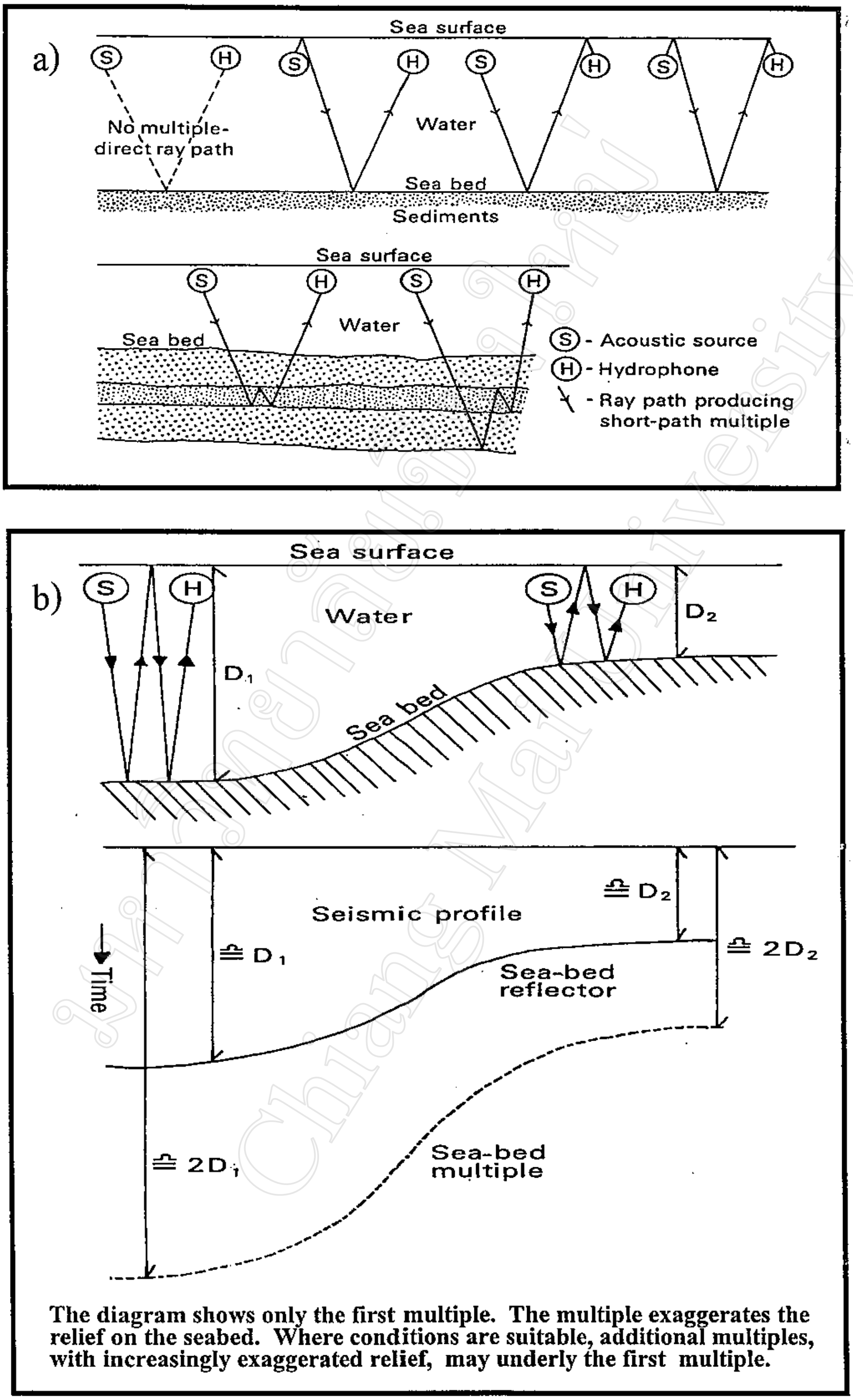
c) Reflection and reverberation

Reflection of an acoustic signal does not directly involve energy attenuation, but reflection can produce diffraction, scattering and reverberation. These processes will result in a reduction in amplitude of primary reflections. Hence, they are considered as the source of energy attenuation as well. A combination of multiple reflections is usually possible from reflecting horizons within the sub-seabed sediments and the sea surface.

Multiple reflections are most commonly associated with strong acoustic impedance contrasts between adjacent layers. The primary reflection usually combines with multiple reflections from horizons within seabed sediment and sea surface. There are two types of multiples, *i.e.* short-path multiple and long-path multiple.

1) A short-path multiple (Figure 2.4a), the surface "ghost" reflector, occurs when the energy generated from source traveling up to sea surface is reflected downward at the air-sea surface, with a phase reversal, being added to the tail of the down going pulse. This phenomena broaden the outgoing pulse. The extent of the pulse tail depends on the depth of acoustic source. Similar effect happens to the immersing receiver.

2) Long-path multiple reflections (Figure 2.4b) can be troublesome to the interpretation when they are difficult to distinguish from primary



The diagram shows only the first multiple. The multiple exaggerates the relief on the seabed. Where conditions are suitable, additional multiples, with increasingly exaggerated relief, may underly the first multiple.

Figure 2.4 **Short-path (a) and long-path (b) multiples produced by reflections at the seabed, sea-air interface, and within the sediments (after Evans et al., 1995)**

reflections. The signal reflected from the seabed may be reflected back to the sea surface and downwards again, producing a false outgoing signal. Where the seabed, in shallow sea, can produce strong reflections, a train of closely spaced multiples (reverberation) will be generated and can obscure sub-bottom reflections beneath the multiples. The most essential one is the first seabed multiple that mostly exhibits strong signals.

2.3 Continuous Reflection Profiling

A need for high resolution seismic of analogue single-channel profiling technique is still necessary to shallow sea survey since it can provide seabed and sub-seabed information at a low cost and relative simplicity. The high resolution seismic technique is widely used in shallow sea survey for searches of economic placers, rig site investigation, seabed mapping, coastal planning and engineering, *etc.* To date, digital technology is being applied to shallow single-channel seismic systems (Evans *et al.,* 1995).

Followings are discussions of the continuous reflection profiling system including geometry of the system, resolution, profile measurement, and basic equipment.

