10. Seismic Stratigraphy

Reflection seismology is compartmentalized into **acquisition**, **processing and interpretation.** Seismic stratigraphy deals with interpretation. It is the study of seismic data for the purpose of extracting stratigraphic information.

Seismic stratigraphy is often divided into several sub-areas:

♥ Analysis of **seismic sequence**
Separating out time-depositional units based on detecting unconformities or changes in seismic patterns;

♥ Analysis of **seismic facies**
Determining depositional environment from seismic reflection characteristics;

♥ Analysis of **reflection character**
Examining the lateral variation of individual reflection events, or series of events, to locate where stratigraphic changes occur and identify their nature; the primary tool for this is modeling by both synthetic seismograms and seismic logs.

♥ Amplitude

Reflection amplitude has to do with seismic wave height and is a function of the energy of seismic waves. On a seismic record, amplitude is measured as the distance from the mid-position of a wave to the extreme position. Amplitude is directly proportional to RC. It is also affected by the spacing between reflecting surfaces. Where bed spacing is optimum, lower energy responses are phased together constructively (constructive interference) to intensity or amplify the reflected energy and thus increase amplitude.

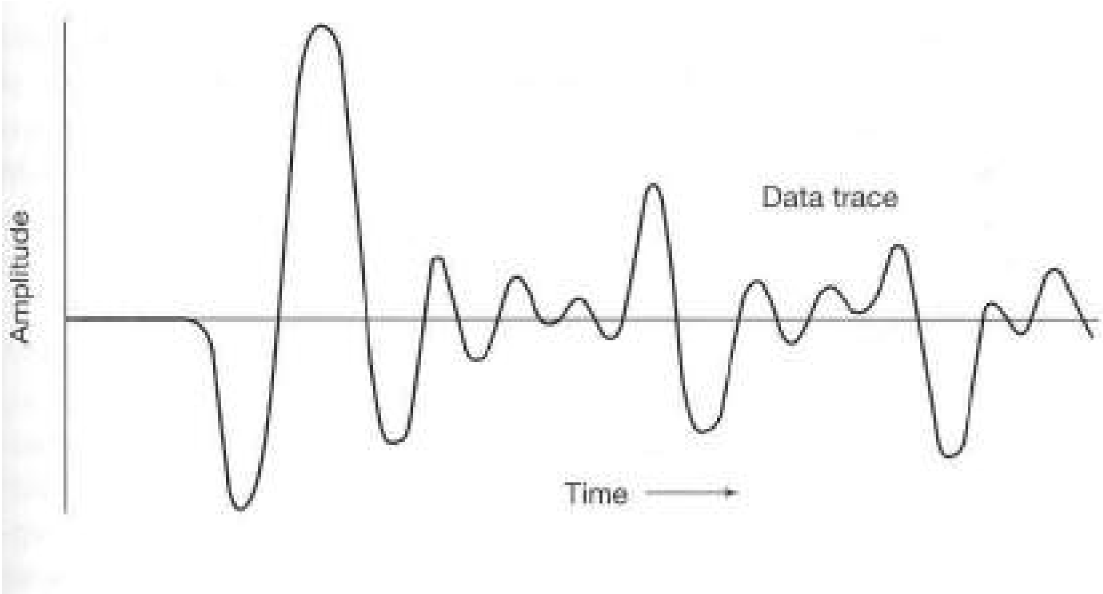


Figure 14.10
Schematic representation of the amplitude of seismic waves. The amplitude is the vertical distance above or below the mid-point line drawn through the wave traces. Time refers to arrival time of the waves at the seismic detector. [After Neidell, N. S., 1979, Stratigraphic modeling and interpretation: Geophysical principles and techniques: Am Assoc. Petroleum Geologists Education Short Course Notes 13. Fig. p. 31, reprinted by permission of AAPG, Tulsa, OK.]

Boggs (2001), p.497

♥ Polarity

Positive RC produces a positive reflection, by definition and negative RC produces a negative reflection. Determine polarity from known impedance boundary, for example the water bottom (positive).

Where to Pick? Actual onset of reflection corresponds to impedance contrast or geological boundary in **Minimum Phase Data**. Data can be processed to **Zero Phase** such that peak amplitude of a symmetrical wavelet lies over impedance contrast. In any case you pick on the peak because that is what is easy and in the case of minimum phase data, make any necessary adjustment for the distance between the reflector and the geologic boundary. Most, if not all, seismic sections are displayed in minimum phase data.
(Definitions: **Minimum phase**: a characteristic of waveforms which have their energy concentrated early in the waveform; **Zero phase**: a characteristic waveforms which are symmetrical.)

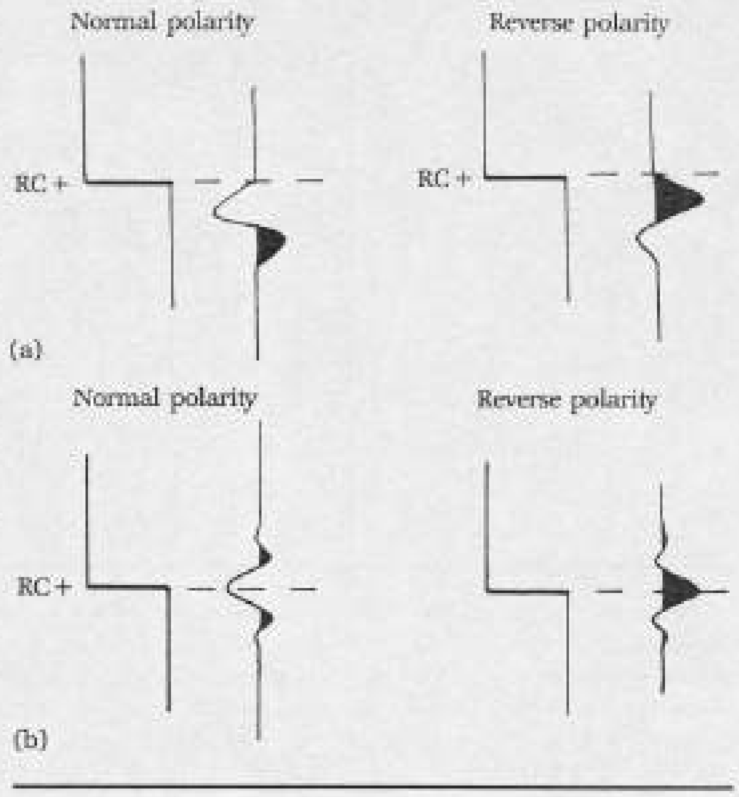


FIGURE 2.6 *Examples of idealized normal and reverse polarity for (a) minimum- and (b) zero-phase wavelets at an acoustic-impedance boundary with a positive reflection coefficient.*

Minimum-
phase
wavelet

Zero-phase
wavelet

Badley (1985), p.9

Frequency: The frequency spectrum of the acoustic signal generated varies according to the energy sources.

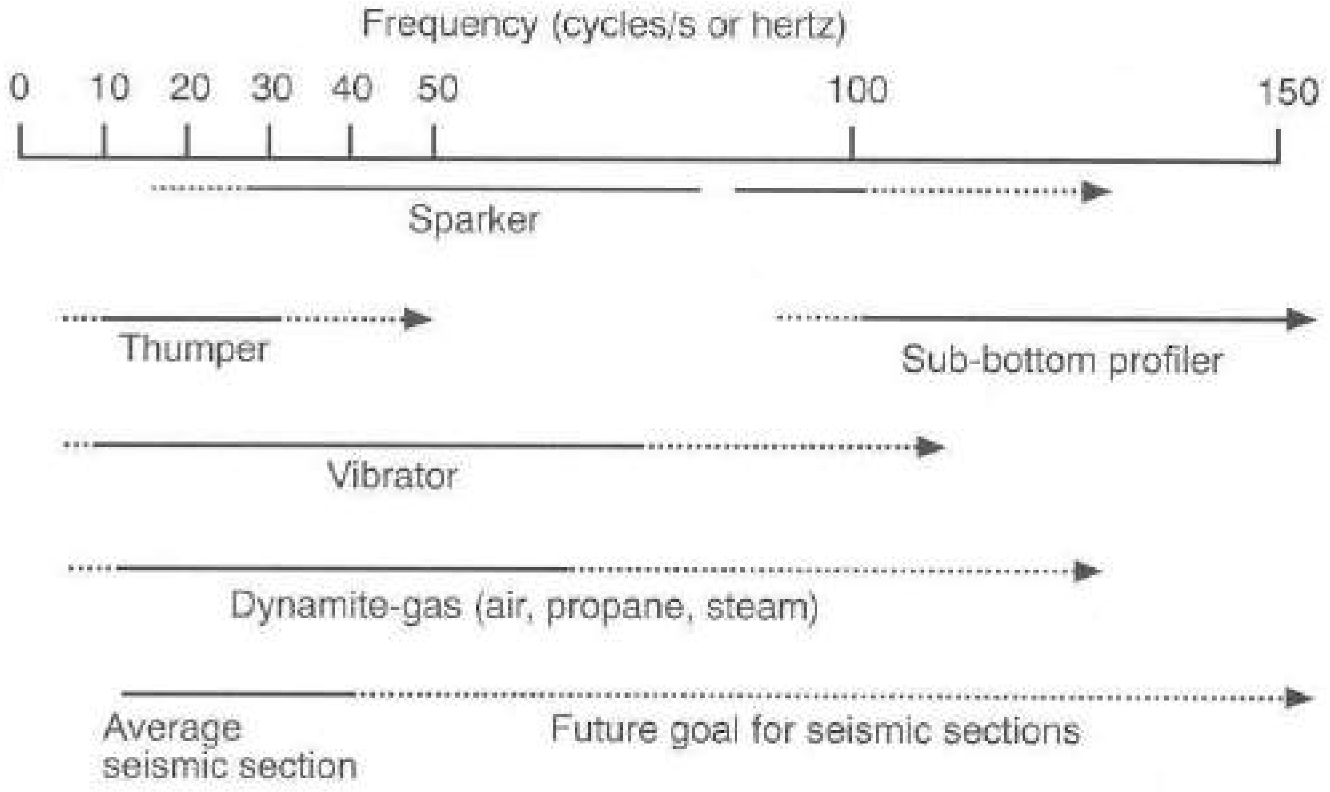


Figure 10.6 *A frequency spectrum acoustic signal from 0 to 150 Hertz (cycles per second) showing frequency ranges for different energy sources. [Modified from: Tucker (1974)]*

Doyle and Bennett (1998), p.284

10.3 Chronostratigraphic significance of seismic reflections

Primary seismic reflections follow chronostratigraphic (time-stratigraphic) correlation patterns rather than time-transgressive lithostratigraphic (rock-stratigraphic) units. In other words, seismic reflectors in many cases are time lines. They cut across major lithologic boundaries, especially those defined by outcrop sections or wells.

(1)

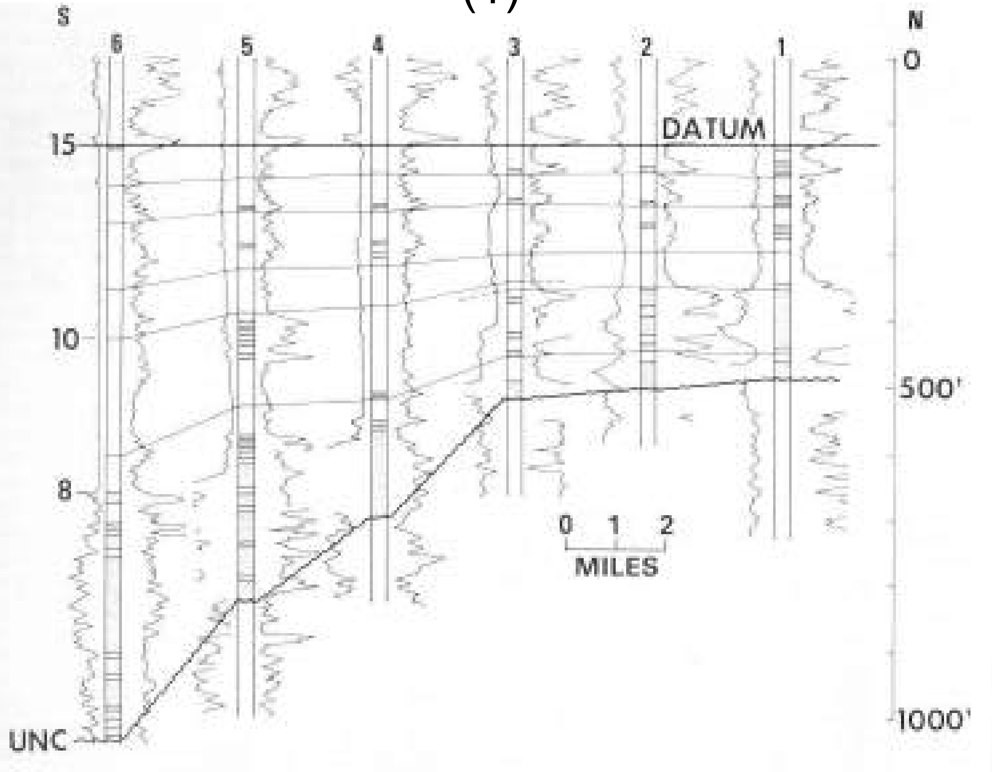
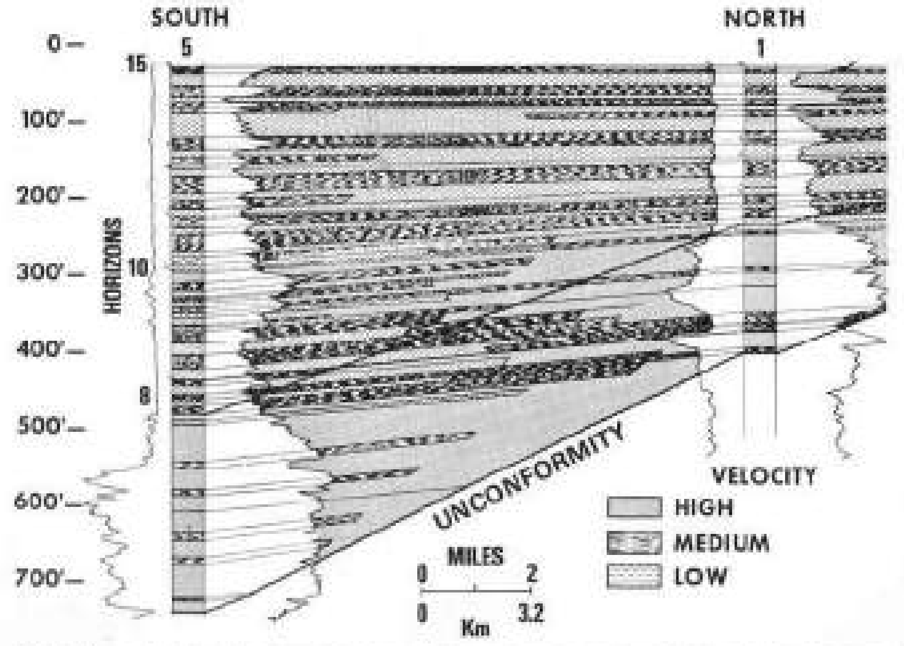


FIG. 2—Geologic cross section showing electric-log correlations, Tertiary example, South America. Stippled pattern in well bore represents sandstone. Key horizons indicated on left.

