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.

10.1 Nature of a reflection seismic section

An example header

A typical oil industry seismic section consists of
(1) a header;
(2) the main body of seismic data that consist of a series of seismic traces;
(3) shot points or common depth points;
(4) velocity analyses.

PROCESSING SEQUENCE

1. FORMAT CHANGE
2. RECORDING GAIN REMOVAL
3. RESAMPLE 4 MSEC
4. GEOMETRY DEFINITION
5. SPHERICAL DIVERGENCE CORRECTION
6. TRACES EDITING
7. DATUM STATICS CORRECTION
8. SHOT DECONVOLUTION
9. GAP DECONVOLUTION
   NO. OF FILTER : 2
   WHITE NOISE : 0.1 PERCENT
   GAP LENGTH : 24 MS
   FILTER LENGTH : 71 SAMPLE POINTS
   DESIGN GATE
   NEAR OFFSET : 150 – 2300 MS
   : 2000 – 4200 MS
   FAR OFFSET : 2500 – 3700 MS
   : 3500 – 4800 MS
10. COMMON CHANNEL DIP MOVEOUT
11. CDP GATHERING : SORT 60 FOLDS
12. VELOCITY ANALYSIS AND INTERPRETATION
13. NORMAL MOVEOUT CORRECTION
14. WHOLE TRACE EQUALIZATION
15. FIRST BREAKS NOISE SUPPRESSION
16. STACK 60 FOLD
17. FINITE DIFFERENCE MIGRATION
   LAYER THICKNESS : 24 MSEC
   STACKING VELOCITY APPLIED :
   0 – 3000 MS : 100%
   3004 – 4000 MS : 100% – 90%
   4004 – 6000 MS : 90%
18. TIME VARIANT BANDPASS FREQUENCY FILTER

TIME GATE(MSEC)	BAND/SLOPE (HZ/DB/OCT)
100	14/18 – 65/36
1200	12/18 – 60/36
2600	10/18 – 50/36
4000	8/18 – 40/36
5000	8/18 – 30/36

19. TIME VARIANT SCALING
   TIME GATE (BALANCE):
   100 – 2000 MSEC. 1000 – 3000 MSEC.
   2000 – 4000 MSEC. 3000 – 5000 MSEC.
   4000 – 6000 MSEC. 5000 – 6000 MSEC.

DISPLAY PARAMETERS

HORIZONTAL SCALE : 50 TPI
VERTICAL SCALE : 1.875 IPS
POLARITY : NORMAL
DATE : SEP. 30. 1994

QUALITY CHECK

SEISMIC : M. T. LIN
GEOPHYSICIST : M. T. LIN
SUPERVISOR : J. W. KU

CHINESE PETROLEUM CORP
GEOPHYSICAL DATA
PROCESSING CENTER

AREA : BLK 1F TAIWAN
LINE : 81 – 1F – 75
S.P. : 101 TO 2254

MIGRATED DMO SECTION
SHOOTING DIRECTION : 332 DEGREE

REPROCESSED BY OPED CPC
HARDWARE : CONVEX C220 SOFTWARE : DISCO 10.0.3

RECORDING PARAMETERS

RECORDED BY : WESTERN GEOPHYSICAL CO.
VESSEL : M/V WESTERN PACIFIC
DATE : JUNE. 1992

NAVIGATION : PRIMARY ------- ARGO.
SECONDARY ----- MAXIRAN

ENERGY SOURCE	: SLEEVE GUNS.	GROUP INTERVAL	: 26.66 M.
GUN DEPTH	: 6 M	CABLE DEPTH	: 6 M AVG.
NO. OF GUNS	: 32	NO. OF GROUPS	: 120
SHOT INTERVAL	: 26.66	PHONES / GROUP	: 12
ARRAY VOLUME	: 2250 CU.IN.	CABLE LENGTH	: 3199.2 M
PRESSURE	: 2000 PSI.	LEAD IN	: 141.23 M

RECORDIND SYSTEM PARAMETERS
RECORDING SYSTEM : LRS-16A
SYSTEM NUMBER : 13
SAMPLE RATE : 2 MSEC
RECORD LENGTH : 6.144 SEC
TAPE FORMAT : SEG D 8024, 6250BPI.
ARRAY DATA RECORDING ONLY

RECORD FILTER :
LO-CUT/SLOPE : 6 HZ, 18 DB/OCTAVE
HI-CUT/SLOPE : 128 HZ, 120 DB/OCTAVE

SPREAD CONFIGURATION

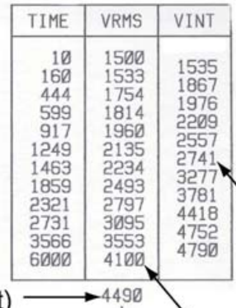
CH 1 3199 M CH 120

Courtesy of Chinese Petroleum Corporation

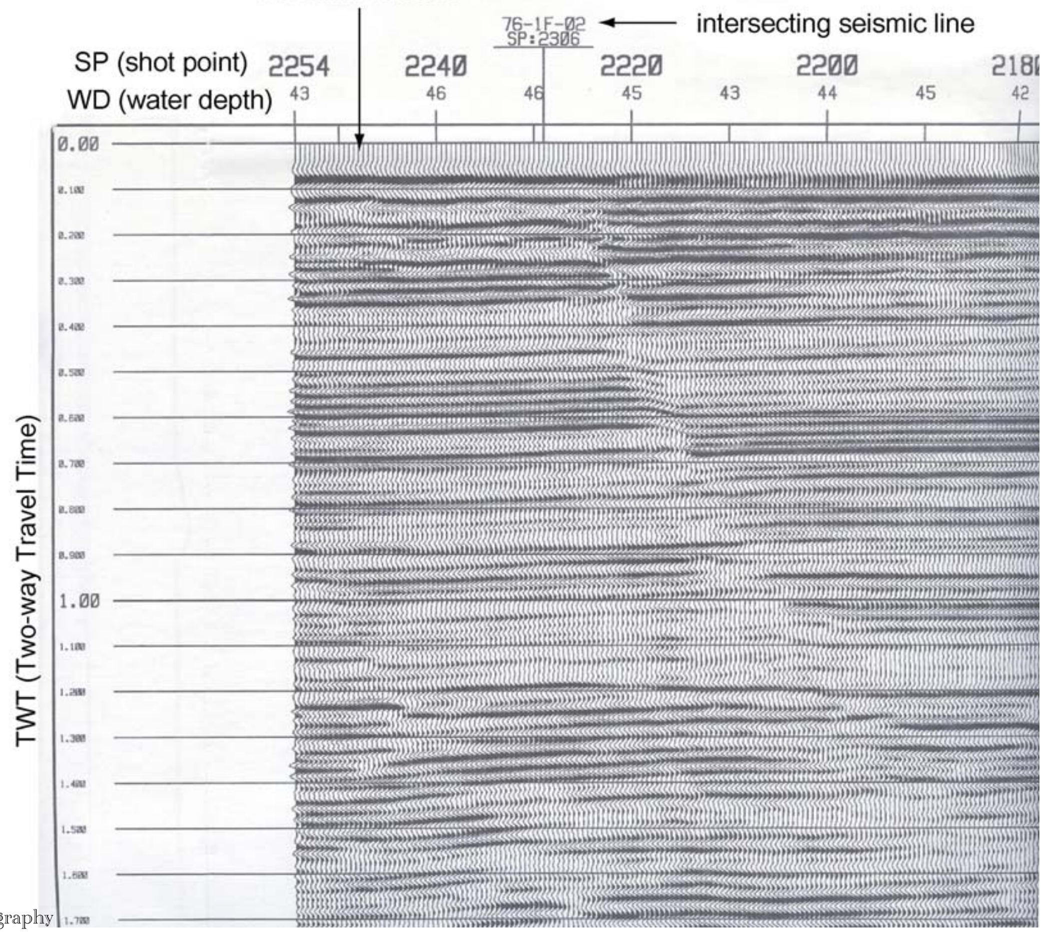
Main body of seismic data

Display of Seismic Data

(courtesy of CPC)

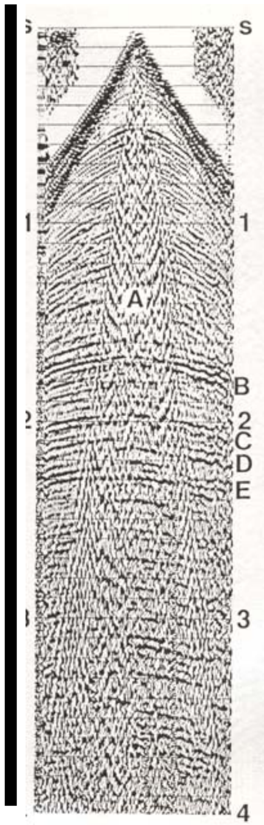


TIME	VRMS	VINT
10	1500	
160	1533	1535
444	1754	1867
599	1814	1976
917	1960	2209
1249	2135	2557
1463	2234	2741
1859	2493	3277
2321	2797	3781
2731	3095	4418
3566	3553	4752
6000	4100	4790



A series of vertical wiggle traces: Most seismic reflection data consists of a series of closely spaced, vertical wiggle traces. These traces resemble a series of shots and receivers at the same location. So called vertical incidence arrangement. A single seismic trace is a stacked trace of a CDP gather as shown on the left.

A CDP gather



Two-way travel time (TWT): Have to reduce time by 1/2 before multiplying times velocity to convert to depth.

The **fold** of stacking refers to the number of traces in the CDP gather and may conventionally be 6. 12, 24, 48..

CDP spacing = $^1/_2$ x group (channel) interval

$$\text{maximum CDP fold} = \frac{\text{number of channels x group interval}}{\text{2x shot interval}}$$

Velocity increases with depth: Time section is compressed in terms of depth at greater times. Hence depth converted profiles have better representations of geometry.

Vertical Exaggeration: Usually significant, and variable in depth.