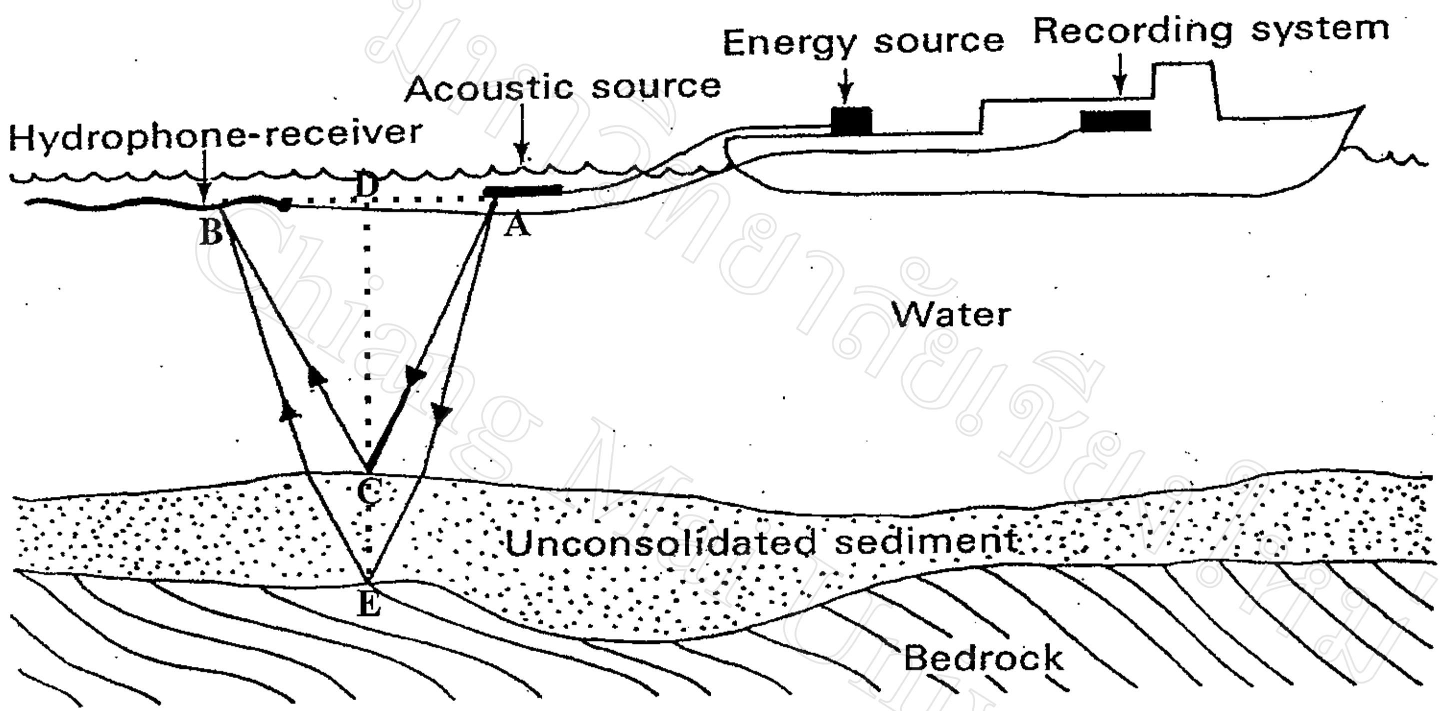
2.3.1 Geometry of the System

A shipboard seismic reflection profiling system requires a sound source, a signal receiver and a graphic or digital recorder. Fundamentally, a sound source gives off an acoustic energy, then immediately traveling through sea water. When acoustic energy strikes the interfaces between any two layers which have different acoustic impedances, reflections will take place at the interfaces. Some of energy will bounce back to the receiver or hydrophone (Figure 2.5), then are electronically recorded by the recorder and displayed onto a continuous paper record. The record displays a graphic continuous time-section beneath the seafloor along the ship's tracks. The two-way travel time can be measured on the graphic record and converted into the depth or thickness if the velocities of acoustic waves in each medium are known. The geometry of the continuous profiling system is shown in Figure 2.5.

2.3.2 Resolution of Seismic Profile

Resolution is the ability of the system to separate two real features on the profile. It depends on the distance between the features and the wavelength of the incident wave (Sheriff, 1977 and 1991; Evans *et al.,* 1995). However, only variable affecting the wavelength which can be controlled is the frequency of acoustic sources (Sheriff, 1977).

Shorter wavelength (higher frequency) sources have a greater resolving power. Nevertheless, higher frequency experiences greater reduction in energy content during propagation and penetration of higher-frequency sources is more limited than that of lower-frequency sources (Evans *et al.,* 1995). An attenuation of seismic signals which is proportional to the frequency strongly affects to the resolution, both vertical and horizontal directions. However, seismic interpretation is concerned with resolution in two directions both vertical (in time or depth) and horizontal (from trace to trace) (Sheriff, 1977).



Two basic assumptions are made. Firstly, the distance between the source and the receiver (AB) is short compared with the distance from the mid point of that line (D) to reflector (C or E); and therefore, the path of the received signal, from source to hydrophone, is normal to the reflector. Secondly, the angle of incidence of the signal (ACD) is equal to the angle of reflection (DCB), but if AB is small, then these angles are small, and the signal is reflected at nearly normal to the interface.

Figure 2.5 Basic elements and geometry of a continuous seismic reflection profiling system (after Evans et al., 1995).

a) Vertical resolution

Maximum attainable vertical resolution is approximately one-quarter of the dominant wavelength of the acoustic source. Reflections of adjacent interfaces can be individually distinguished if the distance of two interfaces is not less than one-quarter of the wavelength. For example, if the dominant frequency of the source is 1 kHz, the maximum resolvable layer thickness in sediments with an acoustic velocity of 2,000 m/sec is 0.5 m and for a lower frequency source of 400 Hz, the resolvable thickness of sediment with the same velocity becomes 1.25 m. The actual resolution obtaining during a marine survey depends on several factors, *e.g.* depth of source-receiver, wave motion, turbulent water, wind and sea conditions, *etc.* However, prevailing weather conditions are usually considered for a design of the configuration of the system.

b) Horizontal resolution

The portion of the reflector between points of contact with the wavefront is the area which effectively produces the reflection; it is called the first Fresnel zone (Figure 2.2 and 2.3). Energy from the periphery of the first Fresnel zone will reach a receiver at the source location one-half wavelength later than the first reflected energy (Sheriff 1977 and 1991; Evans *et al.,* 1995).

Features with dimension less than the first Fresnel zone will not be observed on the seismic record and the limitation on the maximum attainable horizontal resolution depends upon this dimension. To obtain a complete dimension of a feature, it must be ensured that firing rate of the source is high enough and the vessel's speed over the ground is slow enough for which the first Fresnel zone from the adjacent shots overlaps and the reflector is adequately defined on the seismic record (Evans *et al.*, 1995).

For example, the first Fresnel zone for a reflector at depth of 50 m in sediments of velocity 1,800 m/sec is 13.4 m wide for a signal of 1 kHz. A vessel's speed of 4 knots (7.2 km/hr) would give a 2 meter separation over the ground between each firing interval of one second. This situation would allow full overlap on the record for features of less than 13.4 m across.

Arrivals from outside the Fresnel zone can be reduced by using a focus source such as a boomer, and by decreasing the size of Fresnel zone either by increasing the frequency or towing the source-receiver close to the seabed (Evans *et al.*, 1995).

2.3.3 Assumption for the Measurement

The seismic profile represents an acoustic cross-section of the sub-seabed sediments beneath the ship's track. Extraction of geological information from continuous reflection profiling system depends on measuring the time between the emission of an acoustic signal and the reflected signal from interfaces at or beneath the seabed.