Vail et al. (1977) in AAPG Mem.26, p.102

(2)

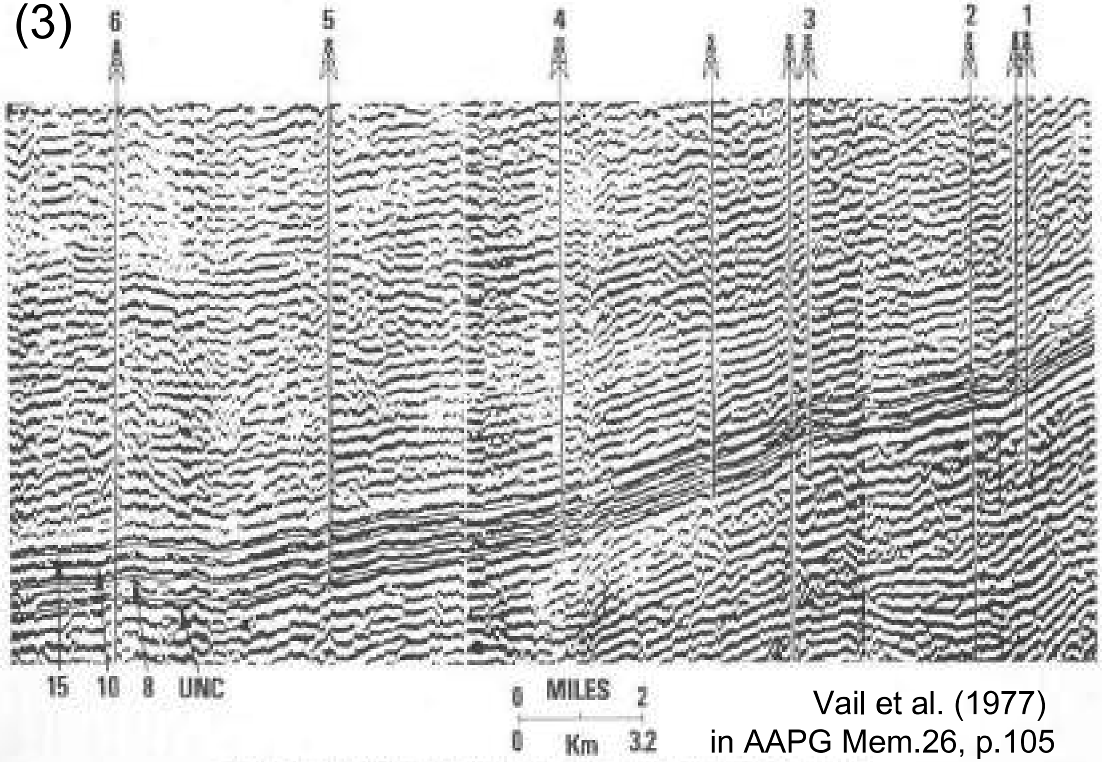


[illegible]

Vail et al. (1977) in AAPG Mem.26, p.103

Another example showing the chronostratigraphic significance of seismic reflections (Sherrif and Geldart, 1995, p. 403)

(3)



Vail et al. (1977)
in AAPG Mem.26, p.105

FIG. 6—Single-fold VDF magnetic tape seismic section from a Tertiary basin in South America.

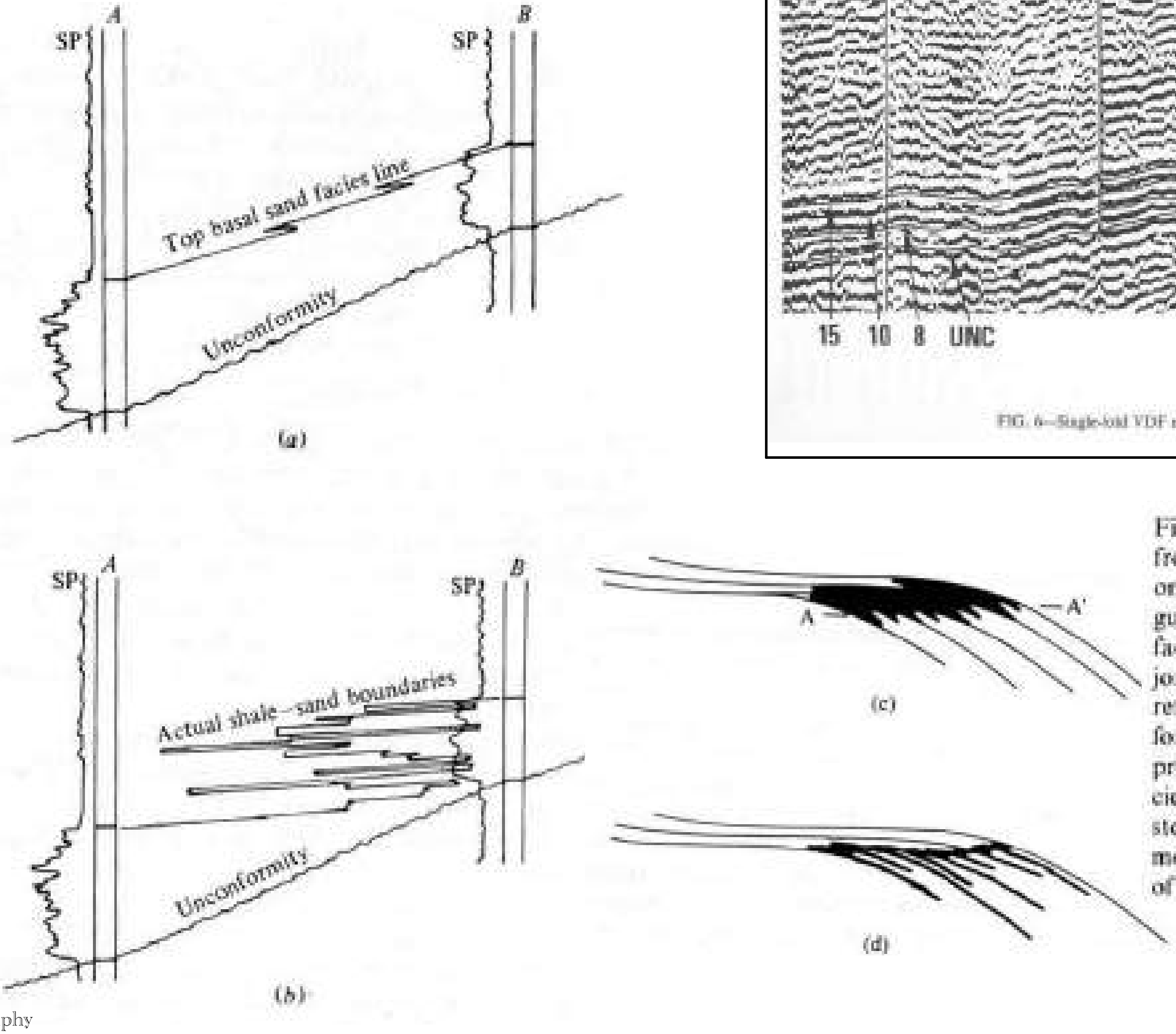


Fig. 10.55 The nature of facies surfaces. (Data for a and b from Vail, Todd, and Sangree, 1977b.) (a) Facies surface based on data from two wells 17 km apart; the *SP*-log curves distinguish the sand from surrounding shale. (b) Redrawing of the facies surface based on intervening well-control points; the major portions parallel stratal or time surfaces. Seismic data show reflections parallel to the time surfaces onlapping the unconformity. (c) Classical picture of sand-rich sediments in a prograding/aggrading system suggests a reflection along the facies boundary *AA'*, which does not show. (d) Occasional major storms and other catastrophic events rework the sand-rich sediments and spread them along time surfaces, which is the attitude of reflections.

10.4 Seismic sequence analysis

The procedures for interpreting stratigraphy from seismic data involve three principle stages: (1) seismic sequence analysis, (2) seismic facies analysis, and (3) interpretation of depositional environments and lithofacies (Vail, 1987).

Seismic sequence (or a depositional sequence): A stratigraphic unit composed of a relatively conformable succession of genetically related strata and bounded at its top and base by unconformities or their correlative conformities.

A depositional sequence has chronostratigraphic significance because all the rocks of the sequence were deposited during the interval of geological time defined by the ages of the sequence boundaries where they are conformities.

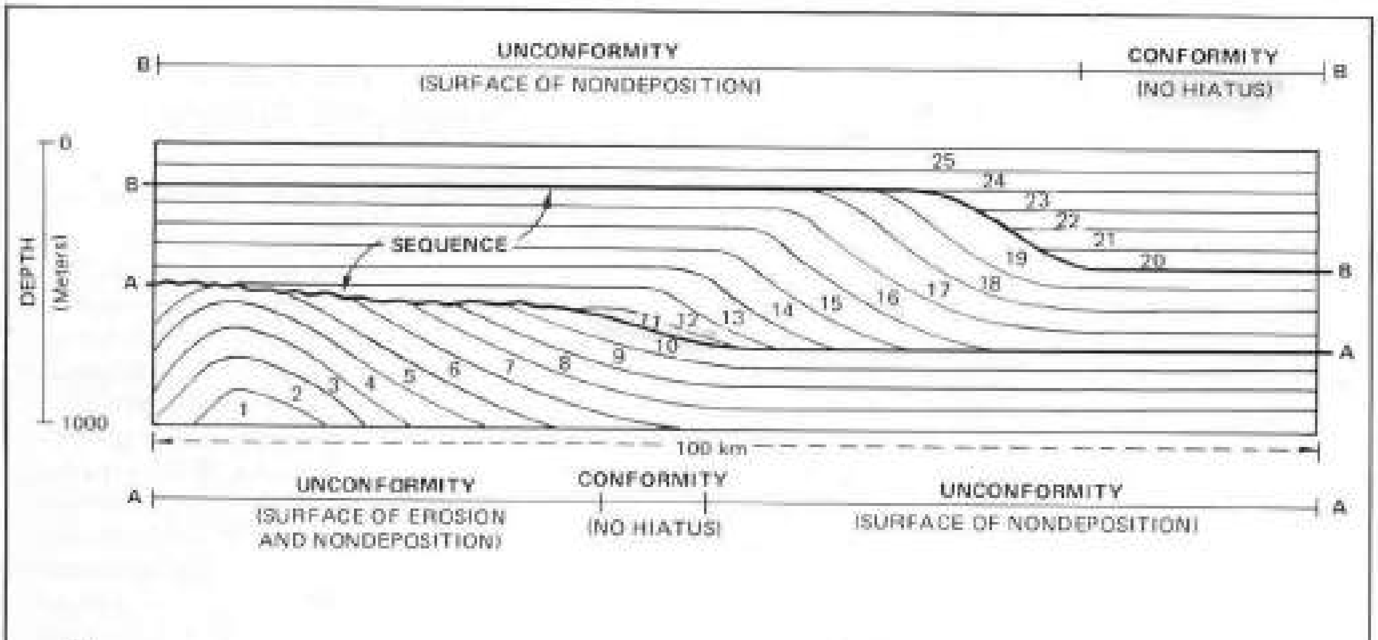
FIG. 1—Basic concepts of depositional sequence. A depositional sequence is a stratigraphic unit composed of relatively conformable successions of genetically related strata and bounded at its top and base by unconformities or their correlative conformities.

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 of unit 19. A sechron is defined as maximum geologic-time range of a sequence.)

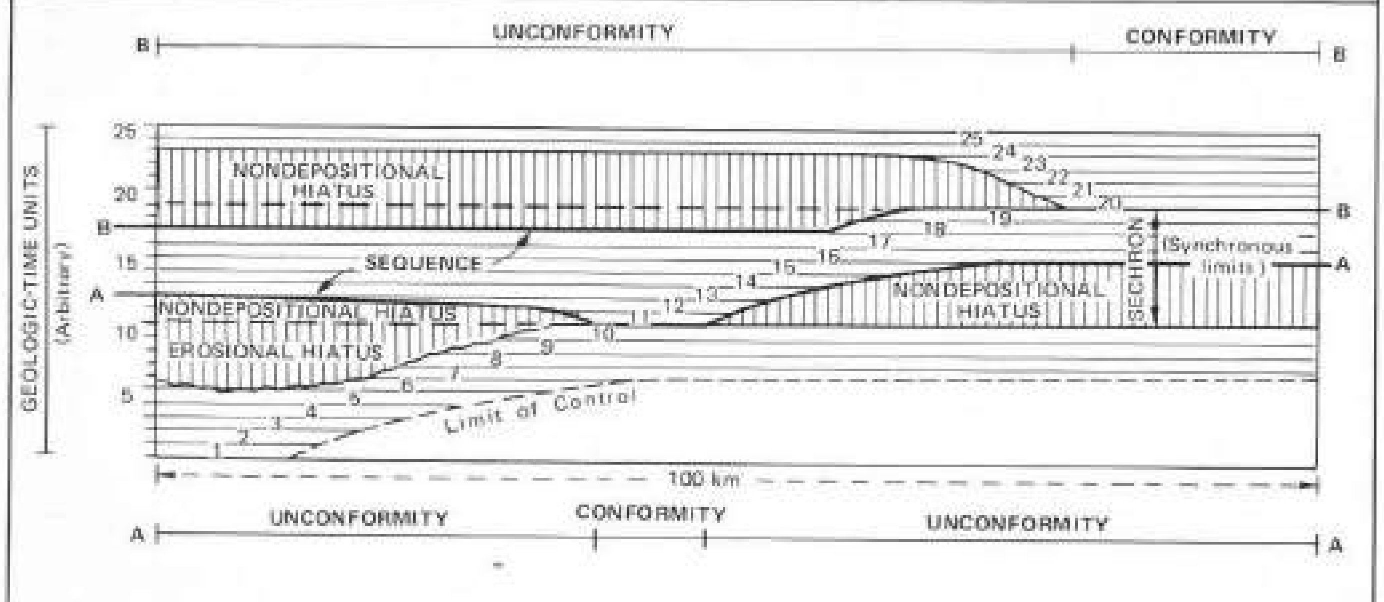
↓ next page

Basic concept of a depositional sequence



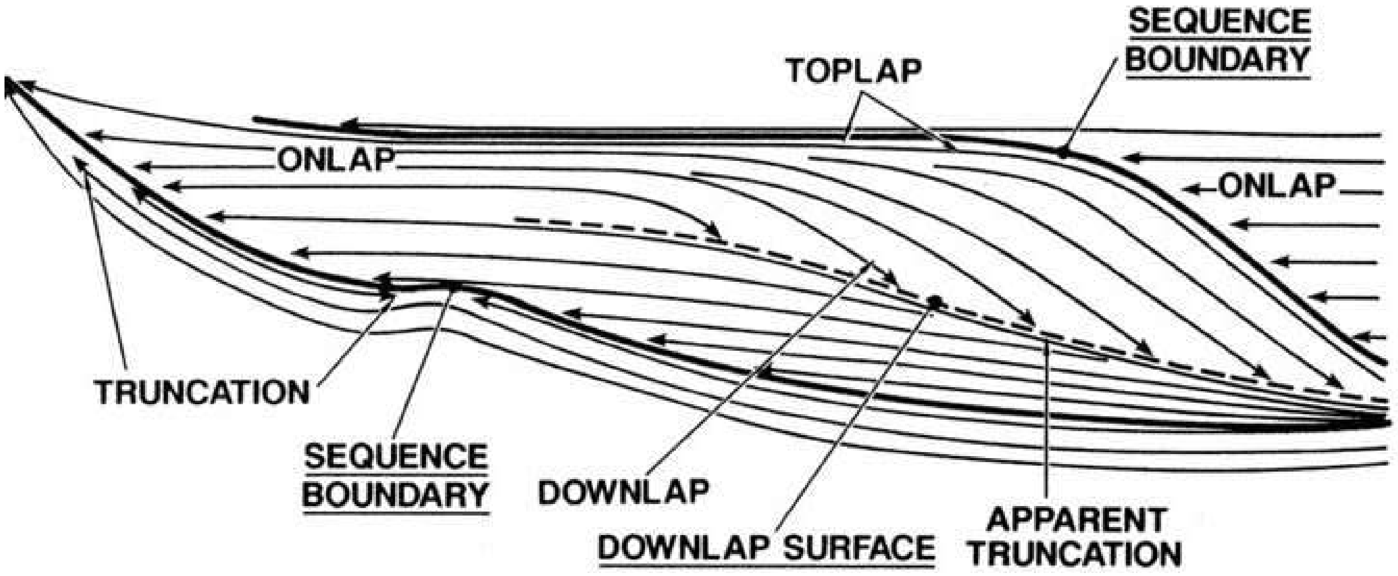
1a

Mitchum et al. (1977) in AAPG Mem.26, p.54



1b

An idealized sequence



Vail (1987)

Figure 1. Diagram showing reflection termination patterns and types of discontinuities. Discontinuity names are underlined.

Seismic sequence analysis involves identification of major reflection “packages” that can be delineated **by recognizing surfaces of discontinuity**. Discontinuities may thus be recognized by interpreting systematic patterns of reflection terminations along the discontinuity surfaces.