Boggs (2001), p.498

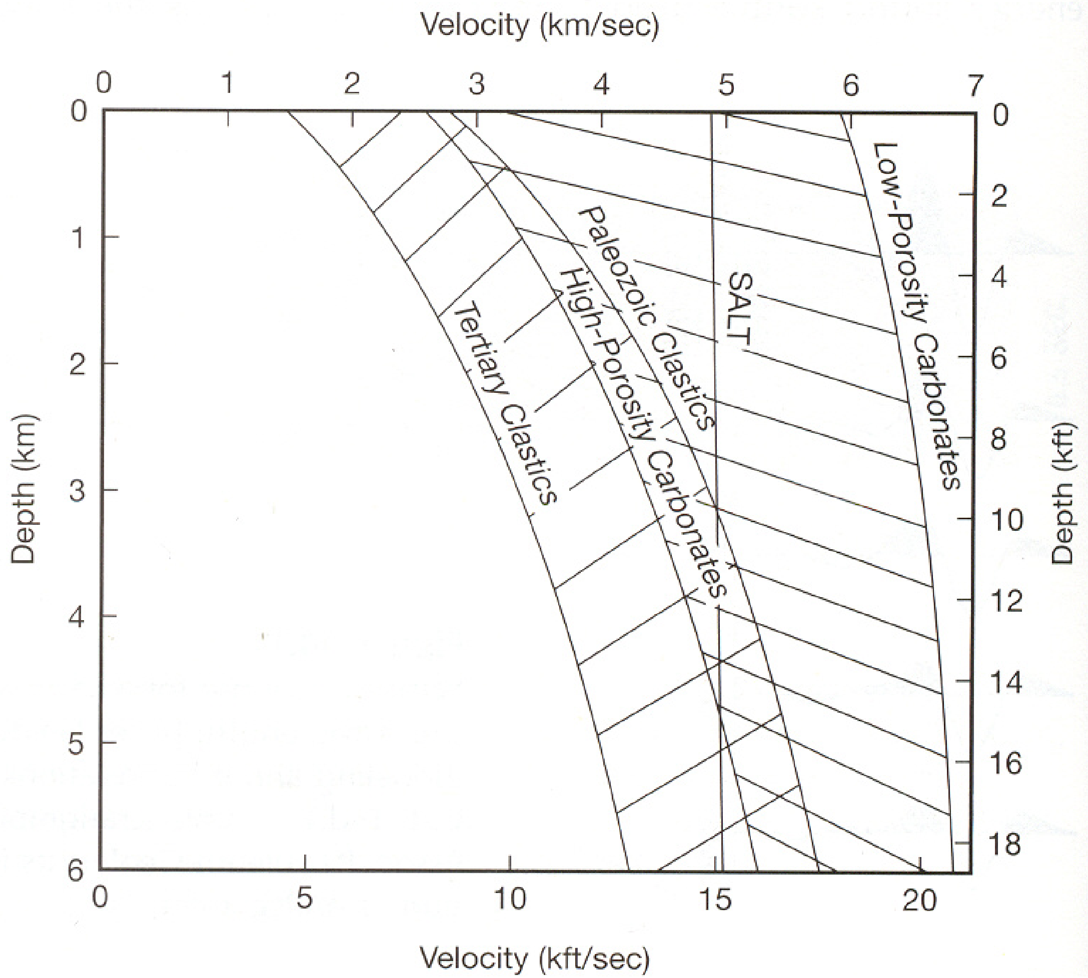
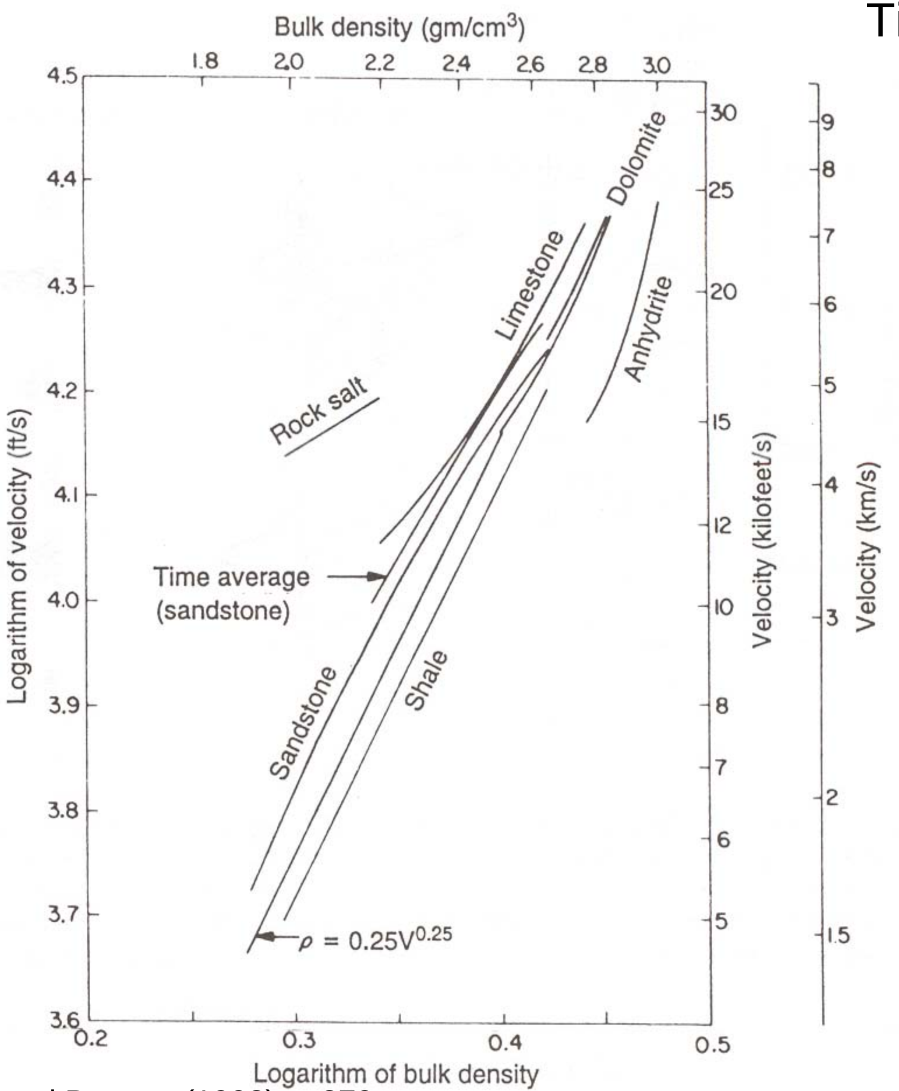


Figure 14.12
Characteristic velocity-depth relations for terrigenous clastic sedimentary rocks, carbonate rocks, and salt. Younger rocks tend to have lower velocities than do older rocks because they generally have higher porosities, are less cemented, and have undergone less deformation. [From Sheriff, R. E., 1976, Inferring stratigraphy from seismic data: Am. Assoc. Petroleum Geologists Bull., v. 60, Fig. 6, p. 533, reprinted by permission of AAPG, Tulsa, OK.]

◎ Nature of a reflection



Doyle and Bennett (1998), p.279

Figure 10.2 Velocity–density relationships in rocks of different lithology, using time-average and Gardner equations. (The time-average equation relates rock velocity to its porosity and fluid content, while Gardner's equation relates density to velocity.) [Reproduced with permission from the Society of Exploration Geophysics, from: Gardner et al. (1974)]

Velocity-porosity relationship

Time-average equation:

$$\frac{1}{v} = \frac{\phi}{v_f} + \frac{1-\phi}{v_m}$$

v: velocity in the saturated rock
Φ: porosity
v_f: fluid velocity
v_m: velocity of the matrix

Velocity-density relationship

$$\rho = 0.23v^{0.25}$$ Gardner's equation

Impedance contrasts: Reflections caused by impedance contrasts. The impedance (Z) of a rock unit is the product of its velocity (v) and density (ρ), that is **Z= v** ρ **.**

At normal incidence, **R**eflection **C**oefficient:

RC = $(Z_2-Z_1)/(Z_1+Z_2)$

♥ 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.

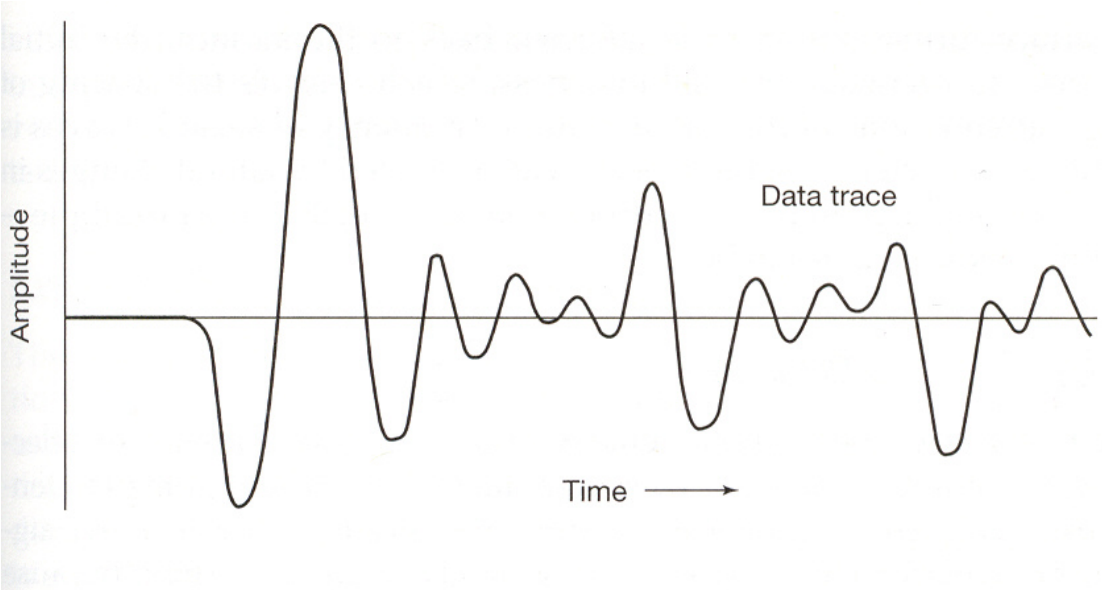


Figure 14.10
Schematic representation of the amplitude of seismic waves. The amplitude is the vertical distance above or below the mid-point line drawn through the wave traces. Time refers to arrival time of the waves at the seismic detector. [After Neidell, N. S., 1979, Stratigraphic modeling and interpretation: 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 <u>pick on the peak</u> 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.)