Two basic assumptions are made convenience for profile measurement, information translation and conversion of time record to depth one. Firstly, the ray path of the received signal from the source to the hydrophone gives a shortest travel time and is normal to the reflector surface from the source-receiver. Secondly, it is assumed that the ray path impinge on an interface at right angle termed as normal incidence. The normal incidence reflections originate from points directly beneath the source-receiver (Evans *et al.,* 1995).

2.3.4 Instrumentation of Seismic Reflection System

The geophysical data collection in offshore areas requires a combination of electronic, navigational and marine skills. For geophysical survey in the Gulf of Thailand Project's areas, a set of navigational equipment, an echo sounder and a continuous seismic reflection profiling system are routinely employed to obtained seabed and sub-seabed geological information of the areas and marine magnetometer set is sometimes used to investigate high magnetic anomaly areas.

All equipment used in the Gulf of Thailand Project are listed in Table 2.2 and photos of the equipment sets are shown in Appendix A. However, only the equipment set used for continuous seismic reflection profiling system will be described. The system consists of three components : an acoustic source usually towed in the water, a hydrophone to pick up the reflection signal, and a graphic or digital recorder providing signal translation to analogue display as cross-sectional profile (Appendix A).

2.3.4.1 Seismic Sources

Normally, the sources used for shallow marine survey are Pinger, Boomer and Sparker. The choice of acoustic sources normally depends on the requirement for resolution and depth of penetration. The seismic survey of the Gulf of Thailand Project generally employs 50 tip home-made sparker, but in

Table 2.2 List of equipment employed in geophysical surveys in the Gulf of Thailand Project
(after Offshore Mineral Exploration in the Gulf of Thailand Project, 1988a, 1988b, 1989a, and 1989b)

1. High Resolution Seismic Profiling System
  1.1 Trigger capacitor bank : model EG&G 231
  1.2 High power supply : model EG&G 232A
  1.3 Graphic recorder : model EPC 3200, EPC 4800 and EPC 9802
  1.4 Band-pass filter : model Krohn-Hite 3700
  1.5 Acoustic energy source : Uniboom EG&G 230A and home-made sparker
  1.6 Seismic receiver : 8-element hydrophone array model EG&G 265 and single element hydrophone model EG&G 262

2. Echo Sounder
  2.1 Graphic chart recorder with 208 kHz transducer : model Raytheon 1170
  2.2 Depth sounder with thermal print recorder : model Inner Space 448

3. Magnetometer Set
  3.1 Marine magnetometer sensor (tow-fish) : model G866 tow system
  3.2 Magnetometer recorder with graphic analogue and digital display : model G 866
  3.3 Base station magnetometer sensor and recorder

4. Navigation System
  4.1 Motorola navigation system : model Falcon IV comprising Range processor unit, VDO control display, Track chart plotter, Transmitter/Receiver unit for mobile vessel and 3 Transponder units for onshore reference stations
  4.2 Motorola DGPS set : model Phoenix

some particular areas which need higher resolution at shallow depth the boomer may be used instead (Appendix A). The seismic system setting which is normally operated for the surveys in the Gulf of Thailand Project's areas is shown in Table 2.3.

2.3.4.2 Receiver

Those acoustic pulses reflected from the seabed and the underlying geological interfaces are received by receiver unit and amplified before displaying. In case of a Pinger employed for the survey, it is rather convenient since the system consists of the underwater transducer (emitting unit) and transceiver (receiver unit), both fixed together in a small container. For other seismic systems, all acoustic sources require a separated receiver known as a hydrophone-streamer or a hydrophone-array (Appendix A). In general, the hydrophone receives the reflected acoustic pressure waves and then converts them to electrical signals through inboard processing and displaying on a graphic recorder.

The hydrophone-array consists of a line of piezoelectric, crystalline elements placed inside an oil filled, flexible tube which is trailed behind the vessel. An advantage in using a hydrophone-array is an improvement in signal-to-noise ratio. That is ambient and organized noises arriving along the line of hydrophone-array are reduced because the returns of reflected waves from seabed and sub-seabed arrive at all elements simultaneously and are summed in phase, whereas noises traveling along the line of array arrive at each element in succession and tend to cancel out (Evans *et al.*, 1995).

Table 2.3 General parameter settings for high resolution seismic reflection profiling system in the Gulf of Thailand Project (after Offshore Mineral Exploration in the Gulf of Thailand Project, 1988a, 1988b, 1989a, and 1989b)

Parameter settings	Values	Unit
Transmitted energy for different sources		
-Uniboom	100-200	joule/pulse
-Sparker (home-made 50 tips)	200-400	joule/pulse
Firing rate	250	msec/pulse
Sweep speed (record length)	125	msec/sweep
Chart speed	0.8	in/sec
Fixed mark interval	1-2	min
Print polarity	negative	
Band pass filtering setting		
-low pass	600	Hz
-high pass	1,800	Hz
Sparker offset (from the ship)	15	m
Hydrophone offset (from the ship)	15	m
Seismic source and hydrophone separation	5	m
Vessel speed	7-9	km/hr

2.3.4.3 Recorder

The reflected signals may be displayed, after amplification, onto a graphic recorder or be recorded on the magnetic tape. An analogue display provides continuous paper cross-sections or profiles of sub-seabed strata and structure beneath the tracks of the survey vessel.

The signals from the sub-seabed reflectors have much lower amplitudes than those from the seabed. Furthermore, the desired reflection arrivals add ambient noise to the return signals. This ambient noise is caused by various source *e.g.* vessel's propulsion, strumming of tow cable, turbulence of waterflows and seawave. Noise is extremely difficult to be eliminated. However, the noise effects can be reduced by inboard processing and filtering out unwanted acoustic signals to improve the signal-to-noise ratio before recording.

2.4 Seismic Stratigraphic Concept

2.4.1 Seismic Stratigraphic Approaches

According to Payton (1977) and Brown and Fisher (1979) the seismic stratigraphy discipline has been developed in two different paths. One approach is to determine stratigraphic information from qualitative analysis of reflection. Regions of distinctive appearance can be grouped from variation in reflection amplitude, continuity and concordance. These are assigned stratigraphic meaning by comparison to sub-surface information. The other approach attempts to duplicate a seismogram by numerical modeling. Reflection coefficient model of the strata thickness, velocity, density and absorption is constructed either from sub-surface data or from the knowledges of the interpreters about the survey areas. The model is convolved with a seismic pulse to produce a synthetic seismogram which, in turn, is compared for similarity to the field record. The two seismic stratigraphic approaches for petroleum exploration were widely used by seismic interpreters (Payton, 1977; Brown and Fisher, 1979; Dobrin and Savit, 1988; Evans *et al.,* 1995). Seismic stratigraphic interpretation (qualitative analysis and numerical modeling) technique can effectively help geoscientists to interpret seismic data in terms of geological models aimed at locating gas and oil reservoirs in hydrocarbon exploration (Dobrin and Savit, 1988).