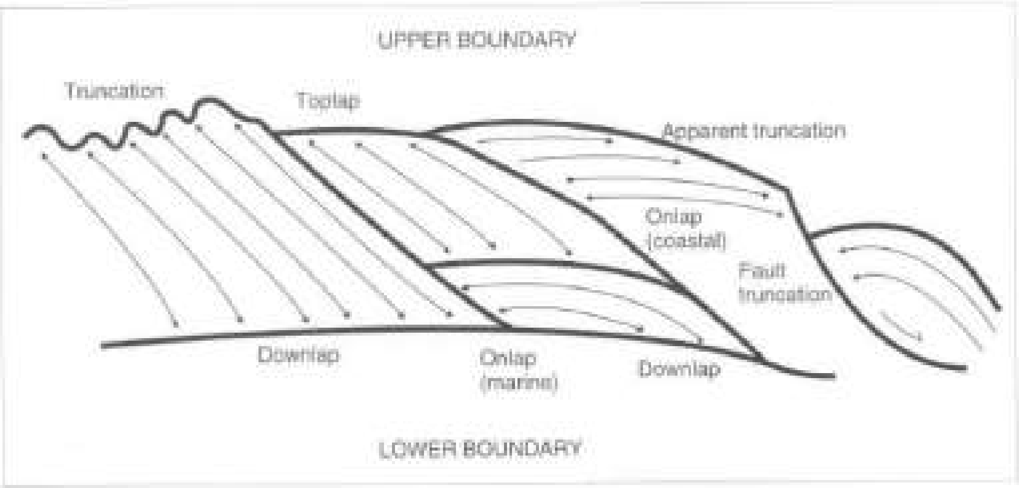
Three main types of reflection discordance

1. Erosional truncation

2. Apparent truncation

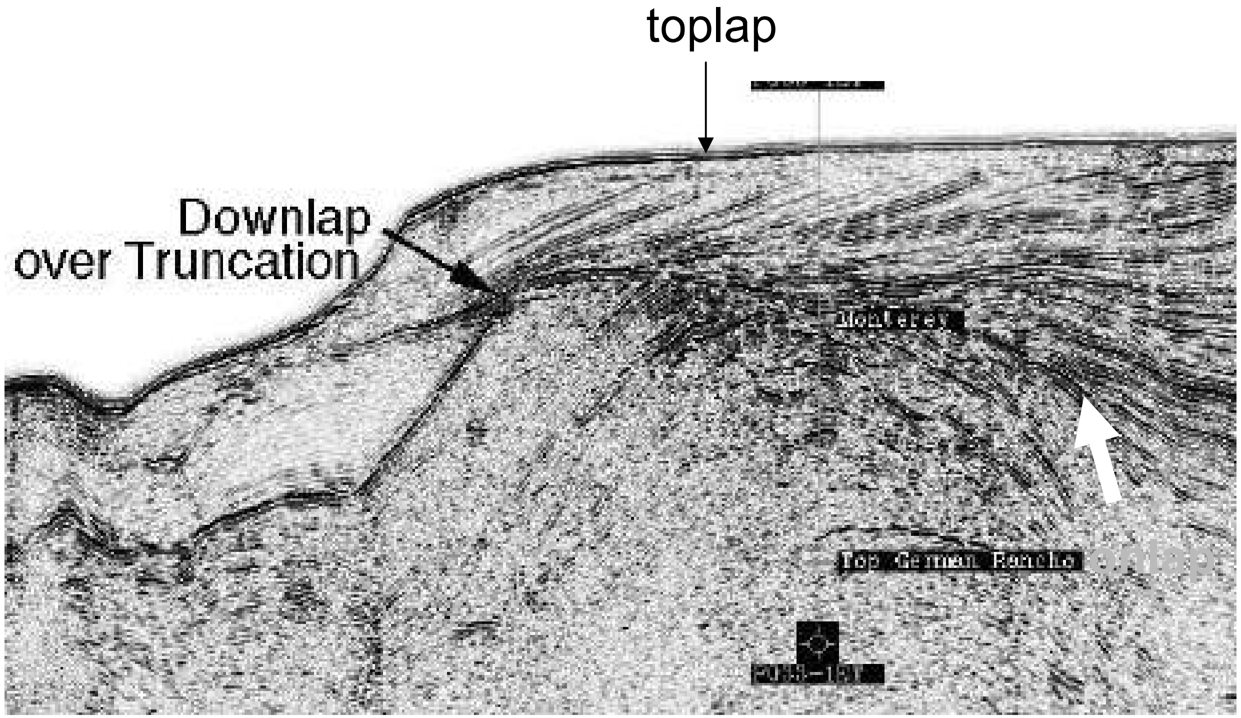
3. Lapout → baselap { onlap, downlap }

3. Lapout → toplap



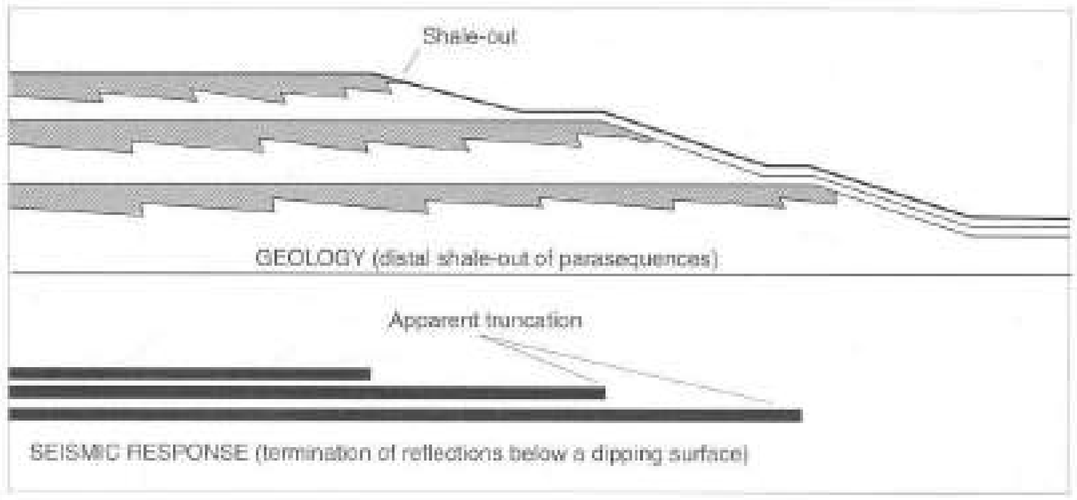
Emery & Myers (1996), p.53

Erosional truncation is the termination of strata against an overlying erosional surface.



http://ic.ucsc.edu/~casey/eart168/Lec.SeisStrat.htm

Apparent truncation is the termination of relatively low-angle seismic reflections beneath a dipping seismic surface, where that surface represents marine condensation.



Emery & Myers (1996), p.54

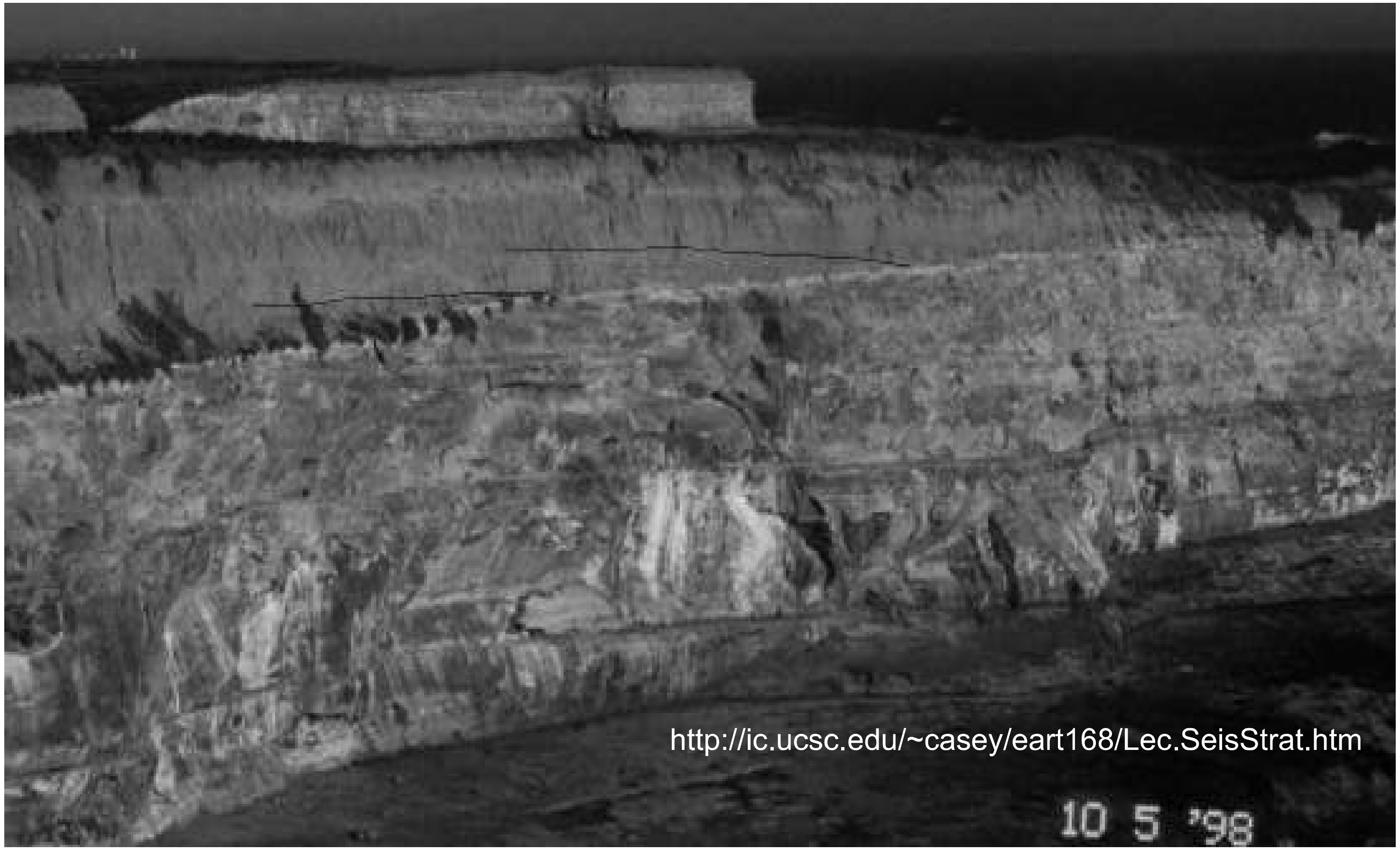
Fig. 3.9 Apparent truncation; the termination of reflections against an overlying surface, which looks like erosional truncation, but represents the original depositional limit of the strata

Lapout is the lateral termination of a reflection (generally a bedding plane) at its depositional limit.

Baselap is the lapout of reflections against an underlying seismic surface (which marks the base of the seismic package). Baselap can consist of **onlap** or **downlap**.

Onlap is recognized on seismic data by the termination of low-angle reflections against a steeper seismic surface. Two types of onlap are recognized: **marine onlap** and **coastal onlap**.

Downlap is baselap in which an initially inclined stratum terminates downdip against an initially horizontal or inclined surface. The surface of downlap represents a marine condensed unit in most cases.

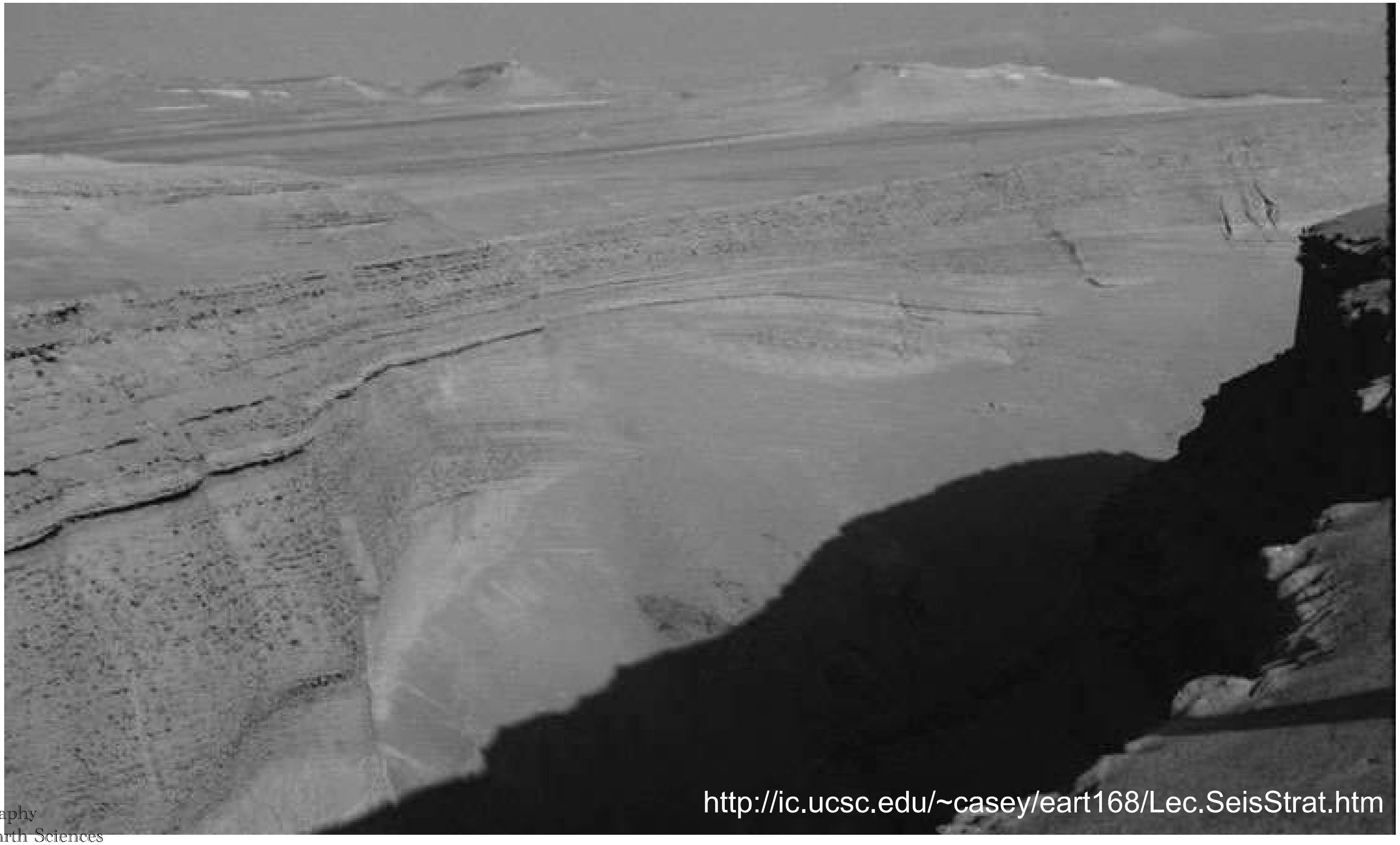

http://ic.ucsc.edu/~casey/eart168/Lec.SeisStrat.htm

Santa Cruz terrace deposits downlapping onto unconformity.

Toplap is the termination of inclined reflections (clinoforms) against an overlying lower angle surface, where this is believed to represent the proximal depositional limit.

Other term:

Offlap: A conformable sequence of inclined strata, deposited during a marine regression, in which each stratum is succeeded laterally by progressively younger units (a **clinoform**).



http://ic.ucsc.edu/~casey/eart168/Lec.SeisStrat.htm

Clinoforms merging into toplap. Peru, a temperate water carbonate of Miocene age.