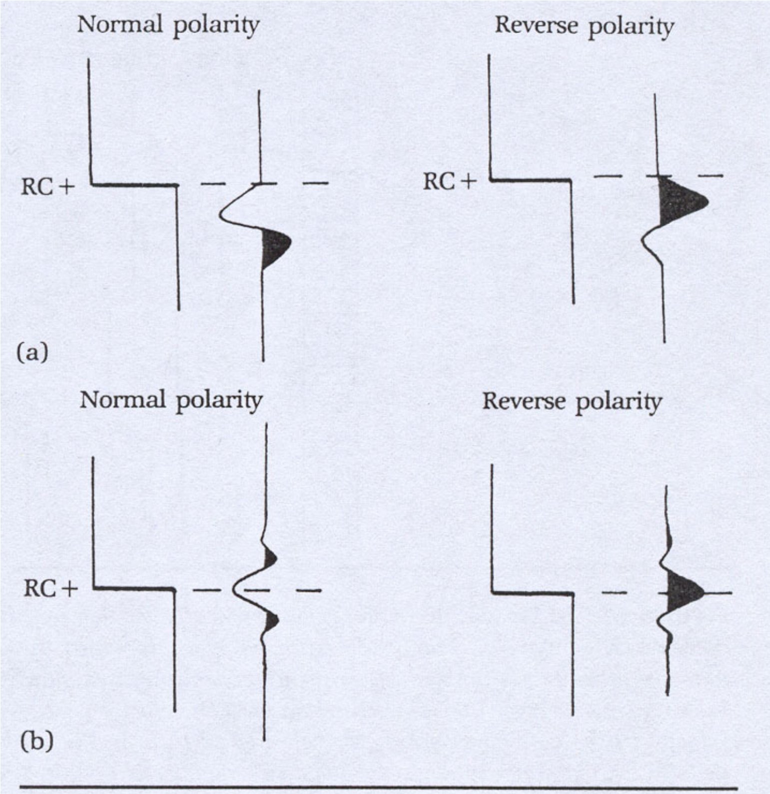


FIGURE 2.6 *Examples of idealized normal and reverse polarity for (a) minimum- and (b) zero-phase wavelets at an acoustic-impedance boundary with a positive reflection coefficient.*

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.

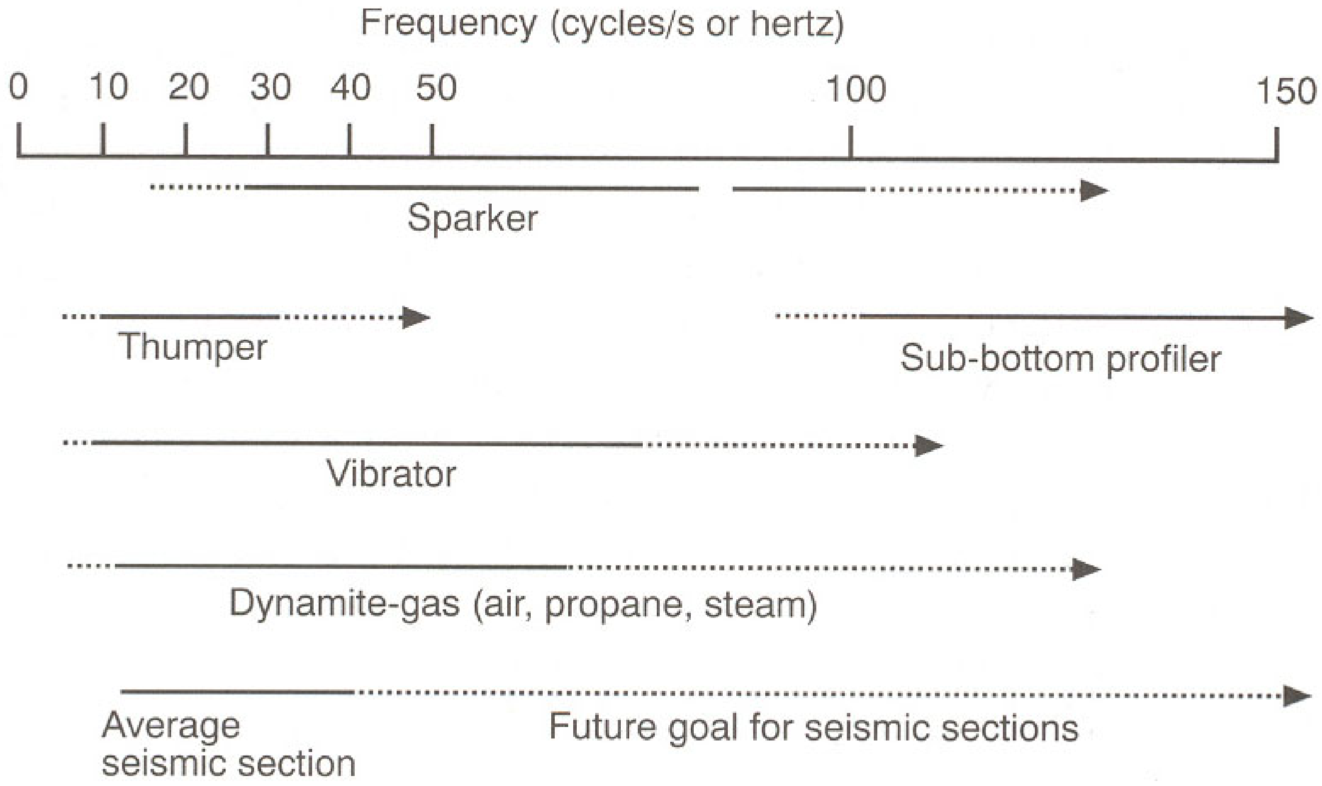


Figure 10.6 A frequency spectrum acoustic signal from 0 to 150 Hertz (cycles per second) showing frequency ranges for different energy sources. [Modified from: Tucker (1974)]

Doyle and Bennett (1998), p.284

10.2 Resolution of seismic data

A. Vertical resolution

This can be defined as the minimum vertical distance between two interfaces needed to give rise to a single reflection that can be observed on a seismic section. Resolution depends on **wavelength** of signal at depth in question, which depends on frequency and velocity.

Wavelength (λ)= Velocity (v) x period (T)
= Velocity (v) /Frequency (f).

The average vertical resolution for oil company seismic reflection data is about 10 m at shallow depth and 100 m in deeper crust depending upon the wavelengths involved.

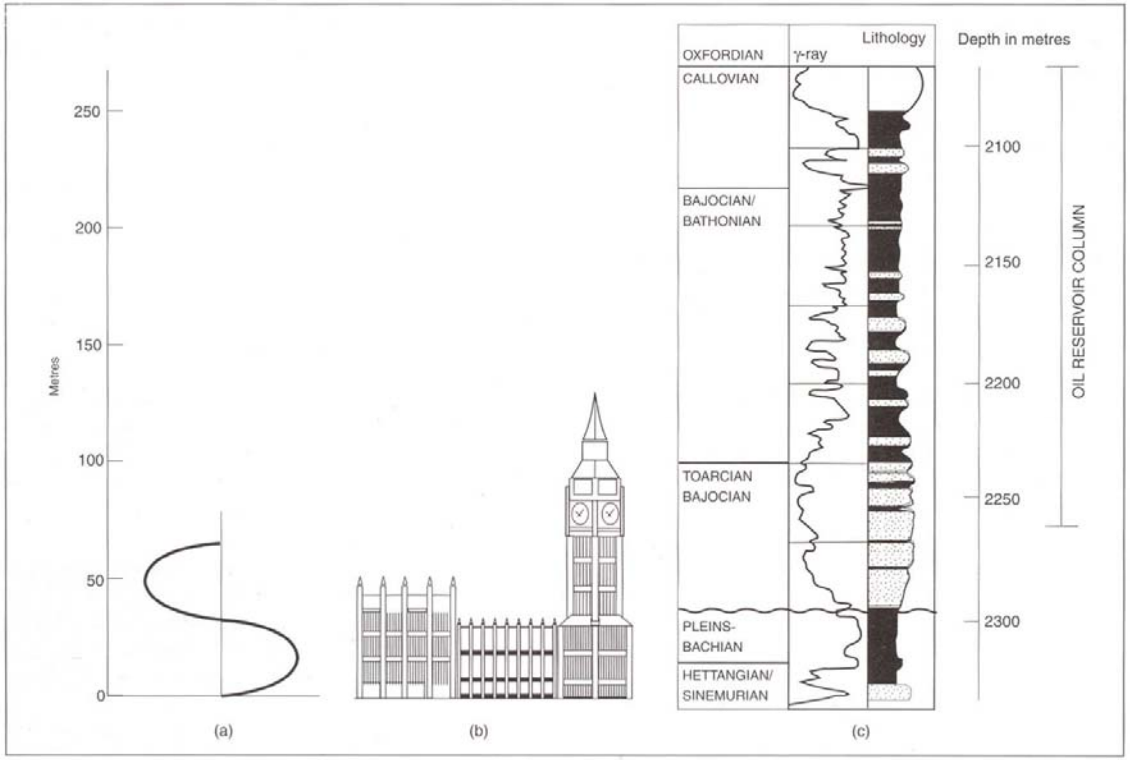


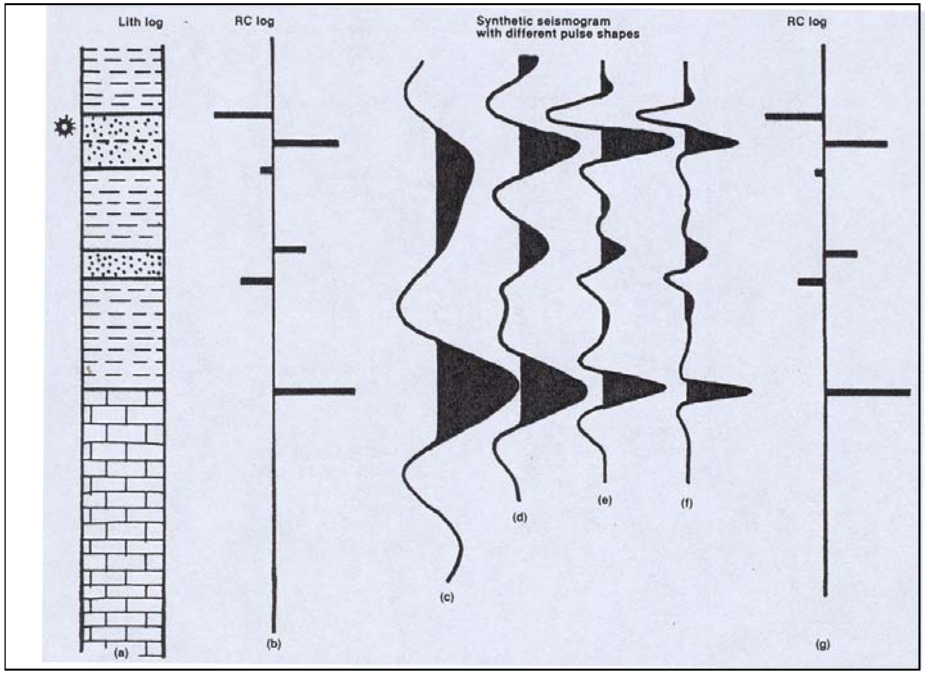
Fig. 3.2 A comparison of resolution of interpretation tools for the Beatrice Field, North Sea. (a) A single cycle sine wave of 30 Hz in medium of velocity 2000 ms^{-1} (or 60 Hz; 4000 ms^{-1}); (b) Big Ben, London, c. 380 ft; (c) A γ-ray log through the Beatrice Oil Field

Emery & Myers (1996), p.46

Photo: Andrew Lin

Big Ben in London

◎ The higher the frequency of the waveform, the greater or better will be the vertical resolution.