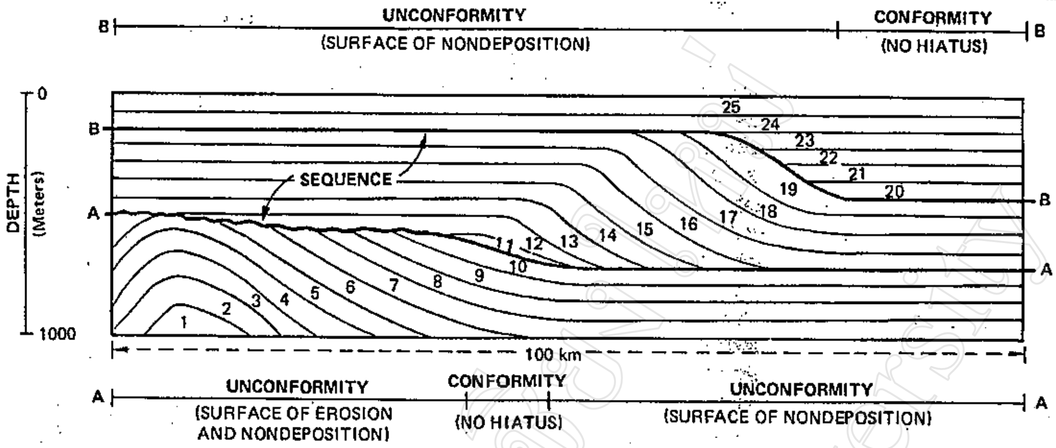
An integration of seismic data with stratigraphic concept has greatly aided in interpretation of depositional system, lithofacies of sequences, new dimension to basin analysis and geological modeling of the survey areas. Vail and Mitchum (1977) considered that, with the two seismic stratigraphic approaches, not only post-depositional structural deformation can be delineated, the following types of stratigraphic interpretation can also be obtained from the geometry of seismic reflection correlation patterns, such as a) geologic time correlation, b) definition of genetic depositional units, c) thickness and depositional environment of genetic units, d) palaeo-bathymetry, e) burial history, f) relief and topography of unconformities, and g) palaeo-geography and geologic history when combined with geologic data.

This study, however, concentrates only on the first approach to extract shallow sub-seabed stratigraphic information (*i.e.* depositional environments of the Quaternary sedimentary sequences, seismic facies changes within the sequences, and history of deposition and erosion of the sequences) with the use of high resolution seismic profiling data, due to the lack of numerical data for modeling (both digital well logging and digital seismic records).

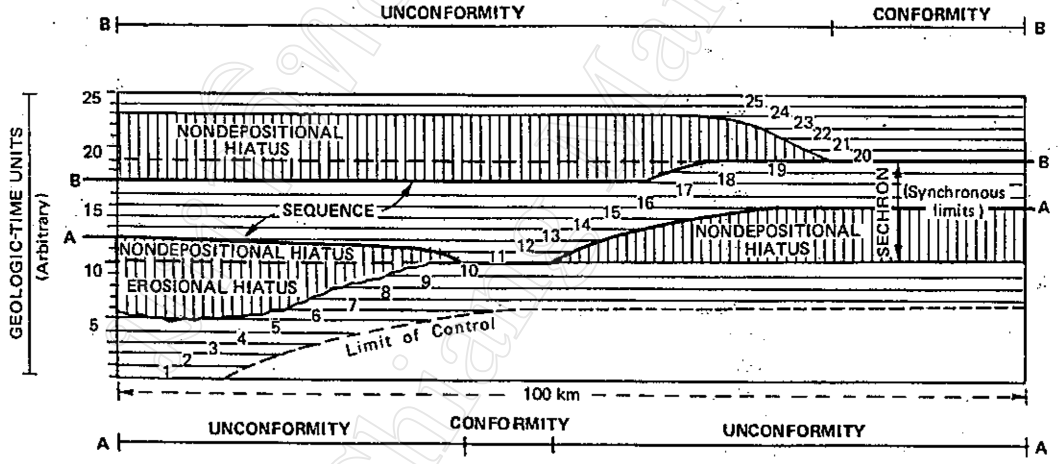
2.4.2 Fundamental of Seismic Stratigraphic Interpretation

An important fundamental of seismic stratigraphic interpretation is an understanding of the geological factors that generate the reflections. Primary seismic reflections are in responses to significant impedance change (change of velocity-density contrasts) along stratal surface or bedding surface, and unconformities (Vail and Mitchum, 1977; Brown and Fisher, 1979; Evans *et al.*, 1995). Primary seismic reflections, therefore, are parallel to stratal surface and unconformities, and these two types of chronostratigraphic surface are closely related to sequences (Vail and Mitchum, 1977). These surfaces are illustrated diagramatically in Figure 2.6.

Stratal surfaces are bedding contacts which represent relict depositional surfaces rather than arbitrarily defined lithostratigraphic boundaries. They also represent conformable changes in depositional regime (energy, sedimentation rate, environment, different types of sediments). Reflections are generated from those surfaces which coincide with a significant change in velocity and density. Reflections generating from a stratigraphic sequence may represent a single specific stratal surface or the reflection may represent the sum of several stratal responses. Reflections usually conform



A. Generalized stratigraphic section of a sequence. Boundaries defined by surfaces A and B which pass laterally from unconformities to correlative conformities. Individual units of strata 1 through 25 are traced by following stratification surfaces, and assumed conformable where successive strata are present. Where units of strata are missing, hiatuses are evident.



B. Generalized chronostratigraphic section of a sequence. Stratigraphic relations shown in *A.* are replotted here in chronostratigraphic section (geologic- time is the ordinate). Geologic-time ranges of all individual units of strata given as equal. Geologic-time range of sequence between surfaces A and B varies from place to place, but variation is confined within synchronous limits. These limits determined by those parts of sequence boundaries which are conformities. Here, limits occur at beginning of unit 11 and end unit 19. A sechron is defined as geologic-time range of a sequence.

Figure 2.6 Diagram showing basic concepts of depositional sequences (after Mitchum et al., 1977b).

with the collective configurations, continuity, acoustic impedance contrast and other physical properties exhibited by the responding strata.

Unconformities are surfaces of erosion or non-deposition which represent gap in geologic time record. Unconformities generate reflection because they commonly separate strata with different physical properties or attitudes. Strata below unconformities are commonly weathered or altered mineralogically, providing an acoustic impedance contrast. An unconformity is often a good seismic reflector. All strata above an unconformity are younger than all strata below it. Therefore, strata between unconformities constitute time-stratigraphic units. Unconformities generally occur at an angle to underlying and overlying stratal surfaces. Generally, time gap (hiatus) varies along an unconformity. Dunbar and Rodgers (1957) illustrated the conventional classification of unconformities and defined the familiar terms; non-conformity, angular unconformity, disconformity and paraconformity.

2.4.3 Seismic Facies Parameters

Seismic facies parameters which are widely used to extract geological information in seismic stratigraphic interpretation were introduced by Mitchum *et al.* (1977a), as shown in Table 2.4. They will be briefly described as follows.

a) Reflection configuration is generally related to geologic origin which is controlled by bedding patterns that are, in turn, related to depositional processes, original depositional topography and bathymetry, erosion, and later development.