10.5 Seismic facies analysis

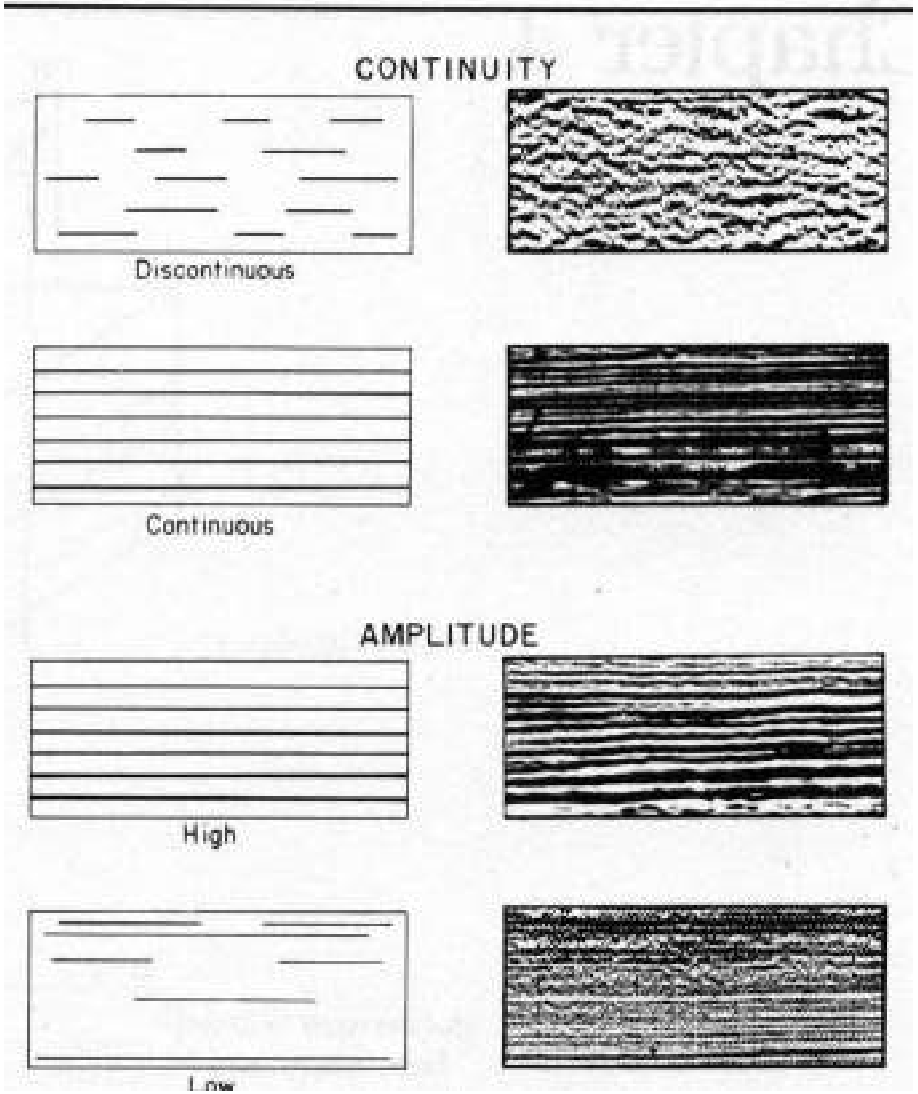
Seismic facies analysis takes the interpretation process one step beyond seismic sequence analysis by examining within sequences smaller reflection units that may be the seismic response to lithofacies.

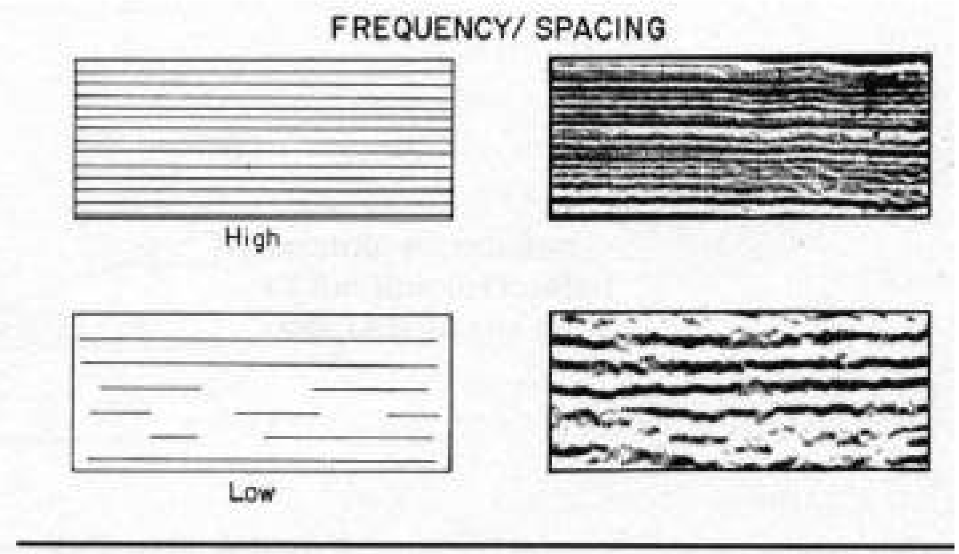
Seismic facies are packages of reflectors with a set of seismic characteristics differing from adjacent units (similar to definition of a “formation”-must be distinguishable from adjacent units and mappable on earth's surface).

Keystones in seismic facies analysis (Sangree and Widmier, 1979):

1. An understanding of the effects of lithology and bed spacing on reflection parameters: **amplitude, frequency, continuity of reflections**.

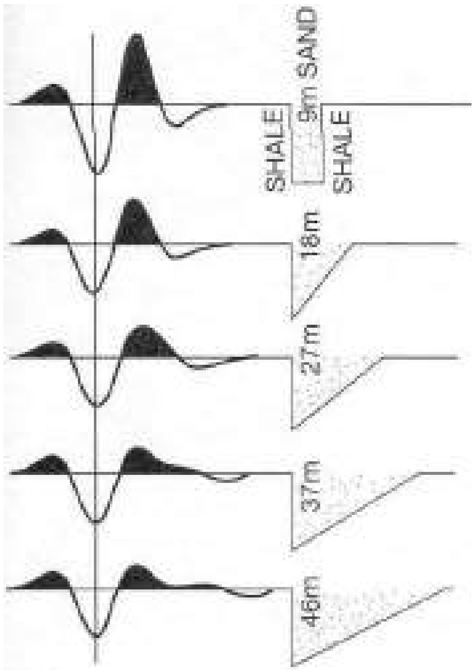
Feature of Reflectors	**Geological Interpretation** (Sangree Widmier, 1979)
Amplitude	Impedance (velocity-density) contrasts, Layer spacing (cause constructive and destructive interference), Fluid content
Frequency	Bed spacing, Fluid content
Continuity	Beddding or layer continuity, depositional processes





Reflection attributes: continuity, amplitude, frequency/spacing. (from Badley (1985) p. 72)

Presence of gas may cause “bright spots” effect.



Seismic response for a sand with a gradational base, which results in lower amplitude. The 9-m thickness is about 1/8 wavelength.

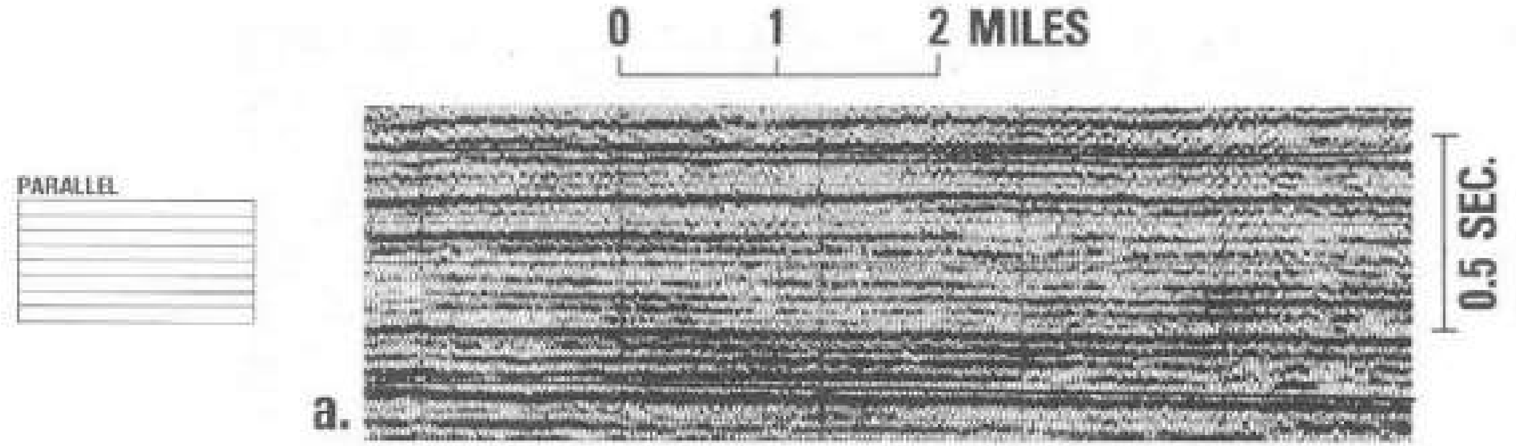
2. Parallelism of reflection cycles to gross bedding, and therefore, to physical surfaces that separate older from younger sediments : **Reflection configurations**.

Reflection configuration refers to the gross stratification patterns identified on seismic records.

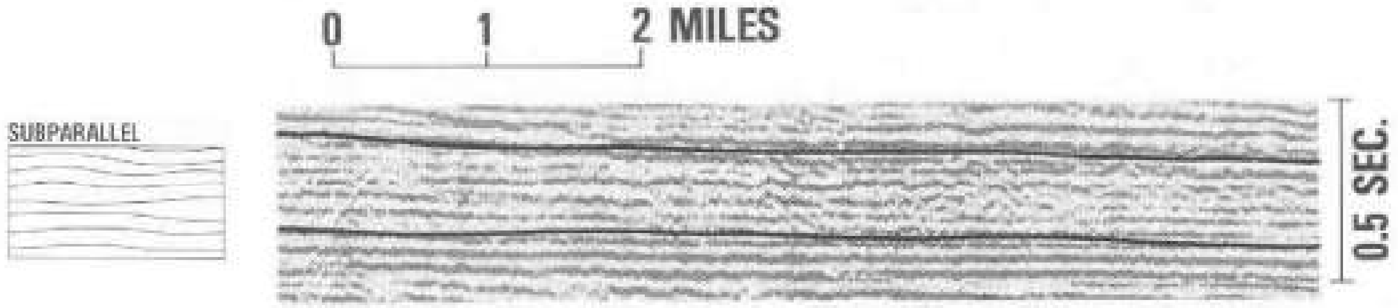
Feature of Reflectors	**Geological Interpretation** (Sangree Widmier, 1979)
Reflection Configuration (pattern)	Stratification patterns, Depositional processes, Erosion and paleotopography
External form and **areal association** of seismic facies units	Gross depositional environment, Sediment source, Geologic setting

Principle reflection patterns

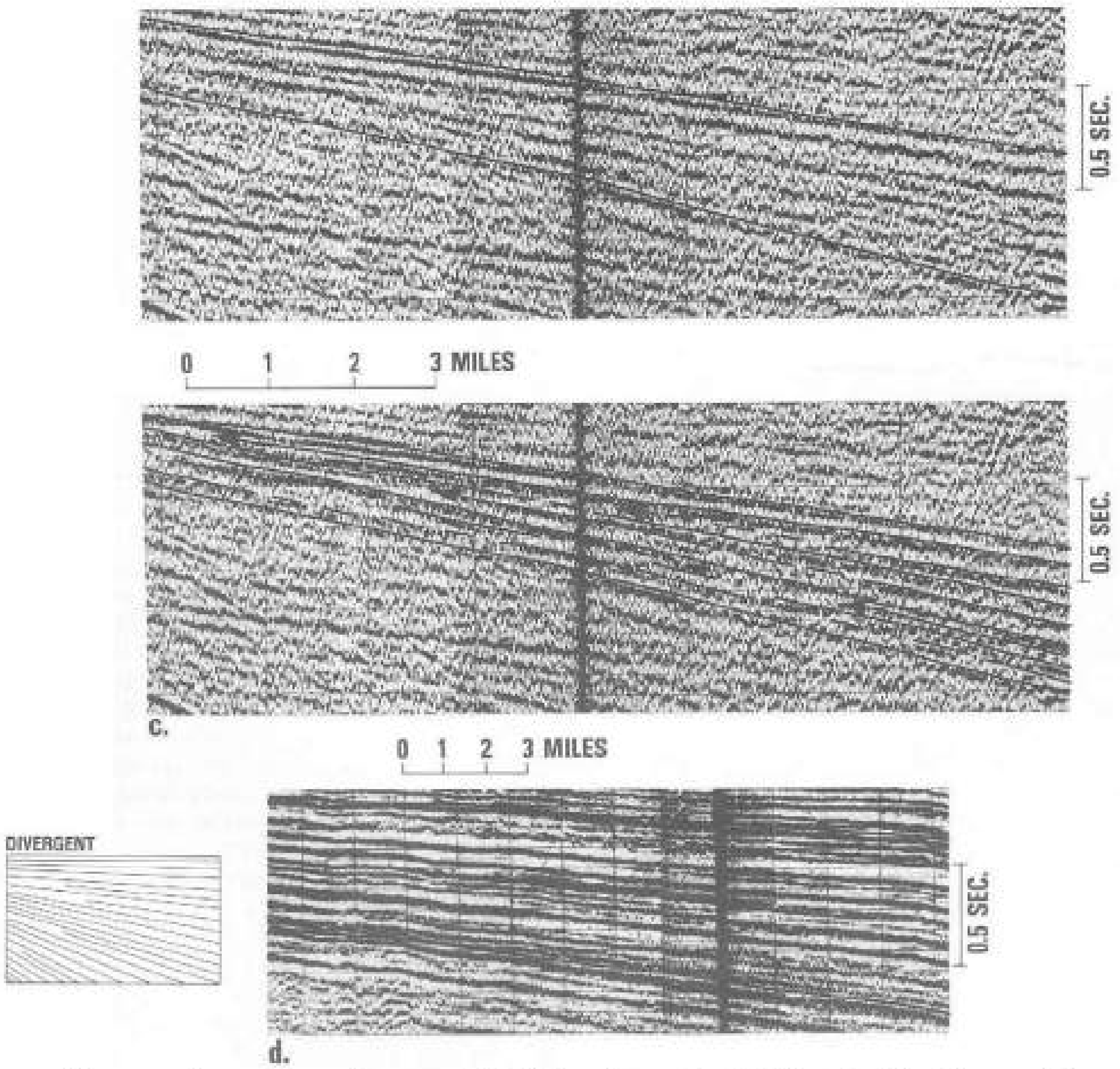
1. **Parallel and subparallel**: generated by strata that were probably deposited at uniform rates on a uniformly subsiding shelf or in a stable basin setting.



Parallel configuration with good continuity and high to medium amplitude



Subparallel configuration with good to fair continuity and high to medium amplitude



Divergent configurations, with thickening of individual reflection cycles in direction of divergence.

2. Divergent: Divergent configurations are characterized by a wedge-shaped unit in which lateral thickening of the entire unit is caused by thickening of individual reflection subunits within the main unit. Divergent configurations are interpreted to signify lateral variations in rates of deposition or progressive tilting of the sedimentary surface during deposition.