Badley (1985), p.26

Doyle and Bennett (1998), p.285

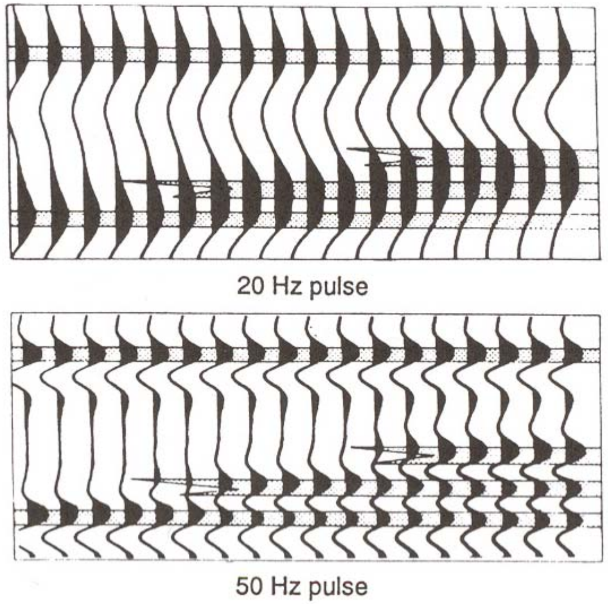


Figure 10.7 Comparison of the effect of higher and lower frequency pulses on the vertical resolution of geology. See text for detail. [P.R. Vail, R.G. Todd and J.B. Sangree, © 1977, reprinted with permission of the American Association of Petroleum Geologists.]

Because velocity increases with depth and frequency decreases with depth resolution goes down. Typically tops and bottoms of beds resolved by TWT of λ **/2**. Once the bed is about λ **/30** thick or less, reflections from the top and base effectively cancel and there is no detectable seismic response.

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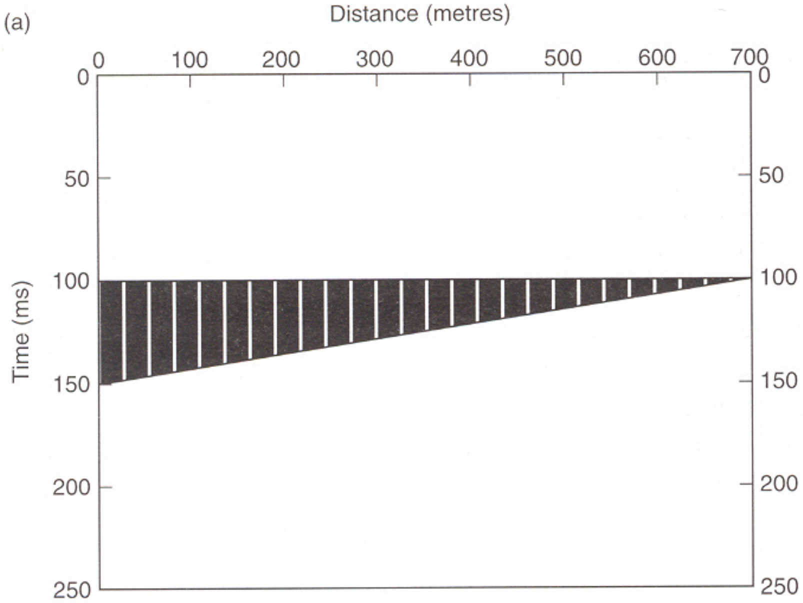
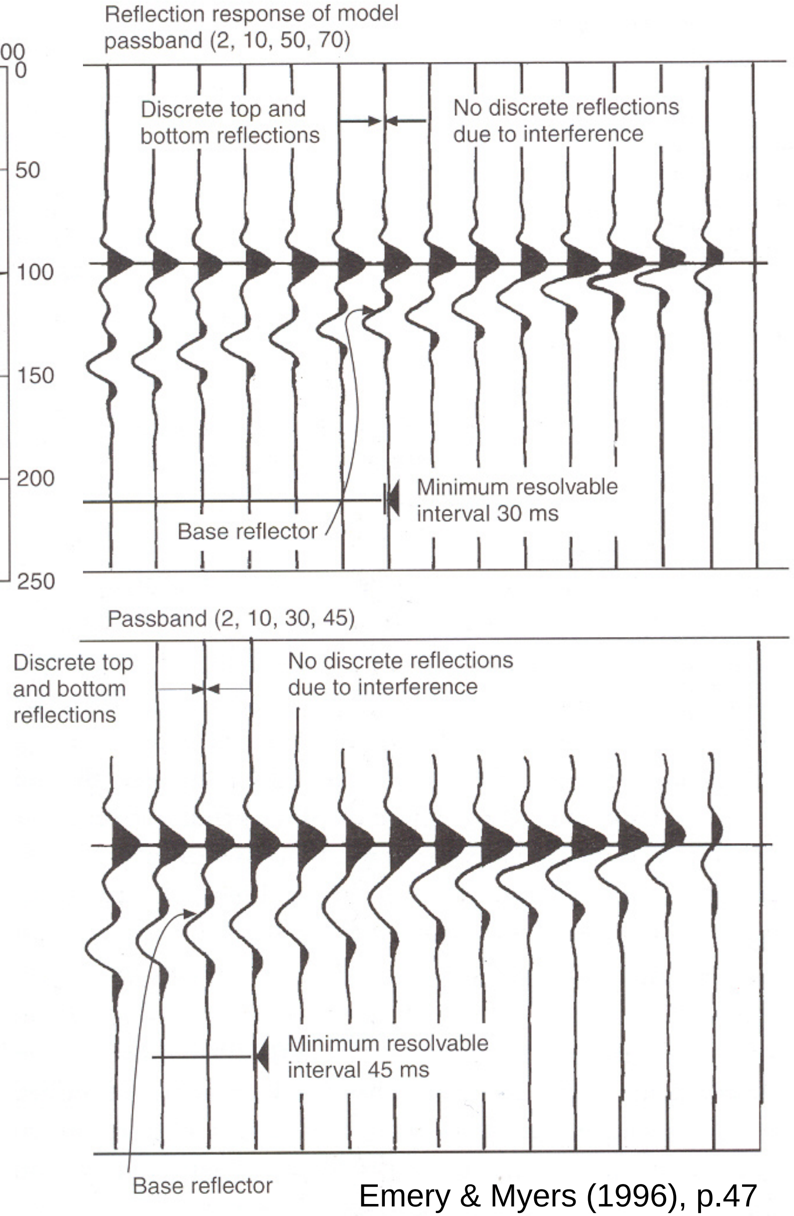
Thin-bed effect or tuning

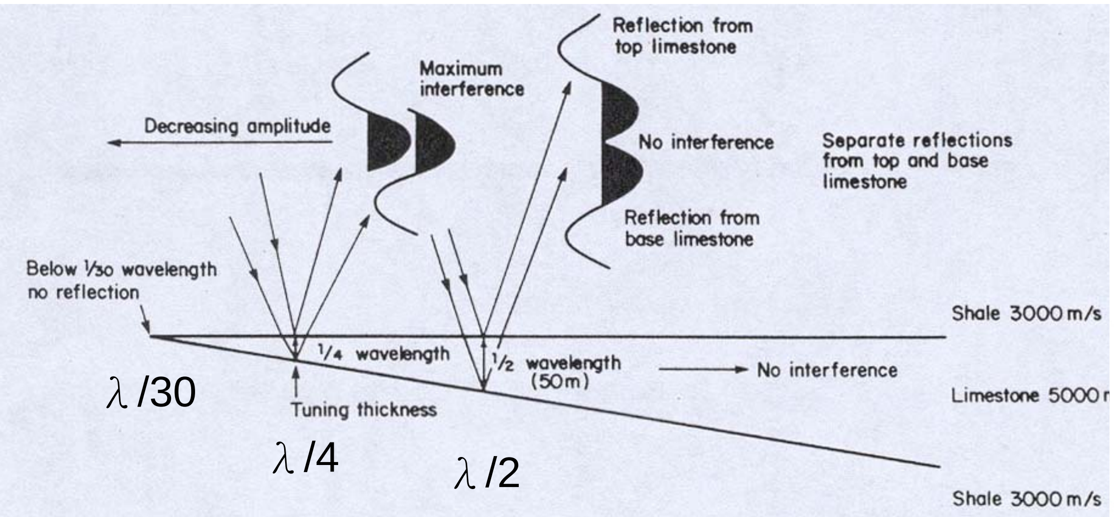
Reflectors that are spaced more closely than one-quarter thick (λ **/4**) of the wavelength have responses that begin to add constructively to produce a reflection with high amplitude.