Table 2.4 Seismic reflection parameters used in seismic stratigraphy, and their geological significance
(after Mitchum et al., 1977a)

Seismic Facies Parameters	Geological Interpretation	Remarks
a. Reflection configuration	Bedding patterns	
	Depositional processes	
	Erosion and Palaeotopography	
	Fluid contacts	*
b. Reflection continuity	Bedding continuity	
	Depositional processes	
c. Reflection amplitude	Velocity-density contrast	
	Bed spacing	
	Fluid content	*
d. Reflection frequency	Bed thickness	
	Fluid content	*
e. Interval velocity	Estimation of lithology	*
	Estimation of porosity	*
	Fluid content	*
f. External form & areal association of seismic facies units	Gross depositional environment	
	Sediment source	
	Geologic setting	

*__Note__ : * = not considered in this study*

b) Reflection continuity depends on continuity of acoustic impedance contrast along the stratal surfaces and bedding continuity is related to depositional processes and environments.

c) Reflection amplitude is principally controlled by the degree of a acoustic impedance contrast along stratal surface. An increase of reflection amplitude is also greatly influenced by fluid property contrasts within strata.

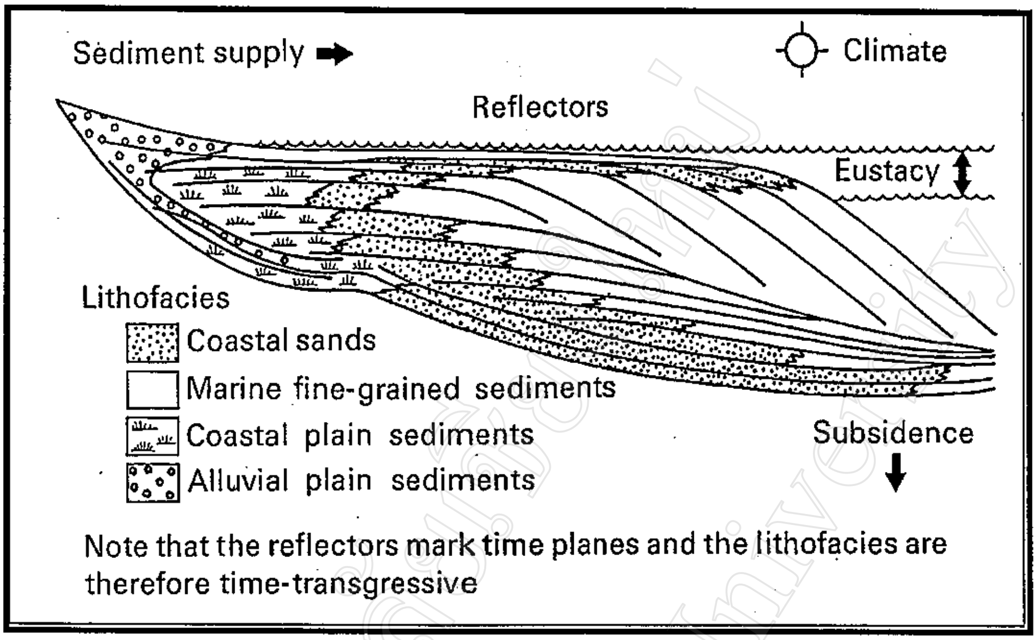
d) Reflection frequency which is induced by the seismic energy source may be modified by bed thickness which controls the spacing of reflectors. Frequency will be affected by lateral velocity change (due to fluid content) and lateral thickness change.

e) Interval velocity is the velocity of an interval in sub-surface layers between two reflections. It is a critical factor in seismic data processing as it can provide information on lithology, porosity, and fluid composition.

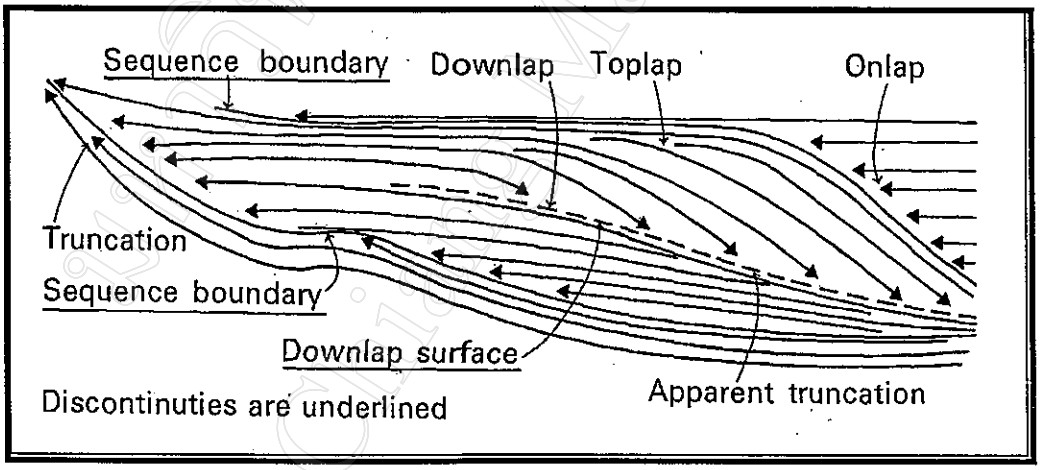
f) External geometry of a group of similar reflections (*i.e.* seismic facies) provides exceedingly important insight about the lithofacies analogues and depositional setting. In addition, lateral variations in the character of a reflection or group of reflections may be used to infer facies change.

The seismic stratigraphic concepts were originally applied to deep seismic profile across sedimentary basin for petroleum exploration (Figure 2.7). However, the concepts are effectively applicable to shallow seismic profiles (Evans *et al.,* 1995).

On shallow seismic profiles in the study area, those parameters in the Table 2.4 will not be all used for seismic stratigraphic interpretation because



a. Diagram showing the seismic reflectors, lithofacies and major variables affecting coastal margin stratigraphy (modified from Bally, 1987).



b. Diagram showing reflection termination pattern and types of discontinuties (modified from Bally, 1987).

Figure 2.7 Diagram showing a) coastal margin stratigraphy of variable depositional facies and b) termination patterns and types of discontinuties related to seismic stratigraphic concept.

they cannot be easily discerned from qualitative analysis. In addition, it is not worth consideration to the fluid contents in the Quaternary sequences for the exploration of sub-seabed detritus within shallow sequences since most of shallow sequences considered are unconsolidated and nearly saturated by water, then this category is negligible. Moreover, the interval velocity is not considered in this study because digital seismic data acquisition and processing were not principally designed for the survey program.

2.4.4. Basic Considerations for Seismic Interpretation

In seismic interpretation, the most important work of all is the translation of seismic information into geological terms (Dobrin and Savit, 1988). Interpretation of seismic profile essentially requires geological knowledge combined with some understanding of the seismic data acquisition technique (Evans *et al.,* 1995). Apparently, as seismic interpretation is becoming primarily a geologic rather than a geophysical skill (Fagin, 1991), a successful interpretation is not only a problem of geophysical skill, but also an application of depositional models and geological thinking (Evans *et al.,* 1995).