3. Prograding: Generated by strata that were deposited by lateral outbuilding or progradation to form gently sloping depositional surfaces called clinoforms. Prograding reflection configurations may include patterns of **sigmoid** (superposed S-shaped reflectors) and **oblique, complex sigmoid-oblique, shingled, hummocky.**

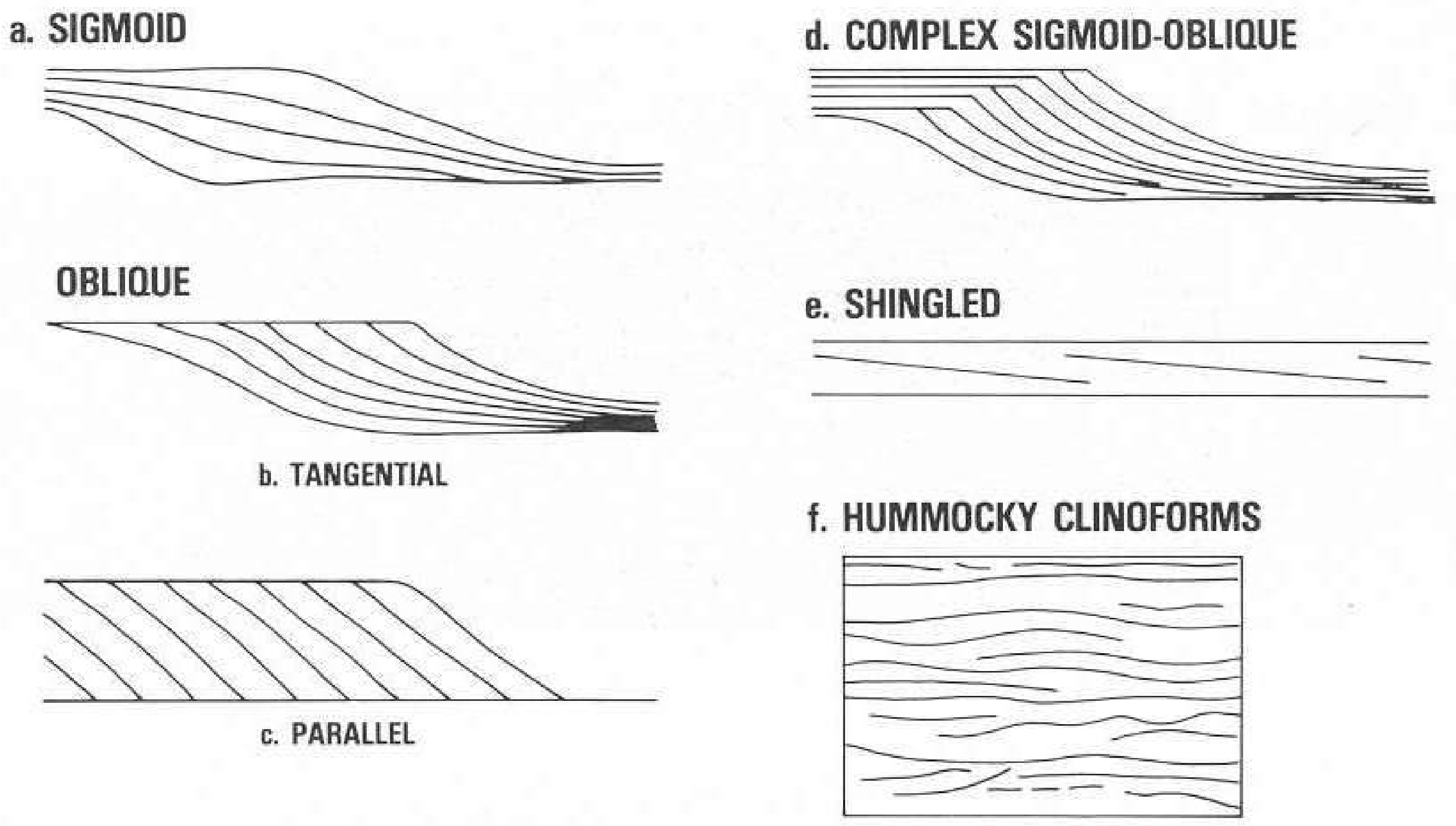


FIG. 6—Seismic reflection patterns interpreted as prograding clinoforms.

Mitchum et al. (1977), p.125

Examples of prograding configuration pattern

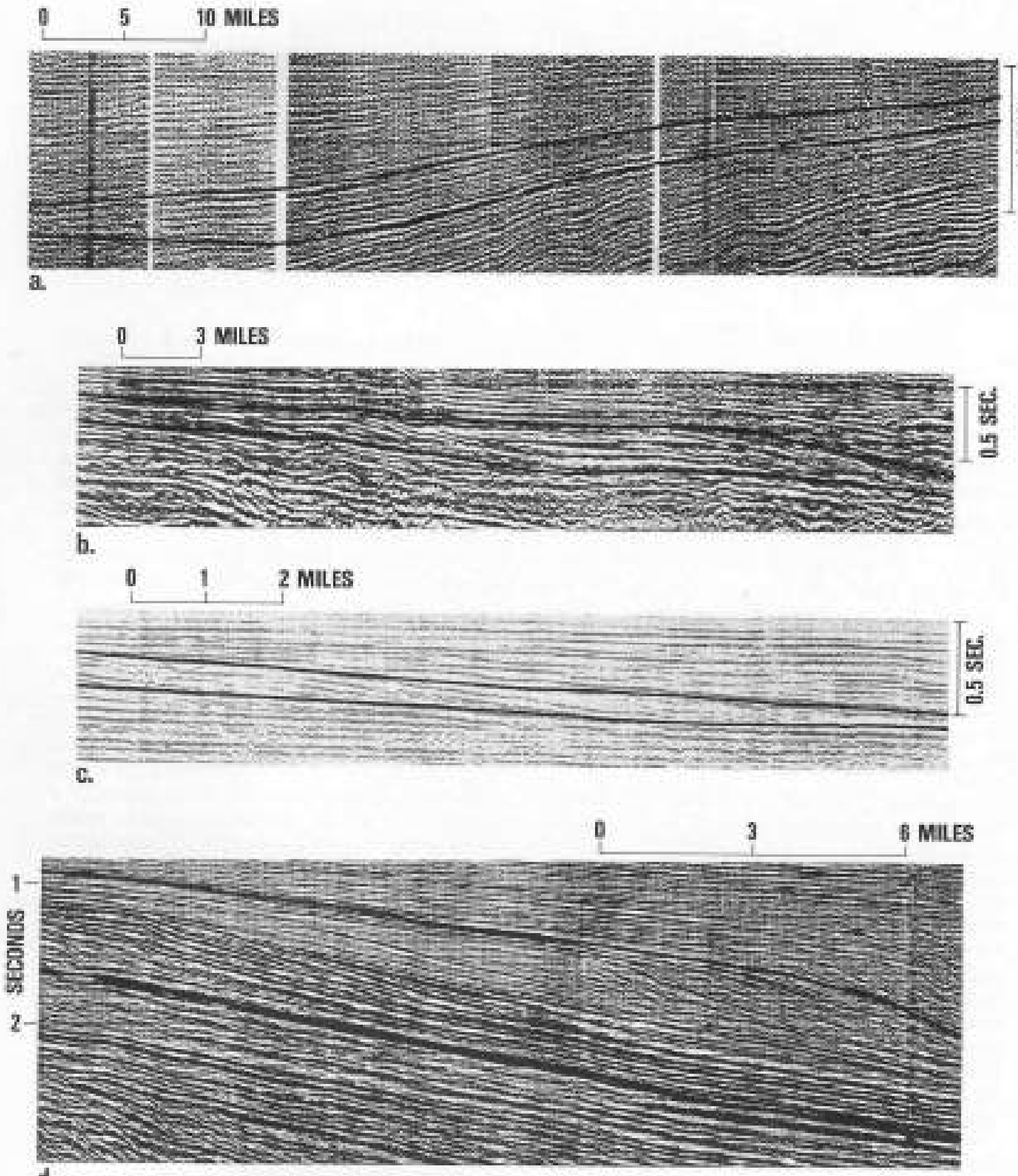


FIG. 7—Examples of sigmoid, oblique, and complex sigmoid-oblique seismic reflection configurations: **a** is sigmoid, **b** is mostly tangential oblique with some sigmoid, **c** is mostly parallel oblique, **d** is complex sigmoid-oblique.

Sigmoid

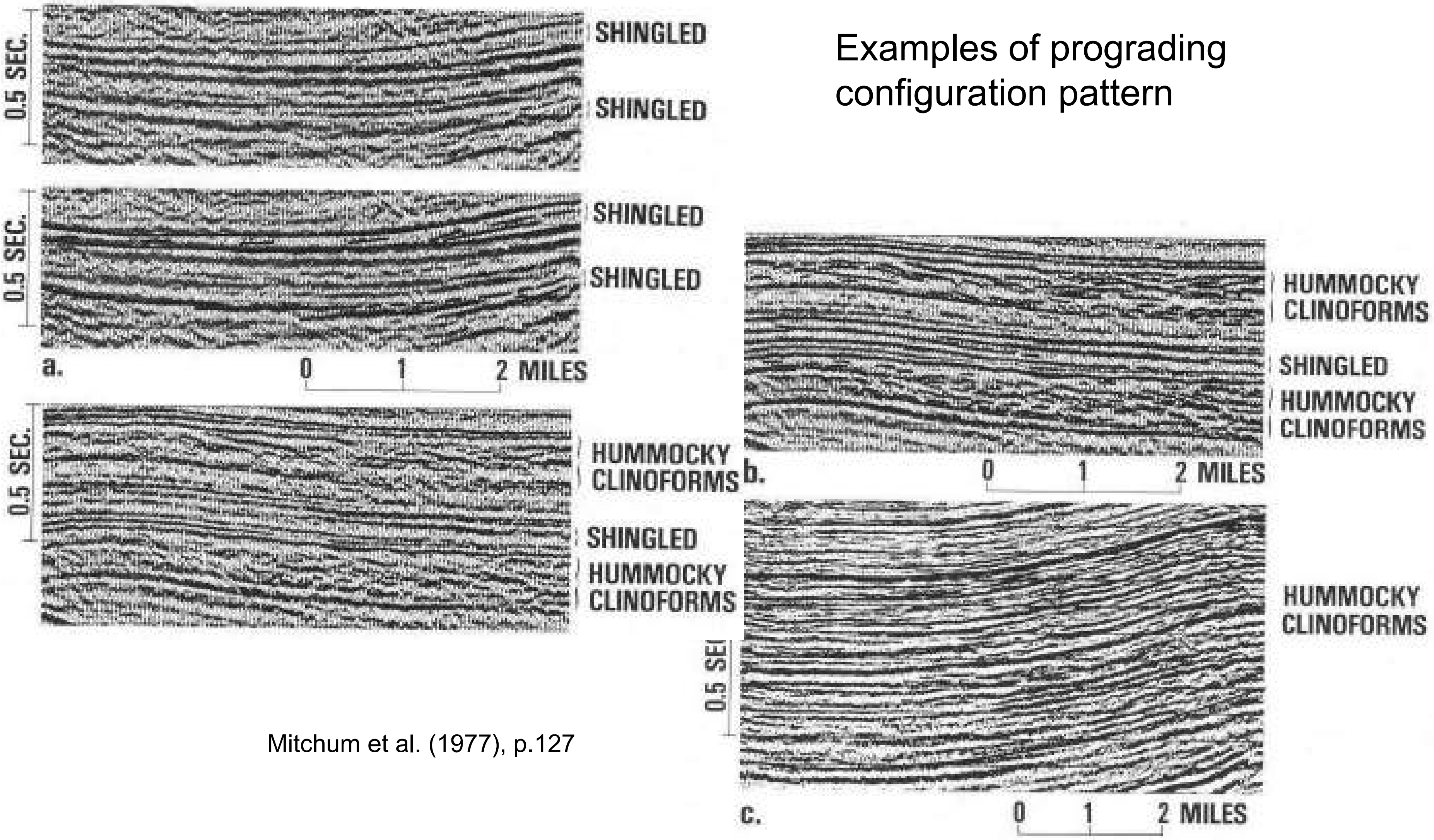
Tangential oblique

Parallel oblique

Complex sigmoid-oblique

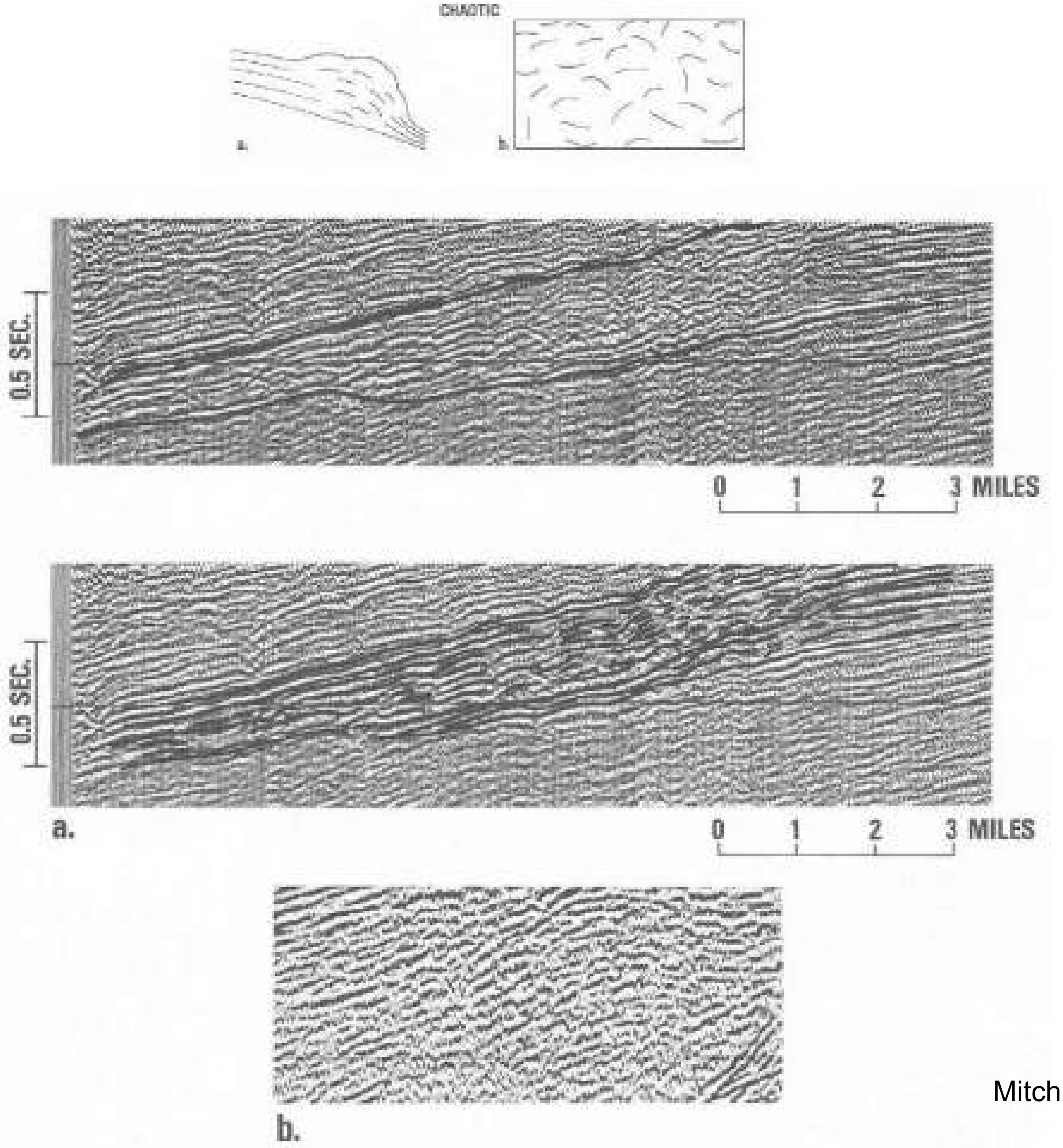
Mitchum et al. (1977), p.126

Examples of prograding configuration pattern



Mitchum et al. (1977), p.127

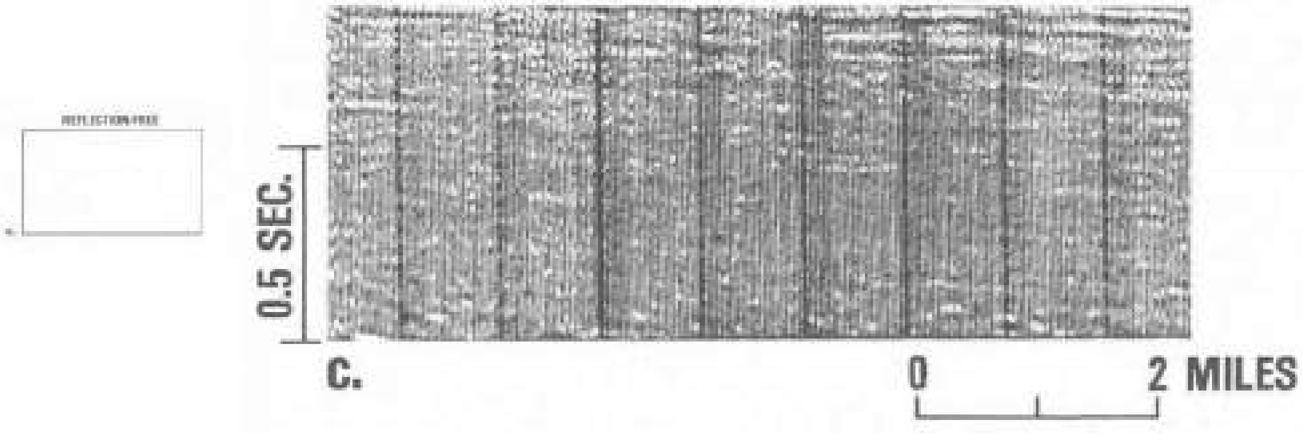
FIG. 8—Examples of shingled and hummocky clinoform seismic reflection configurations: **a** is a shingled configuration; **b** is hummocky clinoform configuration with minor shingling; **c** is hummocky clinoform configuration. Both configurations are interpreted as strata deposited in small clinoforms with relief approaching, or at, the point of seismic resolution. Clinoforms of **a** and **b** are slightly larger than those of **c** with correspondingly better resolution. Second sections of pairs **a** and **b** shows interpretation.