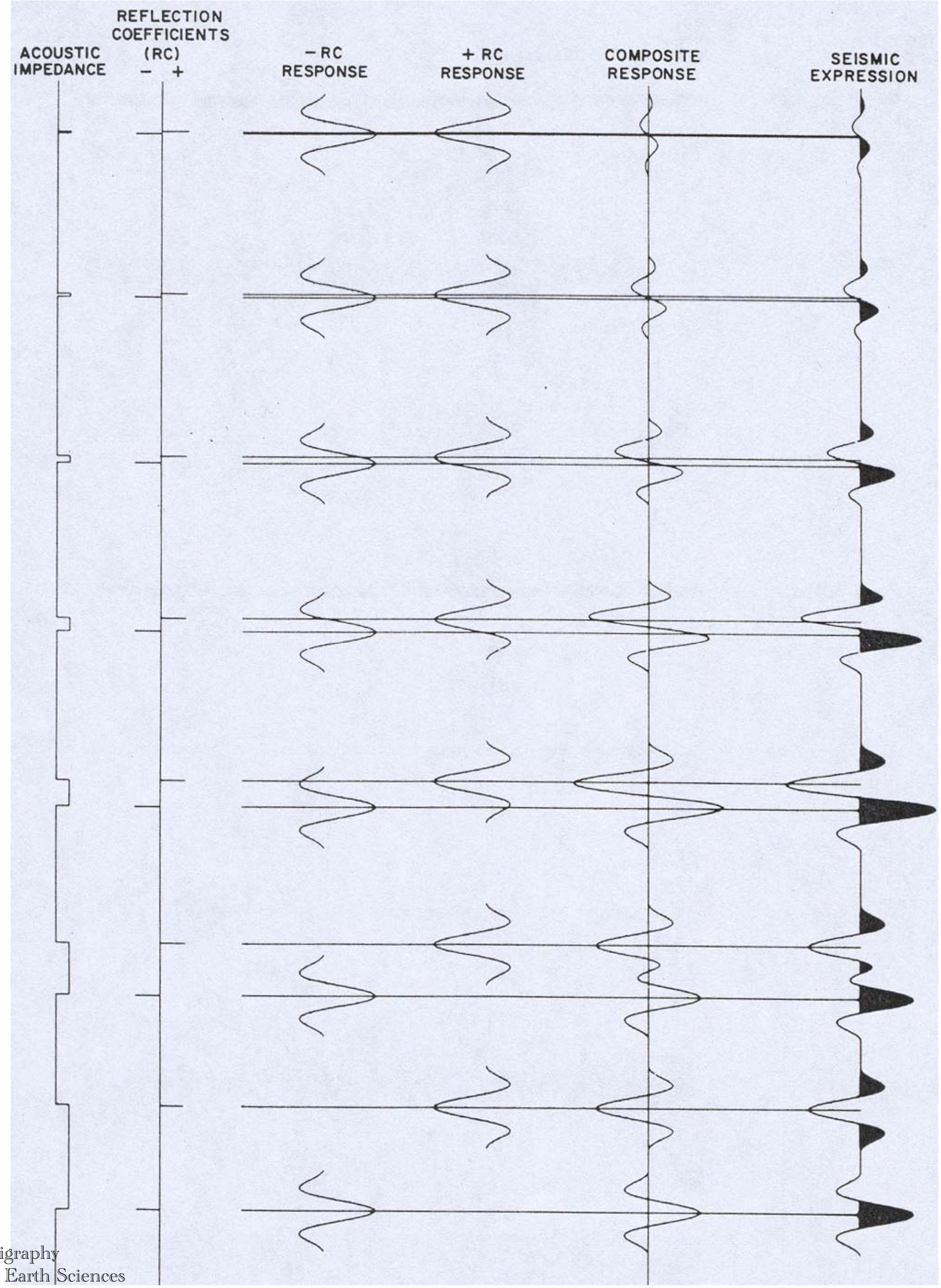


Emery & Myers (1996), p.47

Fig. 3.3 The effects of bed thickness and frequency on vertical seismic resolution. (a) Single layer wedge: acoustic impedance model with laterally varying bed (or time) thickness, i.e., 0–50 ms. (b) Reflection response of model



Badley (1985), p.18



Interference: the superposition of waveforms. Many (perhaps most) reflections are the interference composites resulting from several interfaces. So there is no one-to-one correspondence between seismic events and interfaces in the Earth.

Examples of interference on a zero-phase normal-polarity wavelet for a range of bed thickness and spacings.

Badley (1985), p.16

B. Lateral resolution

The seismic energy travels as wave fronts and the region on the reflector where the seismic energy is reflected constructively is known as the **Fresnel zone**. Lateral resolution is determined by the radius of the Fresnel Zone, which itself depends on the wavelength of the acoustic pulse and the depth of the reflector. Fresnel zone are typically hundreds of meters.

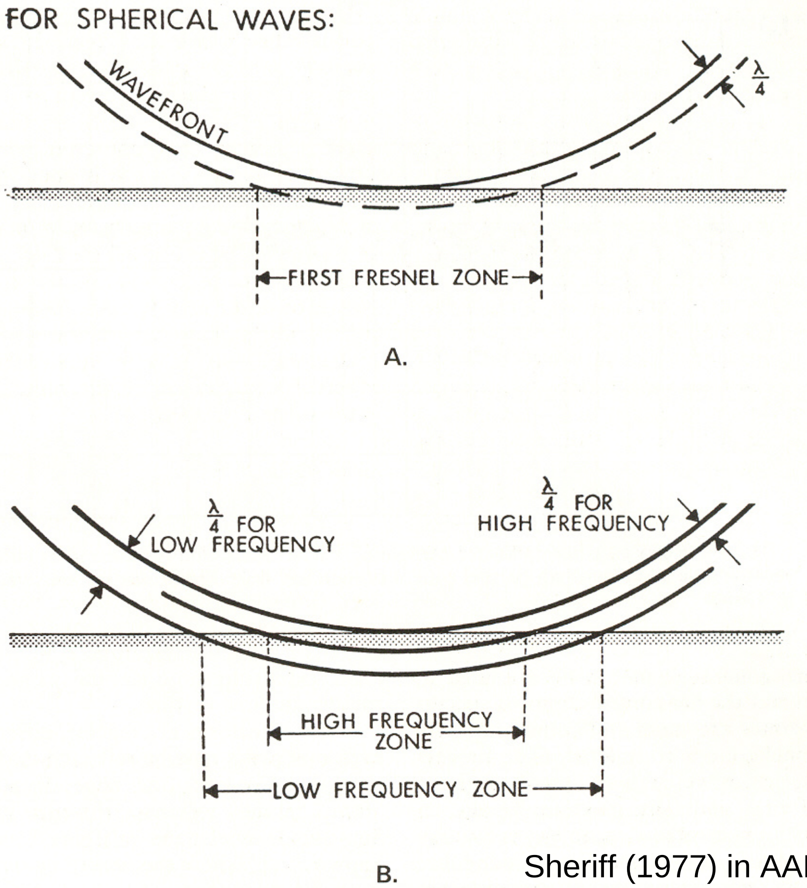


FIG. 7—First Fresnel zone for (A) spherical waves reflected from plane interface. (B) shows how size of the Fresnel zone depends on frequency.

Sheriff (1977) in AAPG Mem.26, p.11

For example, for a plane that reflects interface at a depth of 1,000 m and an average velocity of 2,000 m/sec, the first Fresnel zone has a radius of 130 m for a 60-Hz component and 183 m for a 30-Hz component. For a reflection at 4,000 m with an average velocity of 3,500 m/sec, the first Fresnel zone has a radius of 375 m for a 50-Hz component and 594 m for a 20-Hz component.

A “hole” within a bedding plane

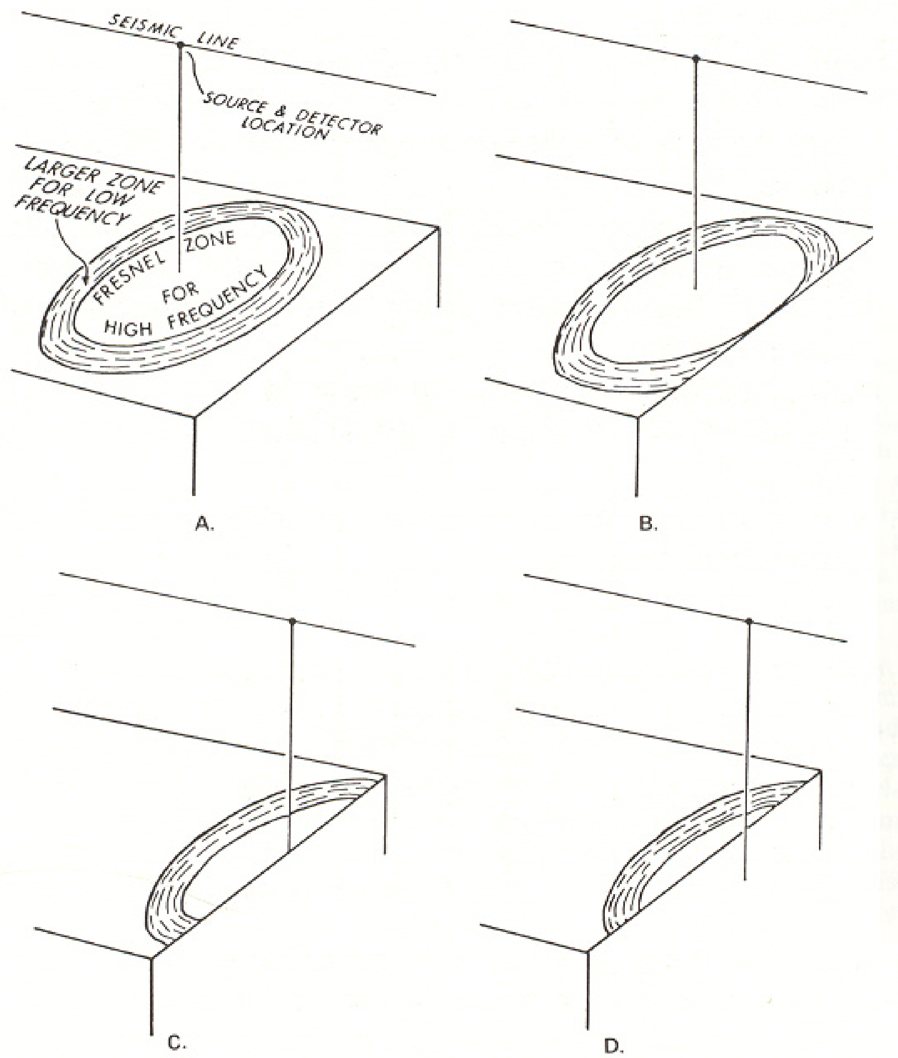


FIG. 9—Fresnel zone explanation for changes in wave-shape produced by edge of feature.