Once seismic signatures can be related to known lithostratigraphic sequences then seismic data can be used to show how far the particular stratigraphy extends and accurate recognition of distinctive seismic features may also help in recognizing similar stratigraphy elsewhere. However, accurate interpreted results mostly also depend on the interpreter's experience gained as much as practical works done (Sheriff, 1977).

A limitation of interpretation is to give the detail and accuracy of subsurface information because seismic events on the record do not display as a proper imaging cross-section (Fagin, 1991). The seismic profile is designed to be a representative of the two-ways travel time-section which could not be directly used as actual depth section.

Another limitation is related to the basic physics of seismic reflection in a medium concerning the characteristics of the earth materials and the matters including spatial resolution, composition of reflections (vertical resolution) and reverberations (Dobrin and Savit, 1988).

In addition, most reflections are interference composite. There is no one-to-one correspondence between seismic events and interfaces in the earth. One should be careful not to assume that, in noise free areas with high quality data, every waveform variation has a geological meaning which only needs definition (Sheriff, 1977).

Though given a reasonably noise-free response, seismic wavelength limits the detail which can be in two dimensions : vertical, or the thickness of stratigraphic units; and horizontal or aerial size of features (Sheriff, 1977; Evans *et al.,* 1995).

2.4.5 Techniques for Seismic Stratigraphic Interpretation

Principle of seismic stratigraphic interpretation needs a general knowledge of the geometry and facies composition of depositional system that fills the basins or other depositional areas (catchment, coastal area and continental shelf).

The seismic stratigraphic interpretation for shallow sea exploration mostly concentrate only in qualitative analysis of seismic profiles to obtain lithofacies and depositional systems (Brown and Fisher, 1979; Evans *et al.*, 1995), as principally emphasized in this study because of non-availability of digital data.

Where seismic data are tied with well data, stratigraphic information is appropriately obtained. The study also uses drill log data to assist the interpretation of lithofacies, depositional systems, chronostratigraphy of the sequence and appropriate geological model of the study areas.

The seismic stratigraphic interpretation techniques have been used for the study, since the previous seismic interpretation of the Area 1 did not apply the techniques for fully recovering the stratigraphic sequence and depositional systems, lithofacies models, sealevel change history and descriptive history of sequence development in the study area. Hence, the present study uses the three-step interpretational procedure introduced by Vail and Mitchum (1977) to accomplished the work. The procedure consists of 1) seismic sequence analysis, 2) seismic facies analysis, and 3) analysis of relative changes of sealevel.

2.4.5.1 Seismic Sequence Analysis

Seismic sequence analysis is an identification of stratigraphic units which are composed of a relatively conformable succession of genetically related strata termed depositional sequence. The upper and lower boundaries of depositional sequences are unconformities or their correlative conformities (Vail and Mitchum, 1977).

The depositional sequence is chronostratigraphically significant because it was deposited during a given interval of geologic time limited by the age of the sequence boundaries where they are conformities, although the age range of the strata within the sequence may differ from place to place where the boundaries are unconformities (Mitchum, *et al.,* 1977b). It provides an ideal framework for stratigraphic analysis. A basic concept of a depositonal sequence is illustrated in Figure 2.6.

The boundaries are usually defined at unconformities and trace to their correlative conformities. Discordance of strata is the main criterion used in determination of sequence boundaries. Type of discordance relation is the best indicator of whether an unconformity results from erosion or non-deposition. Depositional sequence boundaries are recognized on seismic data by identifying reflections caused by lateral terminations of strata termed onlap, downlap, toplap and truncation. Lateral terminations of strata are illustrated in Figure 2.8.

2.4.5.2 Seismic Facies Analysis

Analysis of seismic facies is a process of delineation and interpretation of reflection geometry, continuity, amplitude, frequency, and interval velocity, as well as the external form and association of seismic facies unit within the framework of depositional sequences (Vail and Mitchum, 1977).

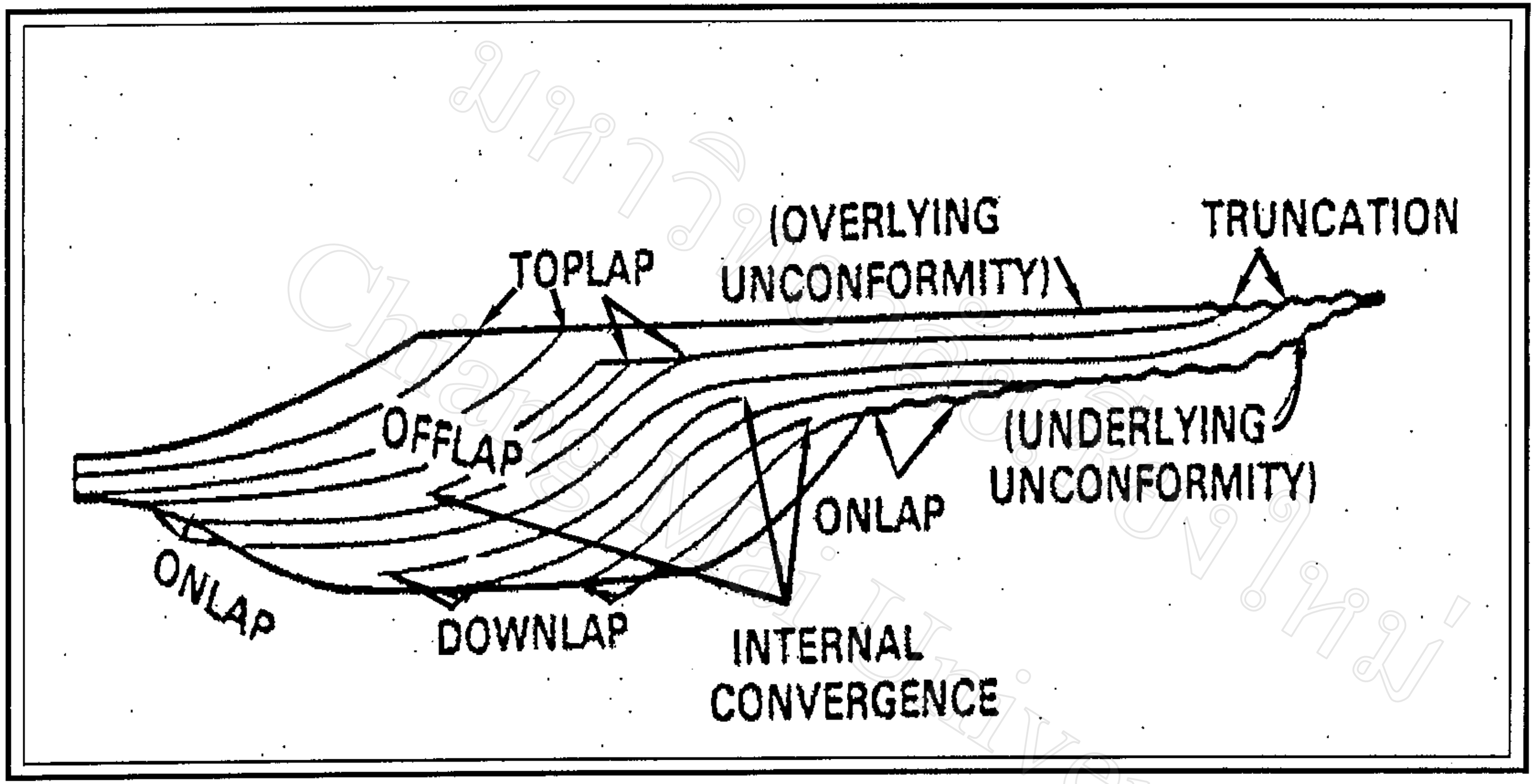


Figure 2.8 Seismic stratigraphic reflection terminations within an idealized seismic sequence (after Mitchum et al., 1977a).