Chaotic seismic configuration. In (a) reflections may be interpreted as contorted stratal surfaces; in (b) no stratal patterns may be reliably interpreted.

4. Chaotic: This pattern is interpreted to represent a disordered arrangement of reflection surfaces owing to penecontemporaneous, soft-sediment deformation, or possibly to deposition of strata in a variable, high-energy environment.

Mitchum et al. (1977), p.129



Reflection-free seismic configuration, where no or very few reflections occur in seismically homogeneous shale.

5. Reflection-free: This pattern may represent homogeneous, non-stratified units such as igneous masses or thick salt deposits, or highly contorted or very steeply dipping strata.

Modifying terms

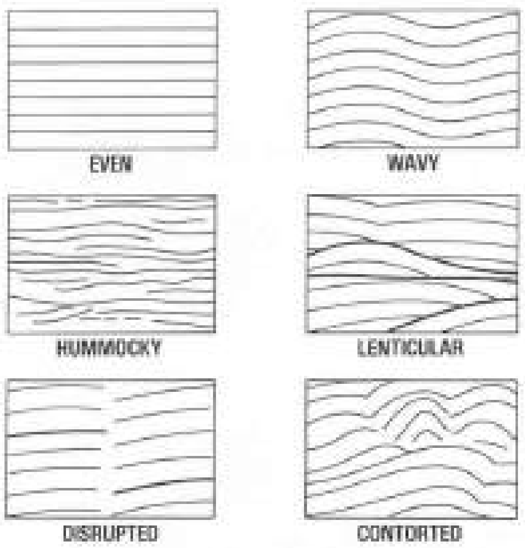
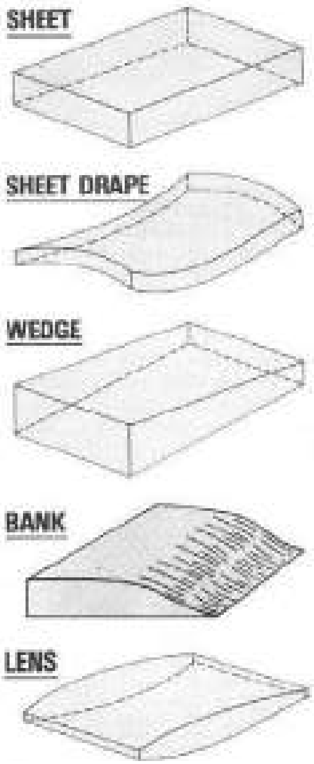
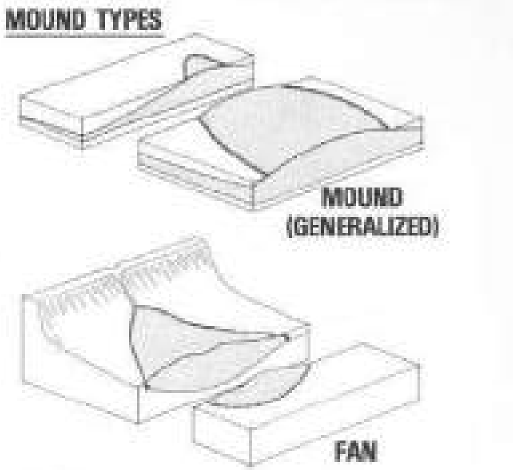


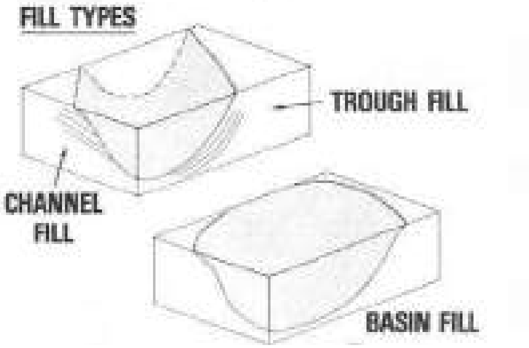
FIG. 11—Some modifying seismic reflection configurations.

Mitchum et al. (1977), p.130

External forms of seismic facies units







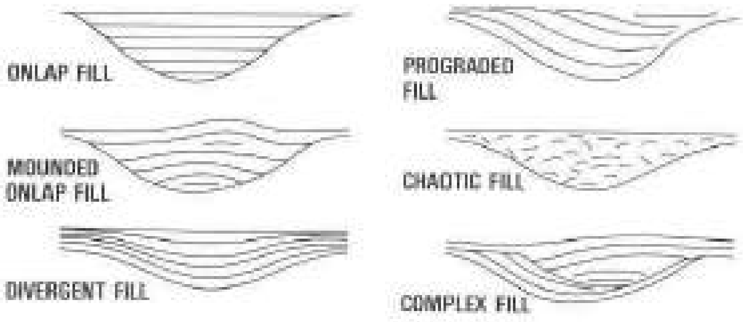
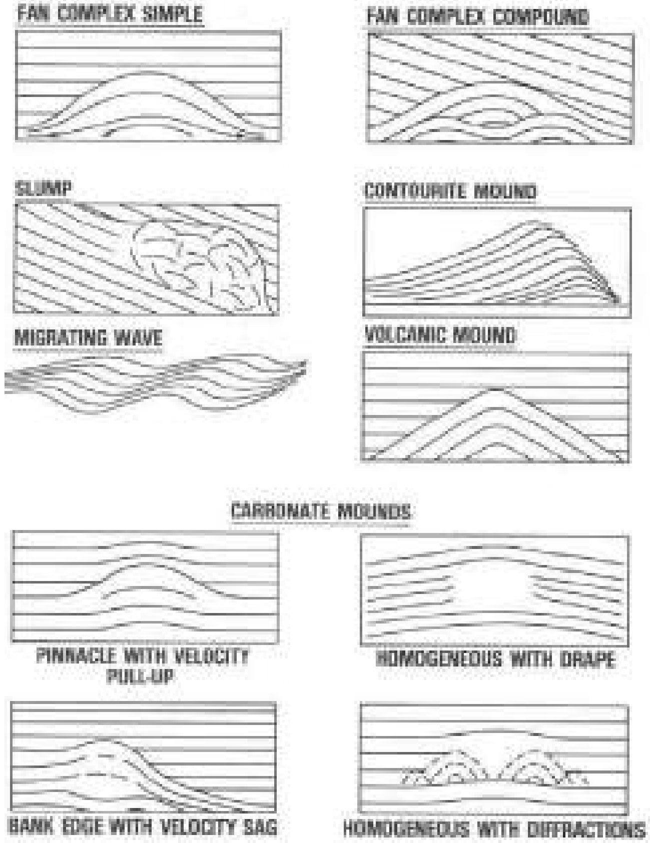


FIG. 15—Some fill seismic facies units.

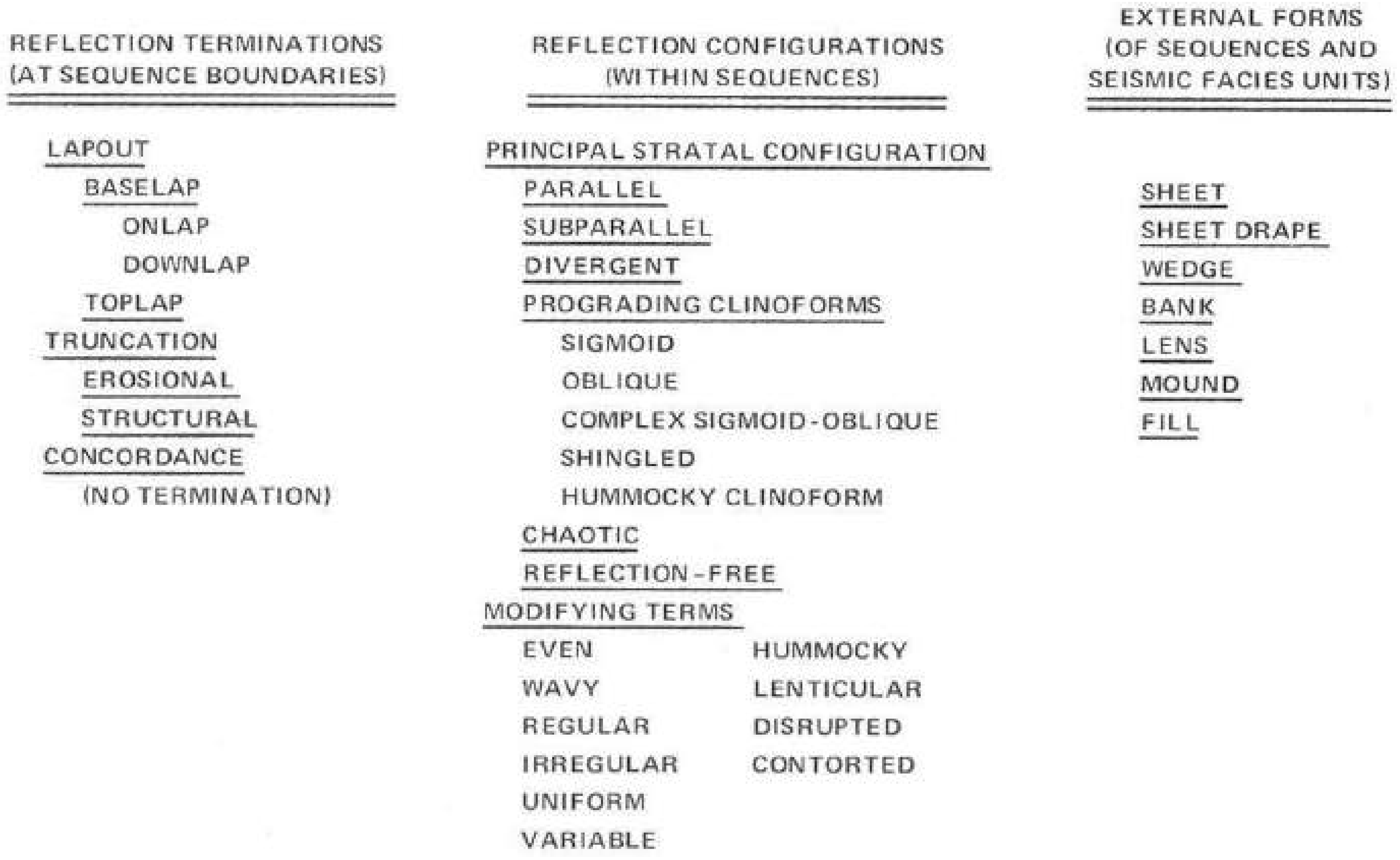


Sediment waves

FIG. 14—Example of migrating-wave seismic reflection configuration.

Mitchum et al. (1977), p.133

A summary for geological interpretation of seismic facies parameters



REFLECTION TERMINATIONS
(AT SEQUENCE BOUNDARIES)

- LAPOUT
  - BASELAP
    - ONLAP
    - DOWNLAP
  - TOPLAP
- TRUNCATION
  - EROSIONAL
  - STRUCTURAL
- CONCORDANCE
  - (NO TERMINATION)

REFLECTION CONFIGURATIONS
(WITHIN SEQUENCES)

- PRINCIPAL STRATAL CONFIGURATION
  - PARALLEL
  - SUBPARALLEL
  - DIVERGENT
  - PROGRADING CLINOFORMS
    - SIGMOID
    - OBLIQUE
    - COMPLEX SIGMOID-OBLIQUE
    - SHINGLED
    - HUMMOCKY CLINOFORM
  - CHAOTIC
  - REFLECTION-FREE
- MODIFYING TERMS
  - EVEN
  - WAVY
  - REGULAR
  - IRREGULAR
  - UNIFORM
  - VARIABLE
  - HUMMOCKY
  - LENTICULAR
  - DISRUPTED
  - CONTORTED

EXTERNAL FORMS
(OF SEQUENCES AND
SEISMIC FACIES UNITS)

- SHEET
- SHEET DRAPE
- WEDGE
- BANK
- LENS
- MOUND
- FILL

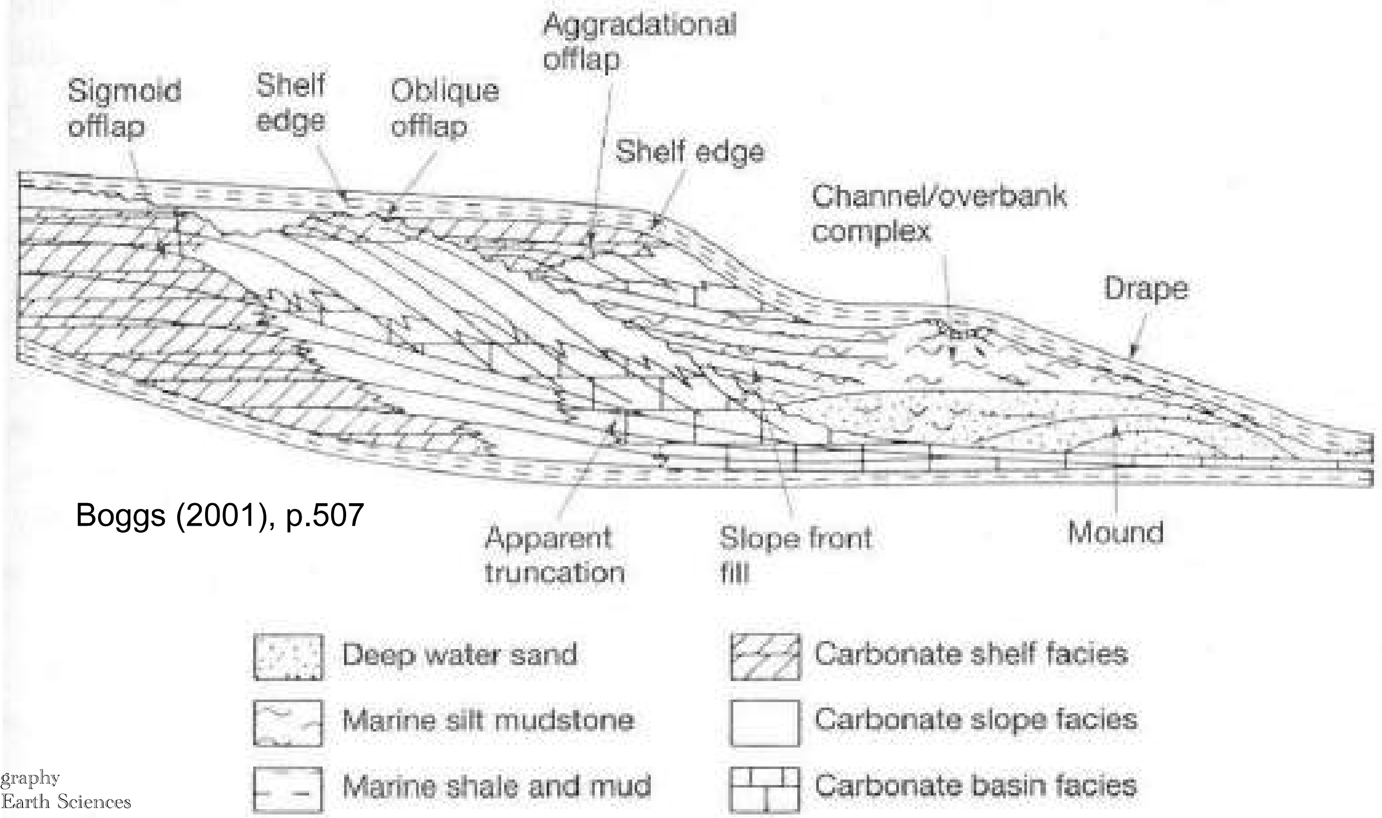
Mitchum et al. (1977), p.118

Interpretation of lithofacies and depositional environments

Once the objective aspects of delineating seismic sequences and facies have been completed, the final objective is to interpret the facies in terms of lithofacies, depositional environments, and paleobathymetry.