Sheriff (1977) in AAPG Mem.26, p.13

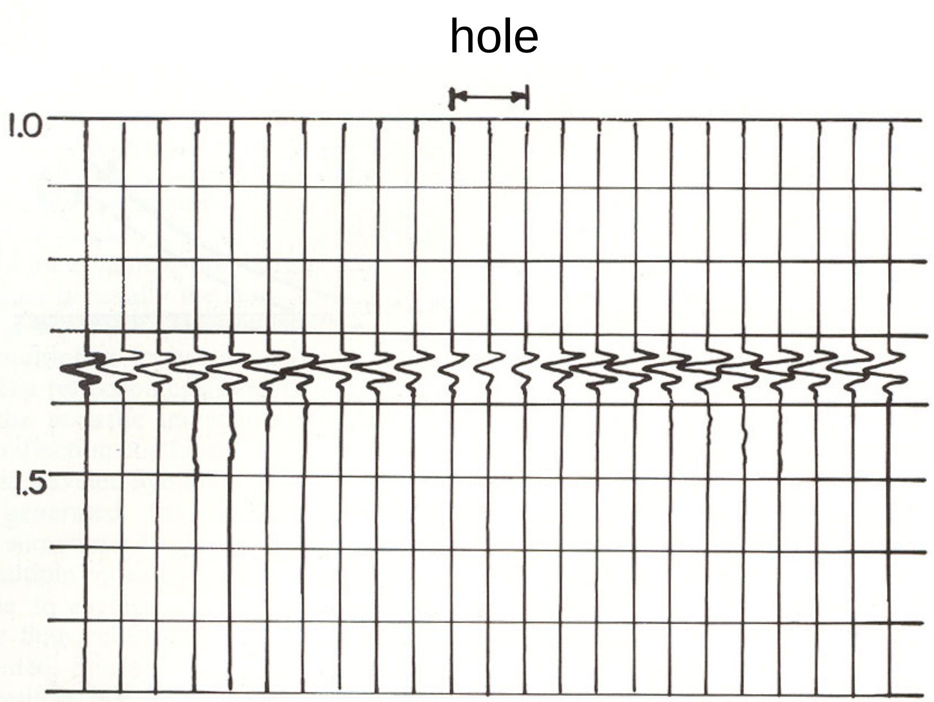


FIG. 8—Reflection from reflector containing a hole. Reflection is observed at hole because hole is smaller than Fresnel zone. Location and hole dimensions are indicated by arrow.

Sheriff (1977) in AAPG Mem.26, p.12

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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 <u>major</u> lithologic boundaries, especially those defined by outcrop sections or wells.

(1)

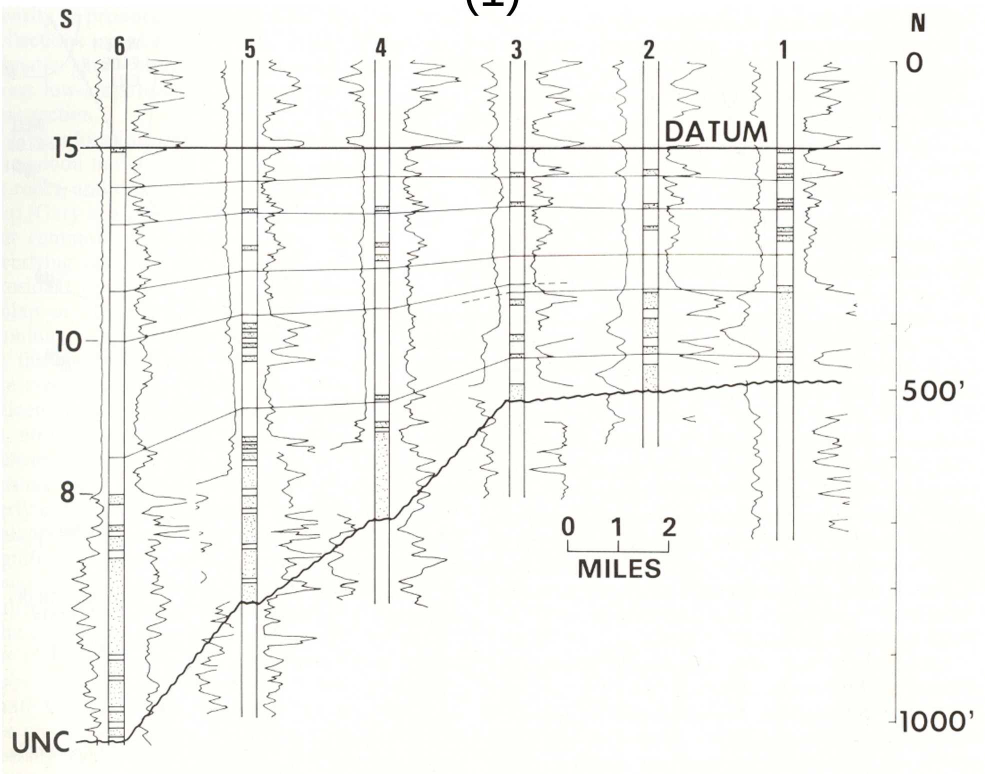


FIG. 2—Geologic cross section showing electric-log correlations, Tertiary example, South America. Stippled pattern in well bore represents sandstone. Key horizons indicated on left.

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

(2)

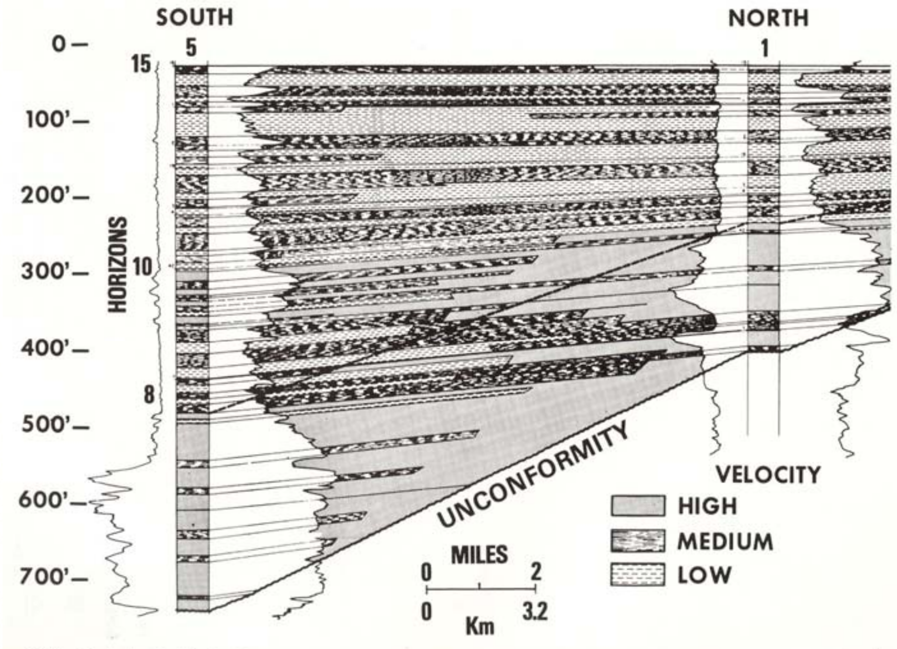
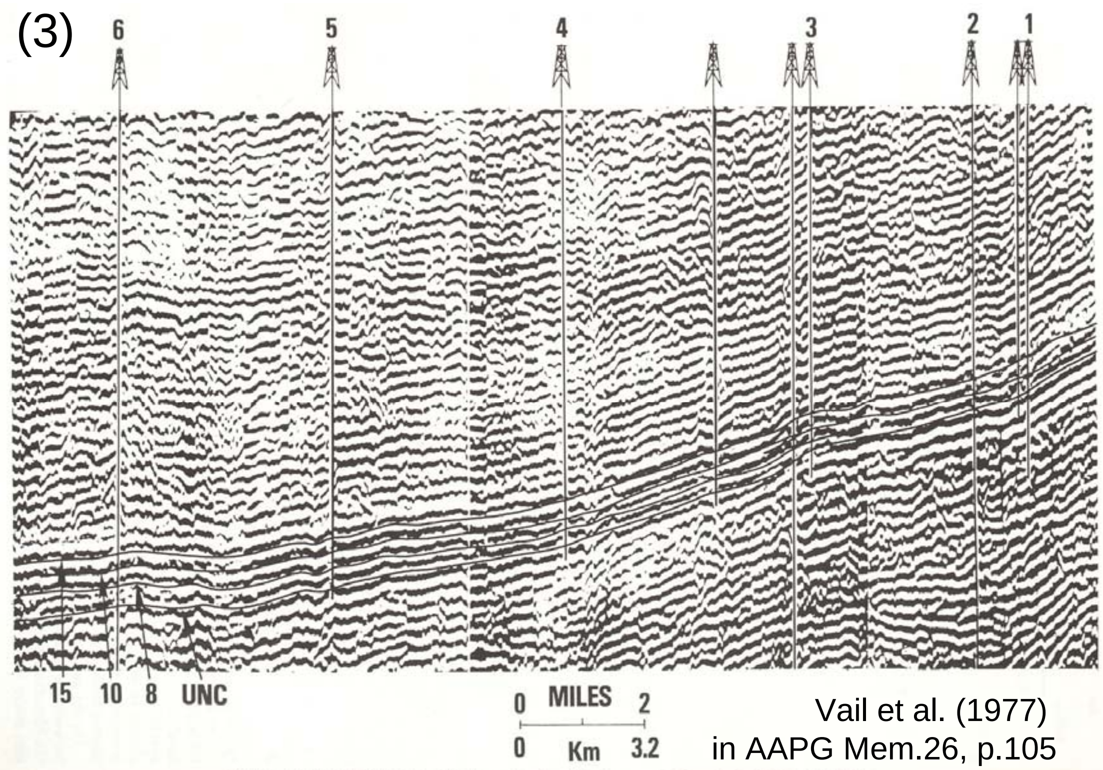


FIG. 3—Distribution of velocity for Tertiary example, South America. Velocity was obtained from CVLs for wells 5 and 1 and distributed laterally using stratal surface correlations.

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)



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.