Seismic facies are groups of similar seismic reflection patterns. Seismic facies are principally defined by internal reflection configuration of seismic facies units. Seismic facies units are mappable, three dimensional units composed of groups of reflections whose parameters differ from those adjacent facies units. The overall geometry of a seismic facies unit consists of the external form and internal reflection configuration. The types of reflection terminations, reflection configurations and seismic facies units are listed in Table 2.5. The external forms of some seismic facies units are illustrated in Figure 2.9.

Seismic facies analysis is based upon the description and geological interpretation of seismic reflection parameters. Where the seismic facies are described and mapped, an interpretation of the sedimentary processes and environmental setting allows interpreter to predict the lithology of seismic facies. Each parameter may provide considerable information on the sub-surface geology (Table 2.4). Reflection configuration can reveal the gross stratigraphic patterns from which depositional process, erosion and palaeo-topography can be interpreted (Vail and Mitchum, 1977). The mappable three-dimension seismic facies units will not be considered as the main theme of the study. The study will emphasize only the seismic facies patterns found in the study area.

2.4.5.3 Analysis of Relative Changes of Sealevel

Analysis of relative changes of sealevel consists of constructing chronostratigrahic correlation charts and chart of relative changes of sealevel

Table 2.5 Geologic interpretation of seismic facies parameters
(after Mitchum et al., 1977a)

REFLECTION TERMINATIONS (AT SEQUENCE BOUNDARIES)	REFLECTION CONFIGURATIONS (WITHIN SEQUENCES)	EXTERNAL FORMS (OF SEQUENCES AND SEISMIC FACIES UNITS)
1. LAPOUT	1. PRINCIPAL STRATAL CONFIGURATION	
1.1 BASELAP	1.1 PARALLEL	1. SHEET
- *ONLAP*	1.2 SUBPARALLEL	2. SHEET DRAPE
- *DOWNLAP*	1.3 DIVERGENT	3. WEDGE
1.2 TOPLAP	1.4 PROGRADING CLINOFORMS	4. BANK
2. TRUNCATION	- *SIGMOID*	5. LENS
2.1 EROSIONAL	- *OBLIQUE*	6. MOUND
2.2 STRUCTURAL	- *COMPLEX SIGMOID-OBLIQUE*	7. FILL
3. CONCORDANCE	- *SHINGLED*	
(NO TERMINATION)	- *HUMMOCKY CLINOFORM*	
	1.5 CHAOTIC	
	1.6 REFLECTION FREE	
	2. MODIFYING TERMS	
	EVEN *HUMMOCKY*	
	WAVY *LENTICULAR*	
	REGULAR *DISRUPTED*	
	IRREGULAR *CONTORTED*	
	UNIFORM	
	VARIABLE	

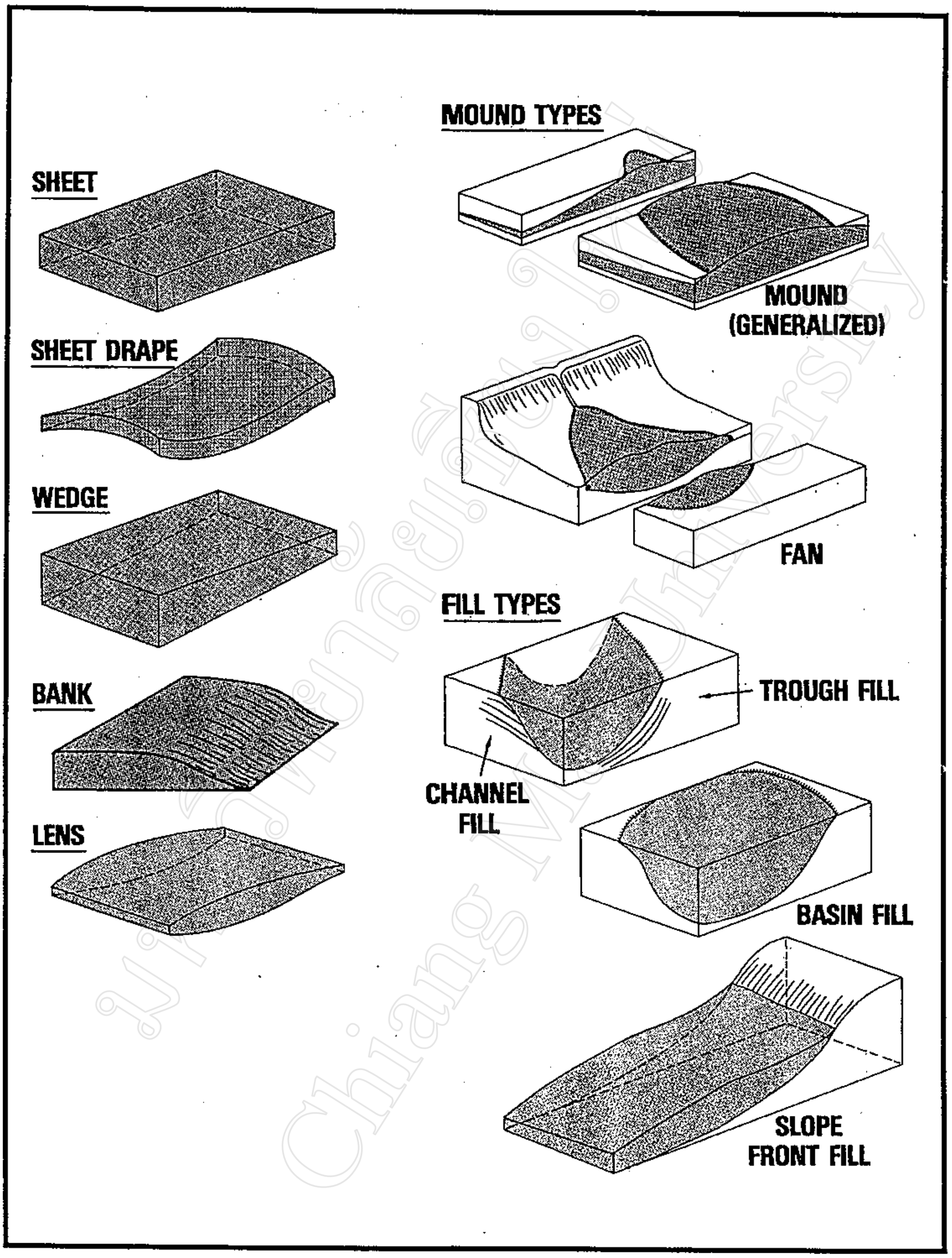


Figure 2.9 Diagram showing various external forms of some seismic facies units (after Mitchum et al., 1977a).