The most useful seismic parameters in seismic faces analysis are the following:

1. The geometry of reflections (reflection amplitude, continuity, frequency) and reflection terminations (onlap, downlap, erosional truncation, toplap…).
1. Reflection configuration (parallel, divergent, sigmoid, or oblique)
2. Three dimensional form.



Boggs (2001), p.507

Figure 14.20 Schematic illustration of lithologic and environmental interpretation of the simulated seismic facies patterns shown in Figure 14.18. [From Vail, P. R., 1987, Seismic stratigraphic interpretation using sequence stratigraphy, *in* A. W. Bally (ed.), Seismic stratigraphy: Am. Assoc. Petroleum Geologists Studies in Geology 27, Fig. 9, p. 10, reproduced by permission of AAPG, Tulsa, OK.]

Seismic facies classification

“A,B,C technique” for two-dimensional seismic facies analysis (Ramasayer, 1979)

These codes can be marked on a map:

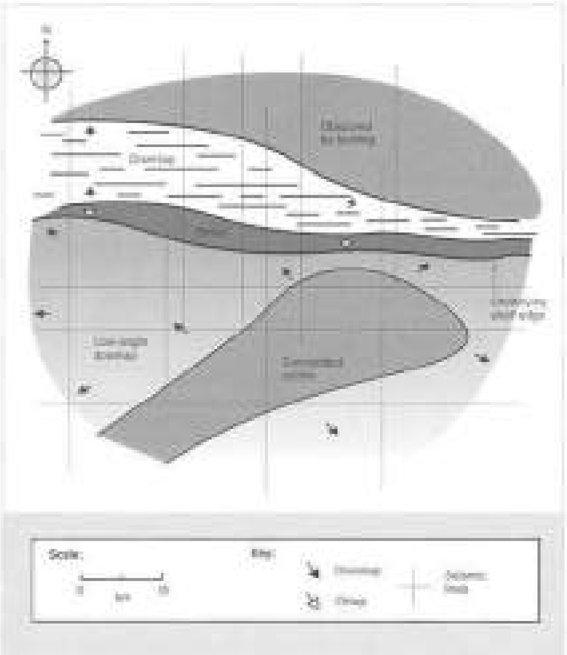


Fig. 3.11 An example of a seismic facies map (from Mitchum and Vail, 1977). This map shows reflection terminations at the base of a Lower Cretaceous package, offshore western Africa.

Emery & Myers (1996), p.56

There is no unequivocal link between seismic facies and depositional systems, with the probable exception of the link between clinoforms and slope systems. Continuous flat-lying reflections may, for example, reflect deep-marine shales, coastal-plain topsets, alluvial plain, or lacustrine facies.

Code system A-B/C

Upper boundary (A)	*Internal configuration (C)*
Te, erosional truncation	P, parallel
Top, toplap	D, divergent
C, concordant	C, chaotic
	W, wavy
Lower boundary (B)	DM, divergent mounded
On, onlap	M, mounded
Dwn, downlap	Ob, oblique progradational
C, concordant	Sig, sigmoid progradational
	Rf, reflection free
	Sh, shingled

Emery & Myers (1996), p.58

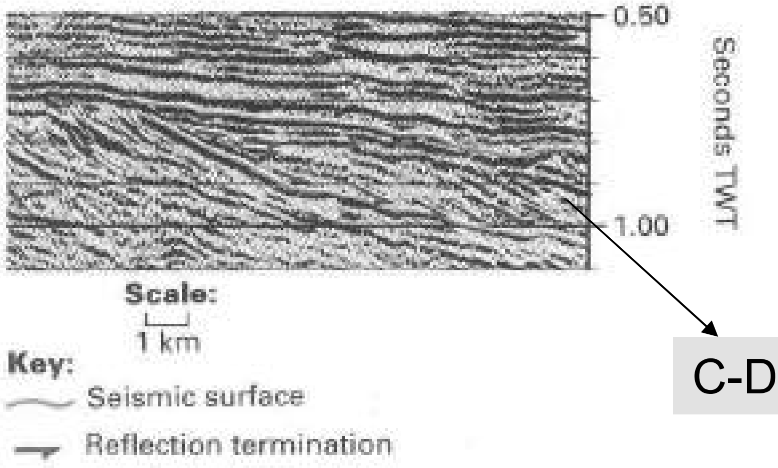


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Fig. 3.13 A lowstand systems tract on seismic data. On this part of this line, only the lowstand prograding wedge is seen. The underlying sequence boundary is recognized by a downward shift in coastal onlap. Late Eocene, Outer Moray Firth, central North Sea

Chapter 8
Evaluation of High-Resolution 3D and 4D Seismic Data

Abstract 3D data have several advantages that include creation of seismic sections in any desired azimuth for display and extraction of multiple seismic attributes. Horizontal viewing of 3D seismic is another advantage that resolves small-scale depositional features better in plan view. Stratal attribute slices are extensively used as a tool to map channel/fan complexes with their associated diverse facies. Horizontal-view seismic is also useful for sequence stratigraphy interpretation (SSSI) to build tectono-stratigraphic frameworks for petroleum system modeling.

Higher resolution and closer spatial sampling of 3D data ensure better delineation of reservoir geometry and characterization of reservoir properties that are the key inputs (static characterization) to initial reservoir modeling for estimating reserves and formulating production profile.

4D seismic is a time-lapse repeat of 3D surveys which evaluates the reservoir parameters (dynamic characterization) altered due to depletion .4D seismic can be useful in studying fluid flow during production, referred as seismic reservoir monitoring (SRM) and can help identify areas of by-pass oil, flow barriers and EOR sweep efficiencies. 4D limitations and in particular, its application restricted to only certain type of reservoirs responding to DHI anomalies with associated conditions are highlighted.

High resolution, high-density 3D and 4D seismic data offer scopes for precise estimation of rock and fluid parameters, which is crucial for reservoir characterization and reservoir monitoring during development and production of a field. The interpretation and evaluation techniques remain essentially similar to those of 2D seismic but require a multi-disciplinary synergetic approach, involving all types of data like seismic, geological, well logs, cores, drilling, reservoir and production data. Obviously, the evaluator is required to have knowledge, expertise and experience, and more importantly, an attitude to work in a team of persons from diverse disciplines, to produce the desired results. Since 3D data is increasingly used for reservoir characterization and 4D for monitoring fluid flow during production, the former may be considered synonymous to '*Reservoir seismic*' and the latter, '*Production seismic*'.

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3D (Reservoir Seismic)

3D seismic is recorded over an area in which data is sampled densely along a regular grid and the processed output is available in a volume. On land, 3D acquisition is done with closely spaced grid of shot and receiver points spread over an area called a 'swath'. Along the swath, receivers are placed on parallel lines and shot points positioned on parallel lines orthogonal to receiver lines (Fig. 8.1). However, there can be several alternate lay outs that can be modelled and designed depending on the geological objective.

Essentially, the survey geometry allows each receiver to record reflected waves coming from several azimuthal directions in contrast to 2D data that records limited reflections coming only from the plane of the source-receiver defined by a single profile of source and receiver. The close spacing of traces in 3D is defined by the "bin" size, which is the minimum area containing the cluster of common depth points (CDP) for stacking and typically varies between grid sizes of 12.5 × 12.5 and 25 × 25 m, depending on the dimension of geologic objective to be imaged. In marine 3D surveys, data however, is mostly recorded in a set of closely spaced lines with multistreamer and multisource (air guns) arrays, towed by the recording seismic vessel for operational efficiency.

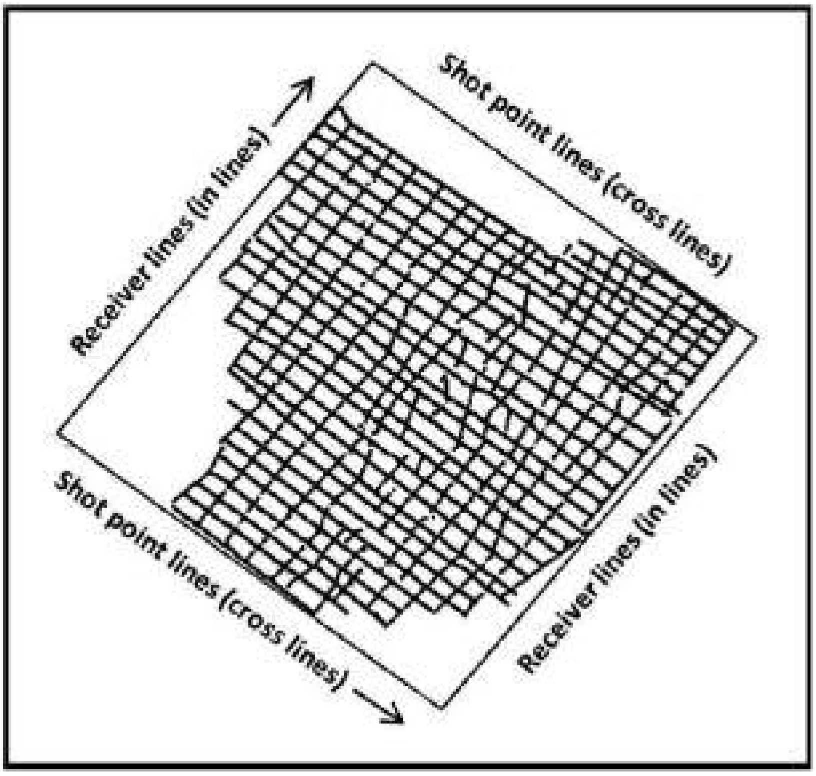

Fig. 8.1 A typical 3D swath survey lay out showing parallel receiver and source lines, orthogonal to each other. Receiver lines are called inlines and the shot point lines the cross lines. Breaks in the grid are due to ground logistic problems

The closely sampled regular-gridded 3D data permit volume-based processing techniques like surface-consistent static and deconvolution, improved velocity analysis and migration that yield much improved seismic resolution**,** both temporal and spatial. Seismic data recorded with multiple azimuths (*MAZ*) help collapse diffractions and out-of-plane events most efficiently and create a more accurate three dimensional image of the subsurface compared with 2D images. Multiple azimuth (*MAZ*) data also permits detecting azimuth-dependent anisotropic and fractured formations present in the subsurface. Specifically, the 3D prestack migration process plays a very important role in enhancing the sharpness and resolution of the images (Fig. 8.2).

The higher resolution and densely sampled 3D volume data proffer an excellent opportunity for volume based interpretation utilising 3D visualization softwares. The volume based interpretation is often convenient and permits to comprehend better the stratigraphic and structural styles that are less evident on conventional section-based display of 2D data that requires line to line interpretation. Interpretation of 3D data results in a superior definition of the reservoir geometry and quantification of rock parameters needed for development of the field. This, however, requires unambiguous seismic horizon correlations to start with after a meticulous well calibration and to be followed by detailed seismic mapping and evaluation of rock properties.

The 3D interactive interpretation is accomplished fast and accurate by use of powerful and sophisticated softwares. Several important 3D techniques like creation of arbitrary and reconstructed seismic sections in any desired azimuth, display of time/depth slices in plain view , extraction of geometric attributes like dip, azimuth, curvature, and coherency and fault-plane mapping (See Chap. 10) can be conveniently used that are not achievable with 2D data. Subtle sedimentary features, such as gentle delta progradations or channel cut and fills, often are seen only on dip or strike lines and may be altogether missed on 2D seismic if the lines are not shot

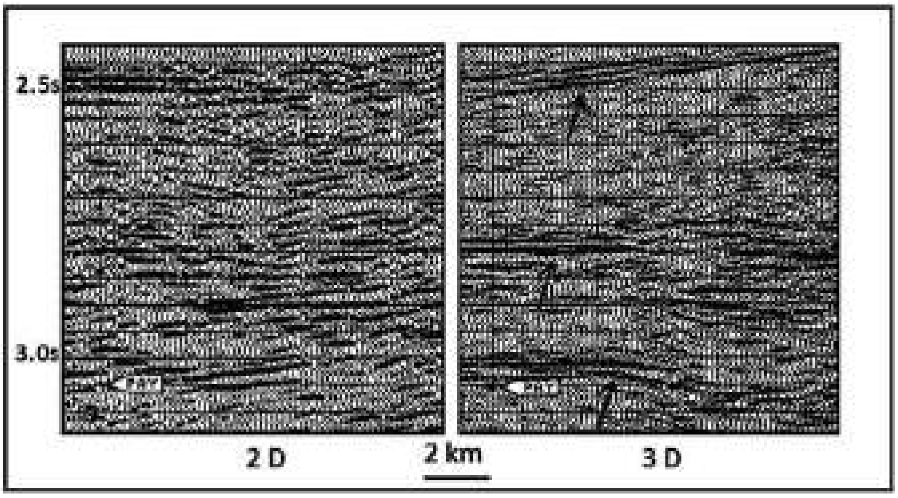

Fig. 8.2 Comparison of 2D and 3D seismic images. Note the improvement in clarity and continuity of events in 3D data (shown by *arrow*) notably by the process of migration, that reduces noise and improves spatial resolution (Image courtesy of ONGC, India)

in those specific azimuths. 3D seismic is free of these constraints as an arbitrary line can be generated from the volume data in any direction the interpreter desires to perceive the geological features. Reconstructed and arbitrary seismic lines connecting wells are simple but extremely useful in analyzing seismic responses in relation to known reservoir properties at the wells. These created profiles passing through hydrocarbon and dry wells, help calibrate seismic and set bench marks to guide prediction of lateral variations of geologic properties in areas between the wells and beyond.

One of the most straightforward and particularly effective means of 3D interpretation is horizontal viewing of seismic as against the traditional 2D vertical viewing. Depositional bodies mostly have horizontal dimensions greater than their vertical dimensions and horizontal-view seismic interpretation is therefore likely to resolve small-scale depositional features better in plan view (Zeng 2006). Though horizontal viewing by cutting slices through the 3D data volume is widely used for all types of attributes only the amplitude slices are described here. Other attribute slices are discussed in Chap. 10 (“Analysing seismic attributes”).

Horizontal-View Seismic: Horizontal Amplitude Slices

Horizontal slices cut across the 3D volume at constant time (known as horizontal or time slices) or along a flattened correlated seismic horizon (known horizon slices), conveniently show the variations in seismic amplitude along a constant time or along a horizon, facilitating fast and precise mapping of the two-dimensional extent of geologic features in plan-view in the entire area. Time slices are also called ‘*seiscrop*’, a term analogous to geologic term outcrops where surface rocks are studied on a traverse and the horizon slices, the ‘*horizon seiscrop*’.

The slicing technique makes it possible to reveal subtle subsurface depositional features like channels, deltas, barrier bars, fan complexes etc., in plan- view, somewhat similar to surface geomorphologic features observed in satellite images (Zeng 2006). Conventional interpretation of vertical sections may detect these features but the smaller and interesting exploratory objects like point bars, levees, crevasse splays etc., may not be resolved due to limited seismic resolution. An illustration of a channel, a common exploration play, mapped clearly by horizon slice but not quite comprehensible on a vertical section, is shown in Fig. 8.3.