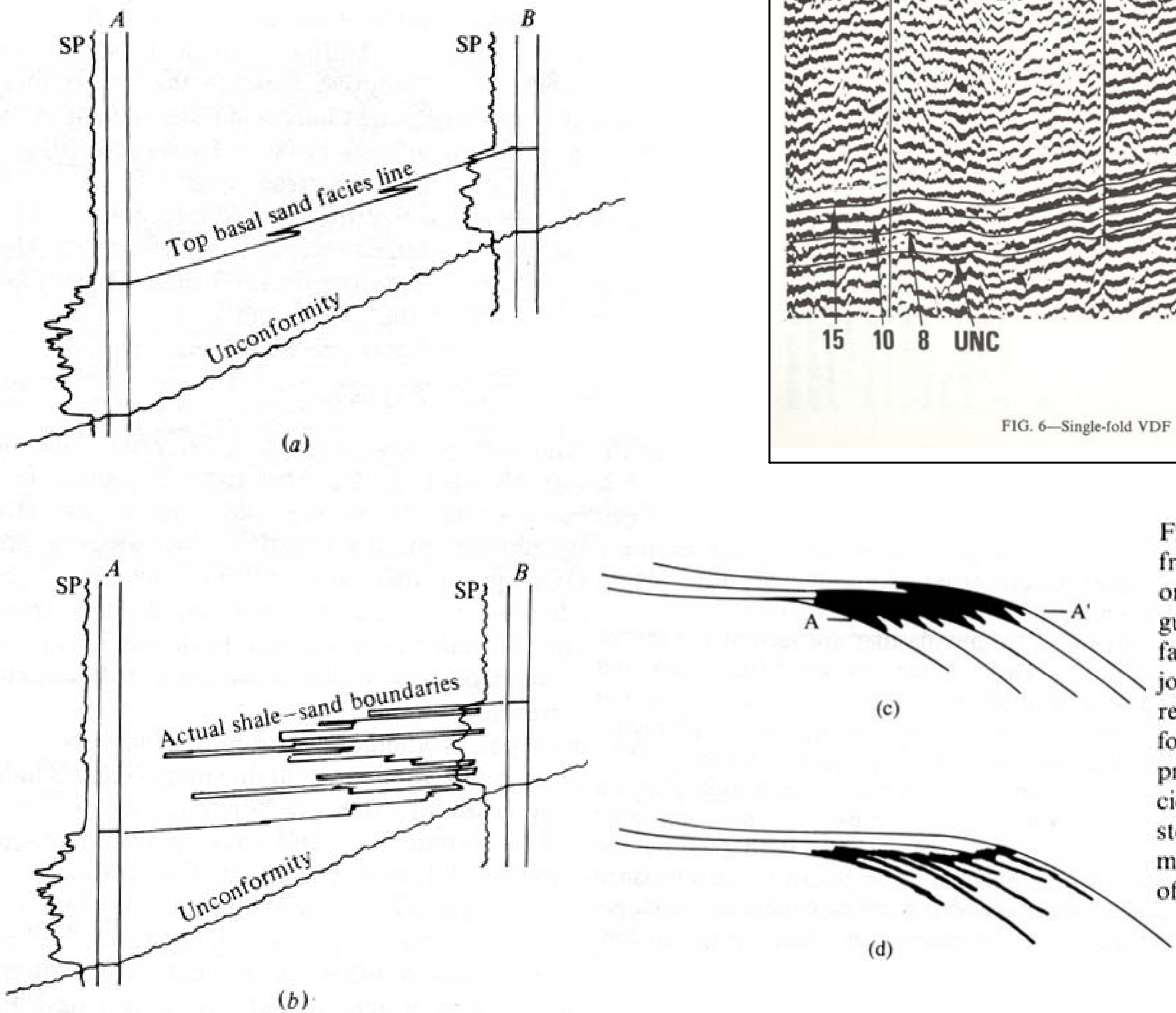


Fig. 10.55 The nature of facies surfaces. (Data for a and b from Vail, Todd, and Sangree, 1977b.) (a) Facies surface based on data from two wells 17 km apart; the *SP*-log curves distinguish the sand from surrounding shale. (b) Redrawing of the facies surface based on intervening well-control points; 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.

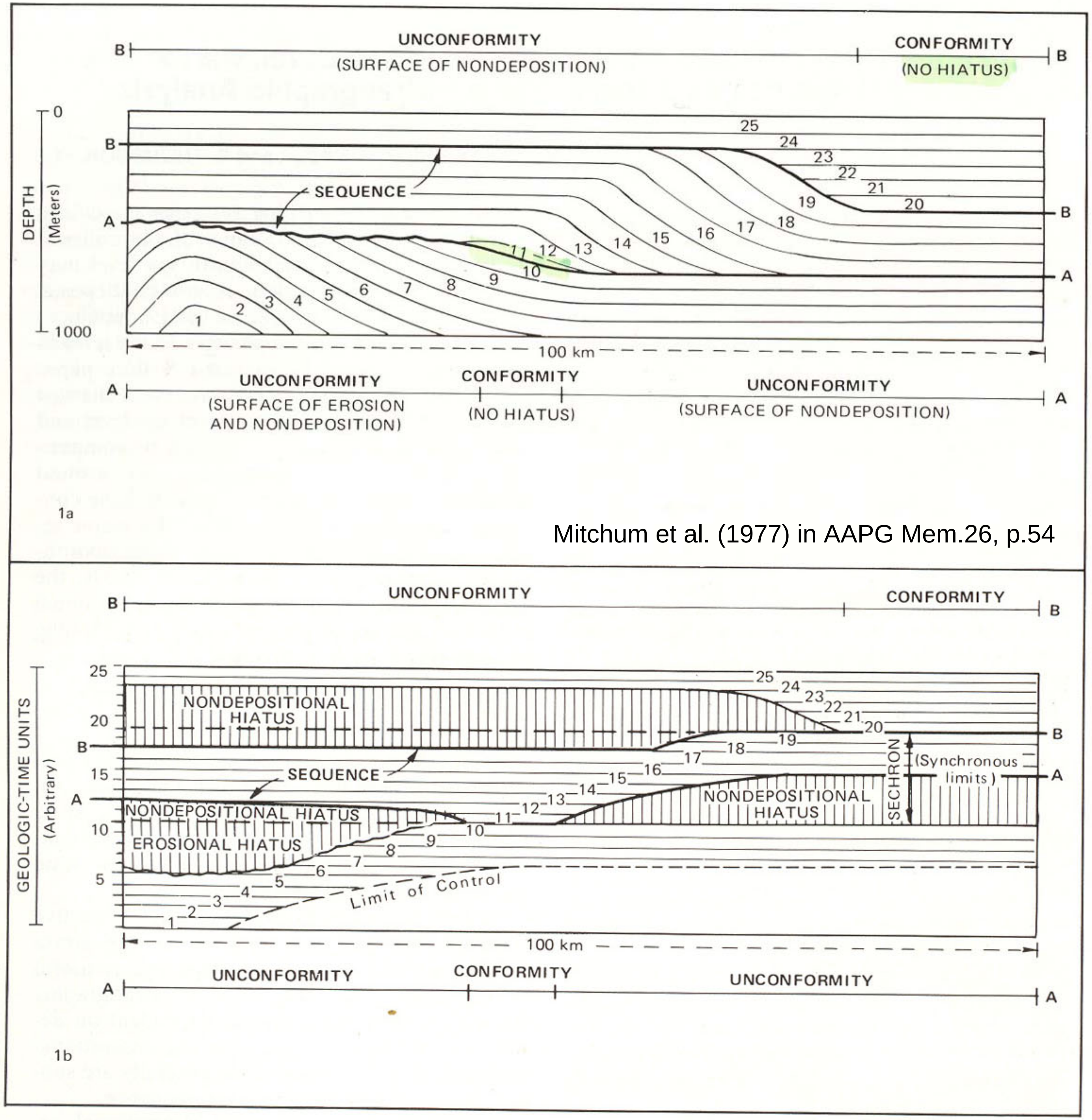
A depositional sequence has chronostratigraphic significance because all the rocks of the sequence were deposited during the interval of geological time defined by the ages of the sequence boundaries where they are conformities.

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

An idealized sequence

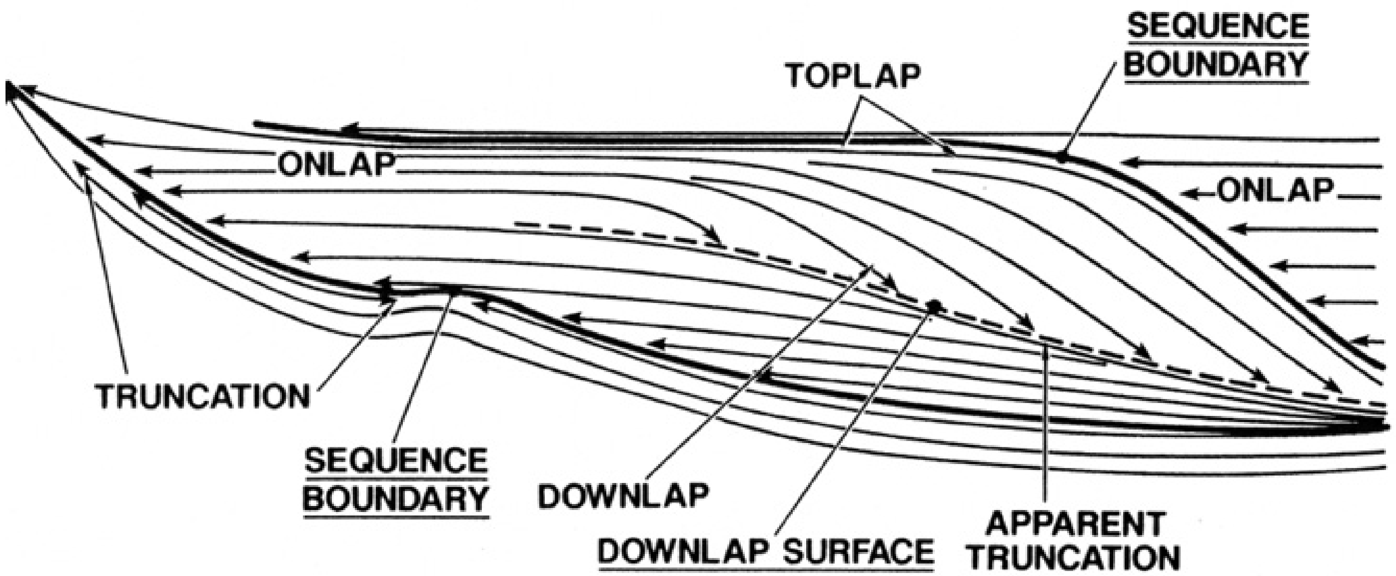


Figure 1. Diagram showing reflection termination patterns and types of discontinuities. Discontinuity names are underlined.

Vail (1987)

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.