on a regional basis and comparing them with global data. Similarities of the regional cycles to the global cycles are significant in seismic stratigraphic analysis because they allow more accurate prediction of age, time of unconformities, palaeo-environments and lithofacies (Vail and Mitchum, 1977). A relative change of sealevel is defined as an apparent rise or fall of sealevel with respect to the land surface. The relative change of sealevel can be determined from the onlap of coastal deposits in sequences. A cycle of relative change of sealevel can be defined as an interval of time during which a relative rise and fall of sealevel takes place (Vail *et al.,* 1977).

The three-step interpretational procedures of the seismic stratigraphic concept can be summarized as follows.

The seismic sequence analysis can determine boundaries of depositional sequences which are unconformities or their correlative conformities. The seismic facies analysis can describe significant patterns, reflection termination and configuration, the procedure, therefore, can introduce the dimension of predictability into stratigraphy. Those two procedures can extract geological information which is directly observed on seismic sections. The analysis of relative changes of sealevel appears to determine comparatively the rise and fall of sealevel which controlled the major sequences deposited in marine and coastal environments. Upon an analysis of relative sealevel changes, age, distribution and facies of the depositional sequences may be predicted in the areas where the seismic coverage is available. In addition, an inter-relation of seismic data with all other forms of geologic information such as chronostratigraphic and environmental information from palaeontology, lithologic data from core (and wireline log) and regional information from outcrop and literature can be used to reconstruct geological history of deposition and erosion of the survey area (Vail and Mitchum, 1977; Mitchum, *et al.,* 1977b).

2.4.6 Application of the Concept to the Quaternary Sequences

Evans *et al.* (1995) summarized that bedding surfaces and unconformities act as seismic reflectors. A relationship between bedding surfaces and unconformities allows a chronostratigraphic interpretation from seismic profiles. In tectonically stable area, it is assumed that all reflectors become younger upwards, or rocks above a bedding surface or unconformity are younger than those below it. A seismic profile, therefore, represent as a record of chronostratigraphic (time-stratigraphic) depositional and structural patterns, not a record of time transgressive lithostratigraphy (Evans *et al.,* 1995); (Figure 2.7a). Another concept is the relationship of sealevel change and subsidence to sediment supply in controlling location of deposition and facies on the continental margin. A well known work on application of seismic stratigraphic concept to Quaternary sequences in relation to sealevel changes was done by Berryhill (1986). He modified a number of reflection configuration patterns from Mitchum *et al.* (1977a) to describe Quaternary sediments (Figure 2.10).

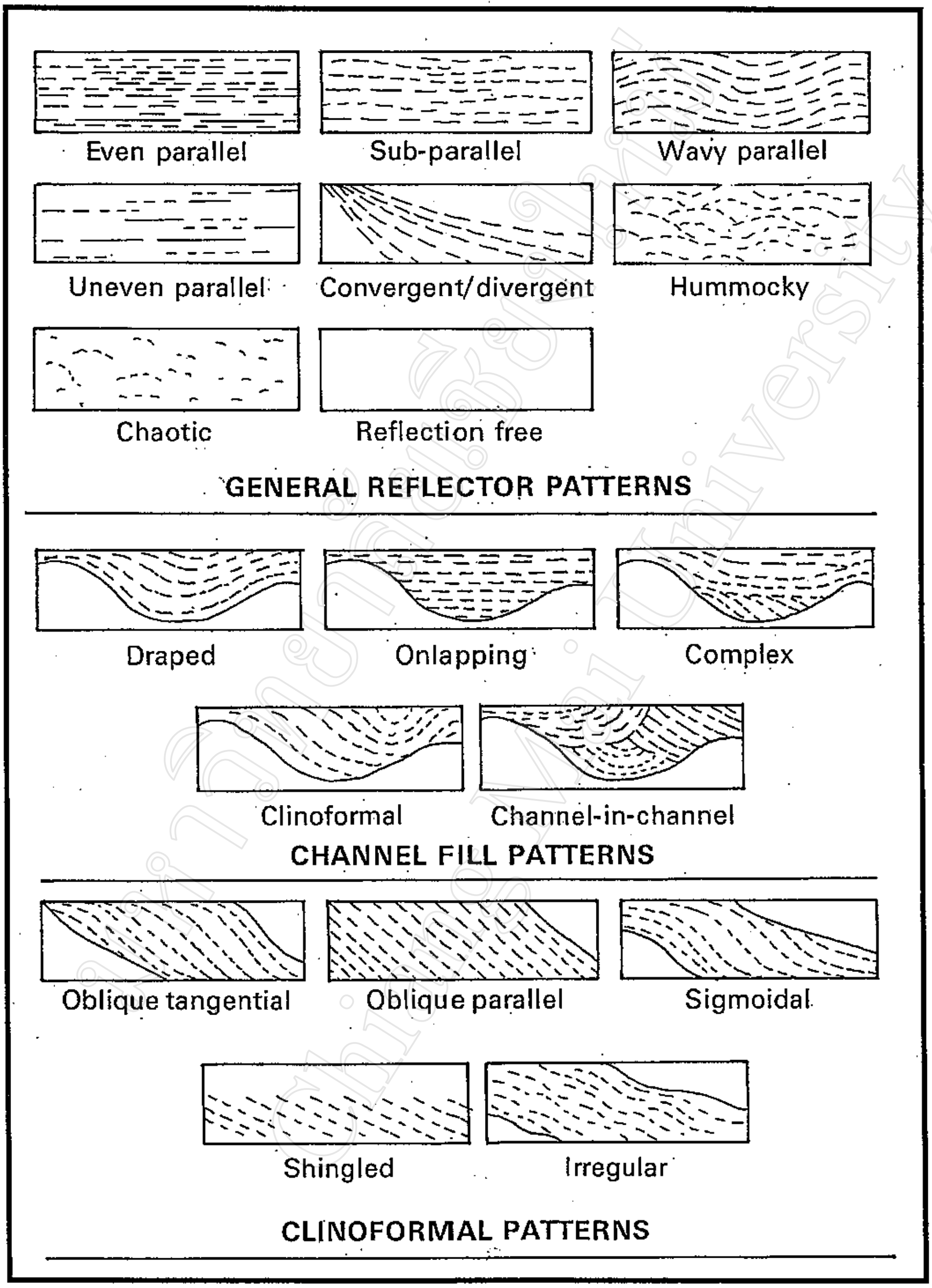


Figure 2.10 Diagram showing various seismic reflection patterns (modified from Berryhill, 1986).