Horizon seiscrop being a slice along a bedding plane (horizon) essentially represents the depositional surface of a feature and works well mostly in conformable sequences that assume beds deposited flat, as in ‘layer-cake’ geology. Horizons along which the slices are generated are flattened so that slicing is along the bedding surface and does not include feature belonging to different geological age. Scanning through horizon slices at close intervals reveals the vertical and lateral changes in a depositional sequence and works fine when it is of uniform thickness. Where the sequences change thickness, as are often found in nature, horizon slices may sample diachronous events of different geologic age. In such cases, to limit slicing along the

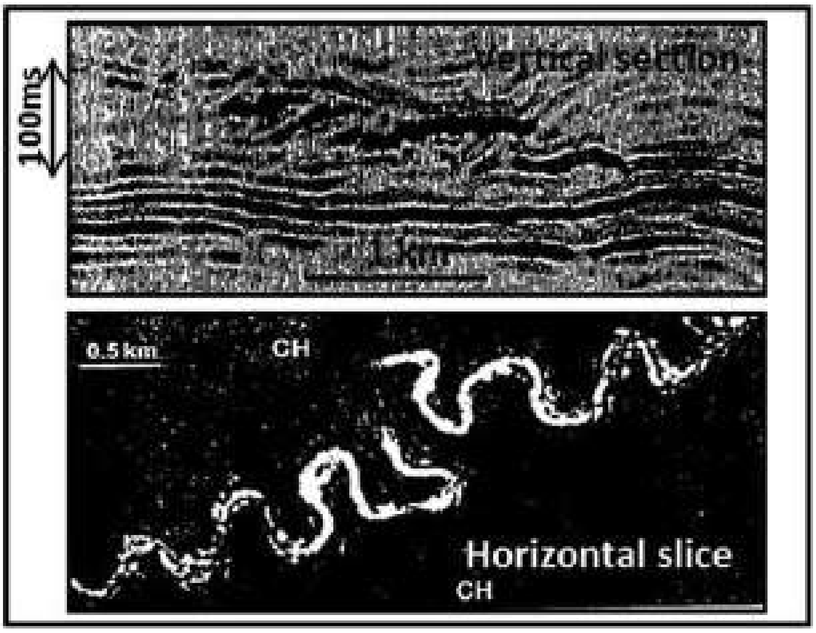

Fig. 8.3 Example of a channel geometry clearly revealed in seismic *horizontal* section (seiscrop), but not intelligible in the *vertical* section (Modified after Figs. 4 and 12 of Kolla et al. 2001)

bedding surfaces, geologic time surfaces (stratal surfaces) are constructed from the seismic volume by dividing the variable time interval between two seismic reference events into a number of uniformly spaced subintervals. Slicing along these surfaces is known as *stratal slicing or proportional slicing* and is likely to provide more details on variability of facies within the sequence. Seismic attributes mapped from the stratal slices can then be analyzed in terms of depositional systems (Zeng 2006).

Another commonly used technique is display of amplitude values in a specified window of stack data. These windowed versions include Average, Maximum, and RMS (root mean square) amplitudes in a specified time window. Essentially the amplitudes for all samples in a selected window are considered for estimating amplitudes to be displayed in a plan view. The average amplitude computes the mean of amplitudes, whereas, the maximum computes the maximum of the absolute value of peak and trough amplitudes in the window. The most commonly used, RMS amplitude computes the square root of the sum of squared amplitude values divided by the number of samples within the specified window. Squaring offers the opportunity for the high amplitudes to stand out best though it is highly sensitive to noise. The windowed amplitudes are basically used as a simple and quick means to identify interesting zones of hydrocarbons for resource estimates in reconnaissance stage. The window selection is critical as different windows will provide varying amplitude patterns having diverse geological implications and requires careful choice of window for the purpose.

Often the horizontal slices of the seismic images are shown riveted to their corresponding position in the vertical sections and are called 'chair displays'. Chair displays make it convenient to cross-refer both vertical and horizontal slices to bring out clarity in interpretation of geologic bodies (as in Fig. 8.4). Stratigraphic resolu-

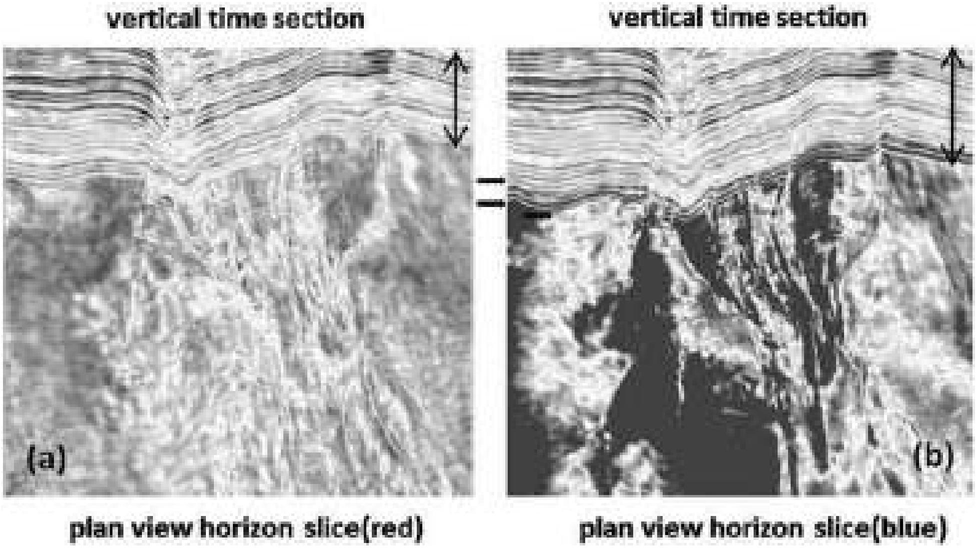

Fig. 8.4 Chair displays of horizon amplitude slices with vertical section. Plan view maps of amplitudes for the reflections (**a**) *red horizon* and (**b**) *blue horizon* shown by *arrows* in the vertical section. Note the differences in amplitude slices displayed in the horizontal views, despite the two reflections looking similar in the vertical view section (Images courtesy of Arcis Seismic Solutions, TGS, Calgary)

tions are best achieved by using both vertical and plan sections and in this context chair displays are extremely useful.

Horizontal-View Volume Seismic: Sequence Stratigraphy Interpretation

Traditionally, conventional interpretations are carried out on vertical seismic sections as the image is expected to replicate the subsurface geology in depth. But with emerging advantages of seismic 'horizontal-view', it has evolved as a powerful and fast technique for seismic sequence stratigraphy interpretation (*SSSI*) of 3-D volume data and the work flow is briefly outlined as below.

SSSI Framework: Horizon Cube

The seismic sequence stratigraphy interpretation of plan view seismic is essentially based on creation of a Horizon Cube and its transformation to Wheeler domain. Horizon cube is a dense set of correlated stratal surfaces each interpreted to represent a relative geological age. Major sequences boundaries are mapped and all possible reflection events within it are auto tracked to create a large number of horizons. Auto tracking is either model based or data driven. In the former mode, tracking is done interactively with a geologic model by calculating or interpolating horizons parallel to upper/lower boundaries (Brouwer et al. 2008). In the data-driven mode it

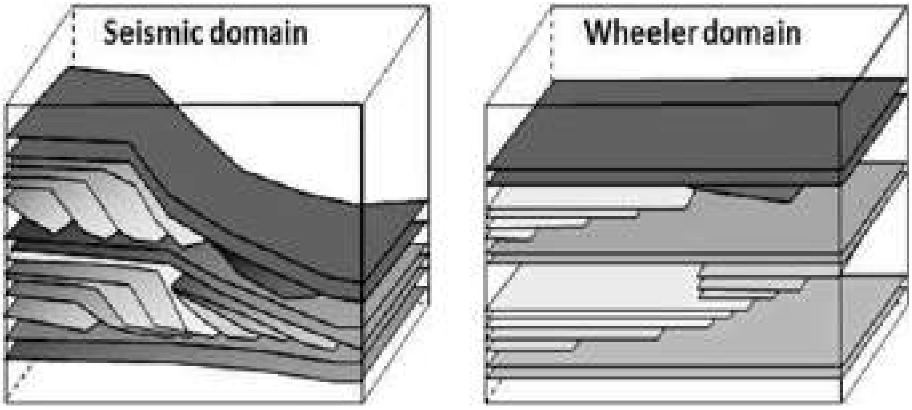

Fig. 8.5 Sketch illustrating transformation of events from seismic to Wheeler domain. Wheeler domain time slices are the horizon slices of seismic domain. Wheeler domain color display facilitates better interpretation of spatial distribution and timing of sediment deposition and environment (After Fig. 2 of Brouwer et al. 2008)

deploys auto-tracking by following dip of the events. Essentially, each created horizon corresponds to a stratal surface and assigned a geologic time, the stratal surfaces effectively represent chronostratigraphic events.

SSSI Framework: Wheeler Domain

The stratal surfaces of the Horizon Cube may be flattened and the data transformed into the Wheeler domain. Time slices in the Wheeler domain are the equivalent of horizon slices in the seismic domain. The Wheeler transformation is an extremely convenient graphic display (Fig. 8.5) for better comprehension of chronostratigraphic study. The Wheeler time slices make it easier to interpret spatial distribution and timing of sediment deposition.

Because of its accuracy and speed in evaluating geologic basins, volume based *SSSI* interpretation techniques have become part of the workflow in many companies. However, the techniques work well in geologic set-ups where sediments are not much distorted by tectonics. It also requires good quality data without noise, suitable for auto tracking which though accurate, may not be correct in many instances.

Prediction of Shallow Drilling Hazards in Offshore

Another important utility of 3D seismic worth mentioning is prediction of shallow drilling hazards in offshore areas. Locations of upcoming drilling wells based on seismic maps are checked for the presence of shallow hazardous zones that could imperil offshore operations. Presence of soft, loose and mobile strata at or near the sea bottom and shallow high pressured pockets can endanger drilling operations. It is mandatory that the sea floor and the sub strata around the prospect area are assessed for their strength and stability for safe drilling and related operational activities. Several surveys like sea bottom sampling, shallow soil coring and high resolution acoustic profiling like *'sparker'*, are carried out to locate the hazardous zones.

Marine 3D seismic images of the sea bottom and the sub-bottom zones, often exhibit adequate resolution that allows detecting and mapping features linked to potential drilling hazards. Buried river channels, clay 'dumps', localised gas pockets and seepages in the sub bottom constitute a few of these hazards and are avoided for safe location of drilling rigs and ships to operate. Mobile clay dumps and channel-fills (Fig. 8.6) are highly unstable and can collapse putting erection and operation of jack-up rigs in risk. Gas seepages through sea bottom, phenomena often observed especially in deep water offshore areas may reduce buoyancy of water and can impede deployment of semi-submersible floaters at the site for drilling. Isolated, high-pressured shallow pockets of gas/water sand (Figs. 8.7 and 8.8) and shale can also cause blow-outs or shale flow into well, posing drilling hazards and difficulties.

By far the most significant interpretive advantage of high density-high resolution 3D volume data is the accessibility of quick and accurate analysis of a multitude of seismic attributes. This leads to better estimates of rock and fluid properties to evaluate

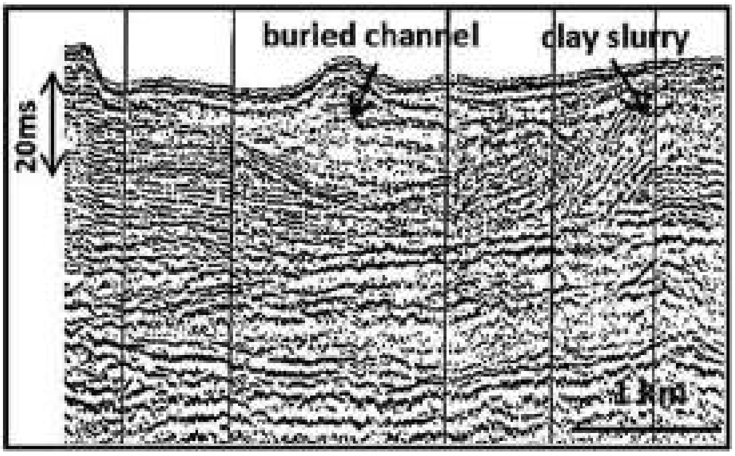

Fig. 8.6 Example of 3D seismic in prediction of shallow drilling hazards in offshore. Buried channel and clay slurry are extremely pliable and mobile which pose potent threats to installation and stability of jack-up rigs for safe operation (Image courtesy of ONGC, India)

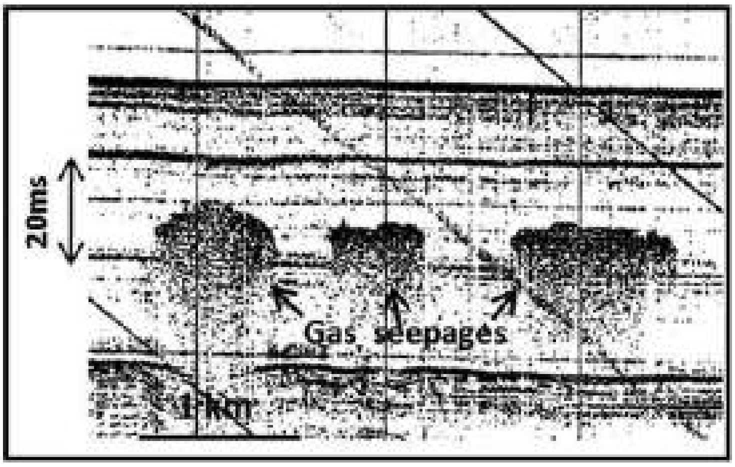

Fig. 8.7 Seismic image of shallow offshore gas seepages, used for prediction of drilling hazards. Gas leaking through sea bottom reduces buoyancy of water, endangering operation of semi-submersible floaters deployed for drilling (Image courtesy of ONGC, India)

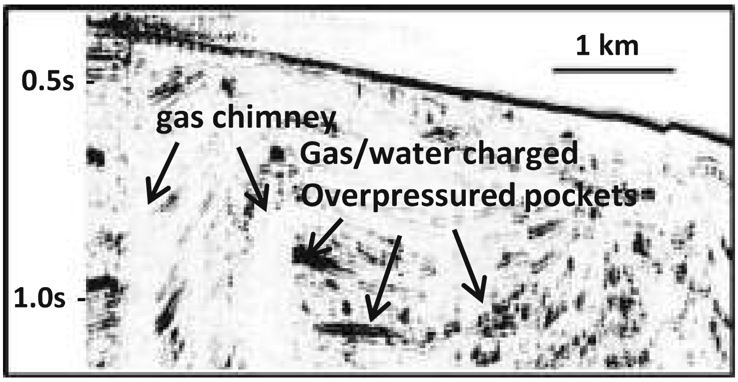

Fig. 8.8 Offshore seismic image of shallow gas/water charged high-pressured pockets (high amplitudes) and gas chimneys (transparent), that Indicate potential drilling hazards (Image courtesy of ONGC, India)

potential prospects for assessing all-important in-place reserves in exploration stage and for reservoir delineation and characterization during development stage. Some of these attributes are discussed later in Chap. 10 (Analysing seismic attributes).

Reservoir Delineation and Characterisation

3D seismic data has become indispensable as based on its evaluation the hydrocarbon reservoirs are defined and assessed for field development. Reservoir delineation and characterization parameters estimated from seismic contribute the prime inputs for initial static reservoir modeling to plan production profile. A hydrocarbon reservoir may be defined by the basic parameters:

A. Reservoir geometry (shape, size and thickness)
B. Depth to reservoir top
C. Fluids and contacts (GOC, OWC, OSC, GWC, etc.)
D. Rock and fluid properties (porosity, permeability, fluid saturation etc.)
E. Reservoir heterogeneity (facies change, barriers, faults and fractures)

The first three parameters may be subsumed under the term ‘reservoir delineation’ to differentiate from the latter two, termed as ‘reservoir characterisation’.

Reservoir Delineation

Hydrocarbon discovery in a well requires as a follow up, proper delineation of the reservoir for appraisal of production potential of the prospect. This is achieved through a set of fresh structural and facies maps prepared in the prospect area after a seismic tie with the well. Emphasis is put on stringent calibration for picking the exact reflection phase (peak/trough/zero inflection) correlated to the reservoir top and bottom and its lateral continuity is strictly decided on the basis of reflection character to map the reservoir limit (Fig. 8.9). Reservoir delineation is a crucial step