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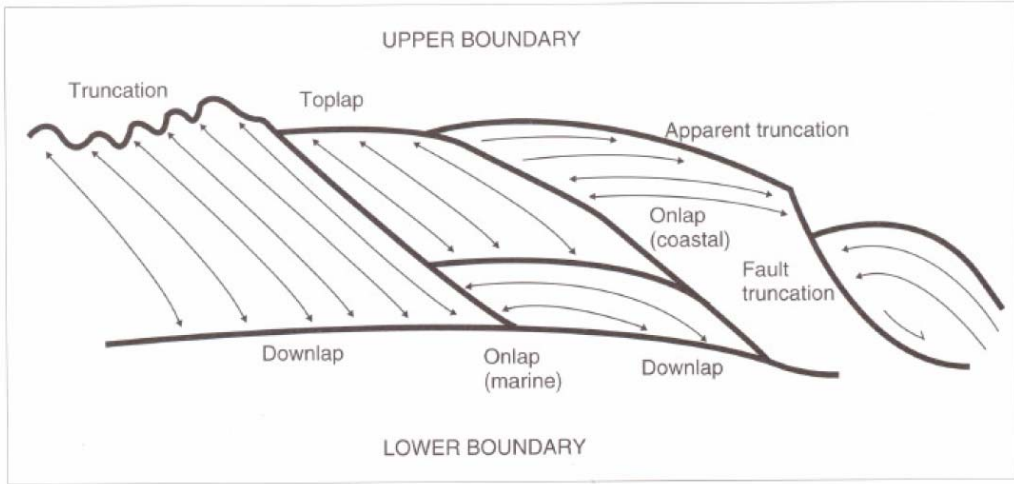
Three main types of reflection discordance

1. Erosional truncation

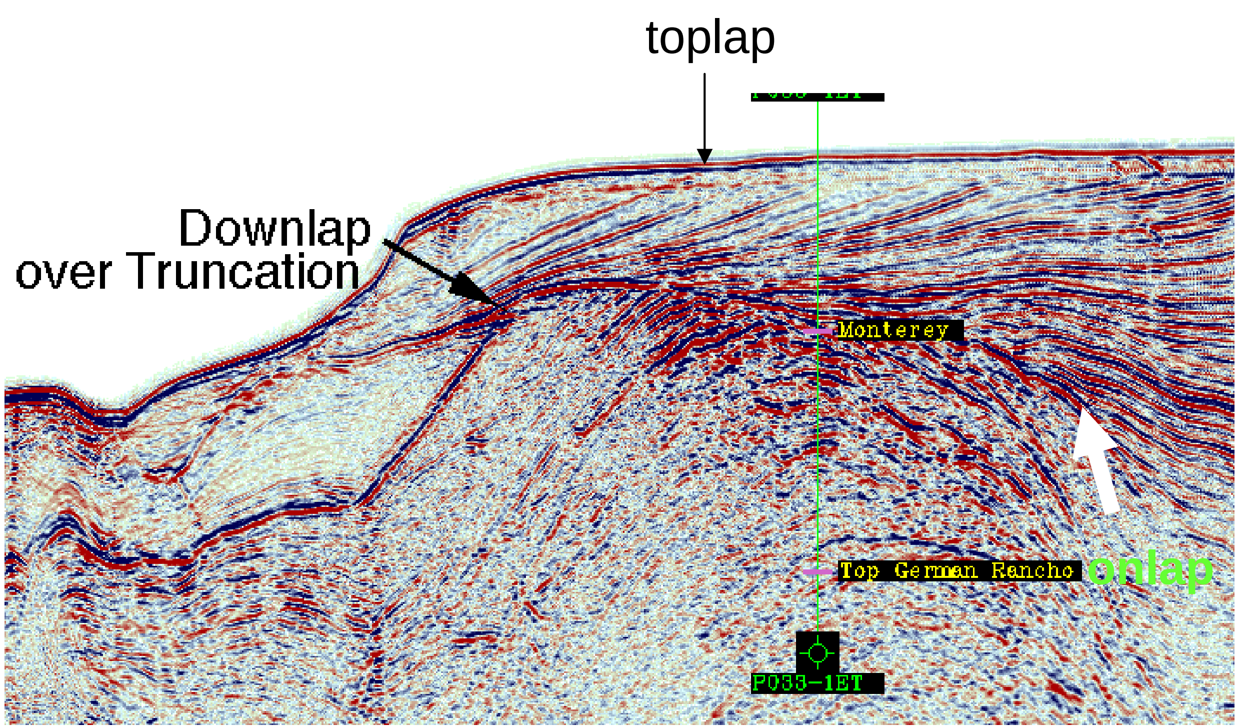
2. Apparent truncation

3. Lapout
   - baselap
     - onlap
     - downlap
   - toplap



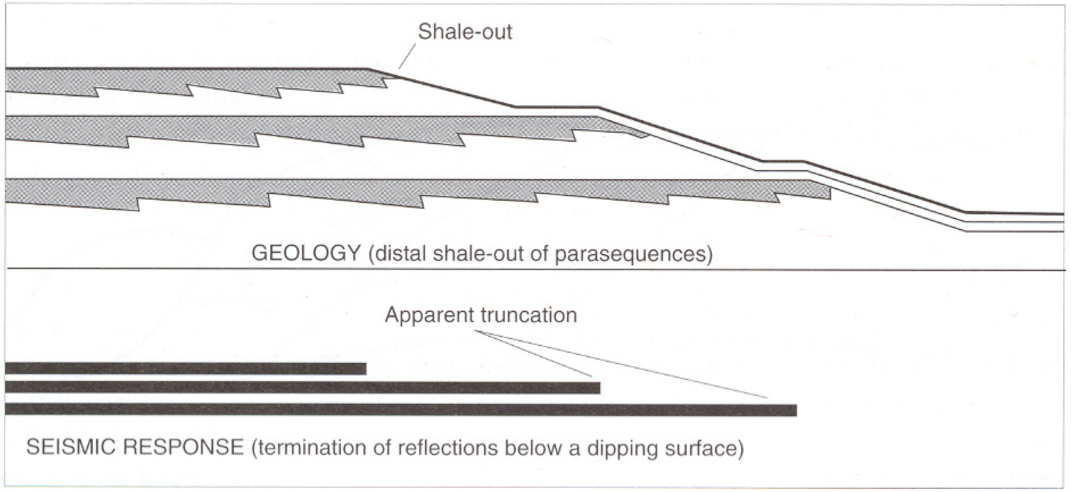
Emery & Myers (1996), p.53

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.

Santa Cruz terrace deposits downlapping onto unconformity.

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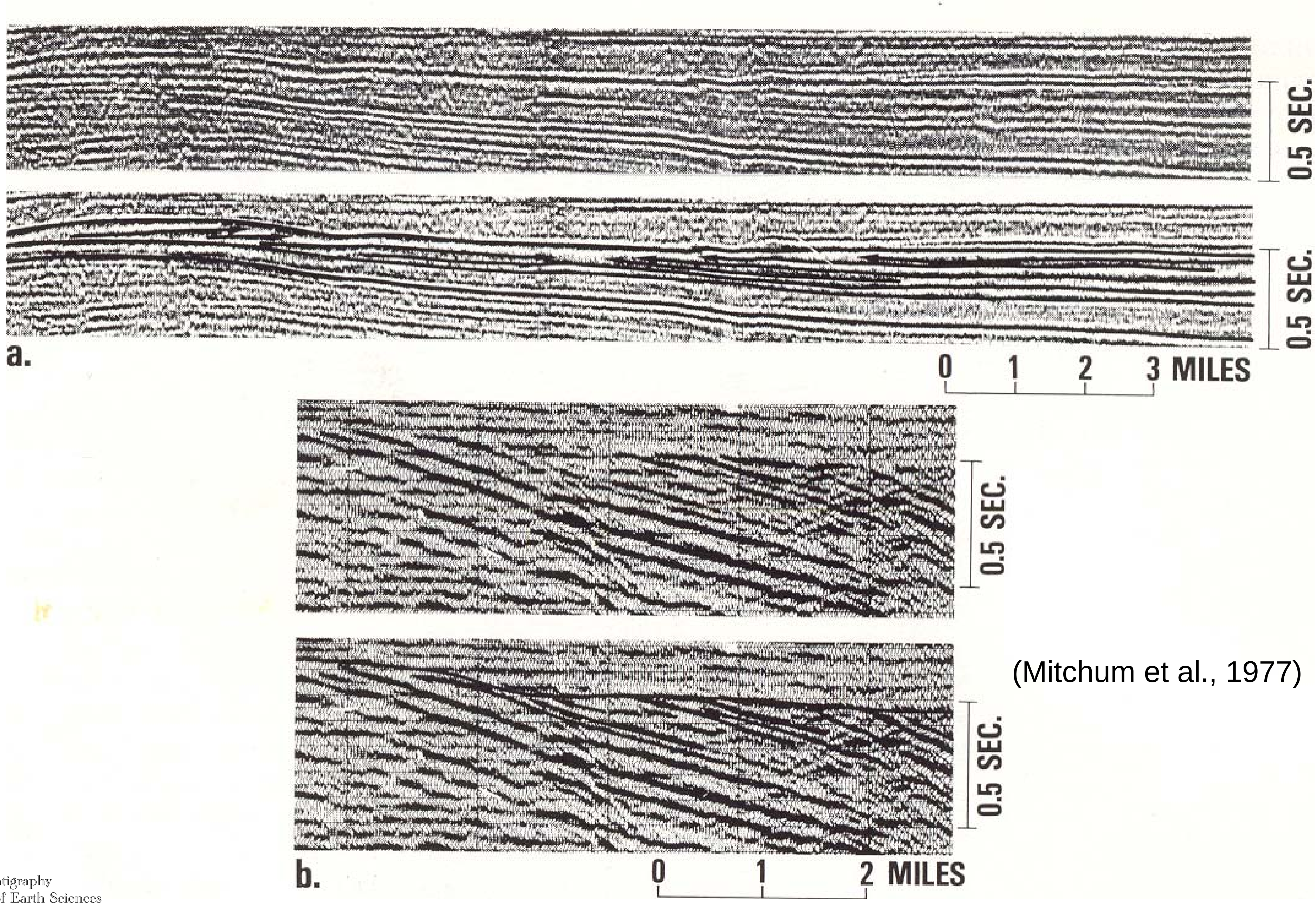
Toplap is the termination of inclined reflections (clinoforms) against an overlying lower angle surface, where this is believed to represent the proximal depositional limit.

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**).

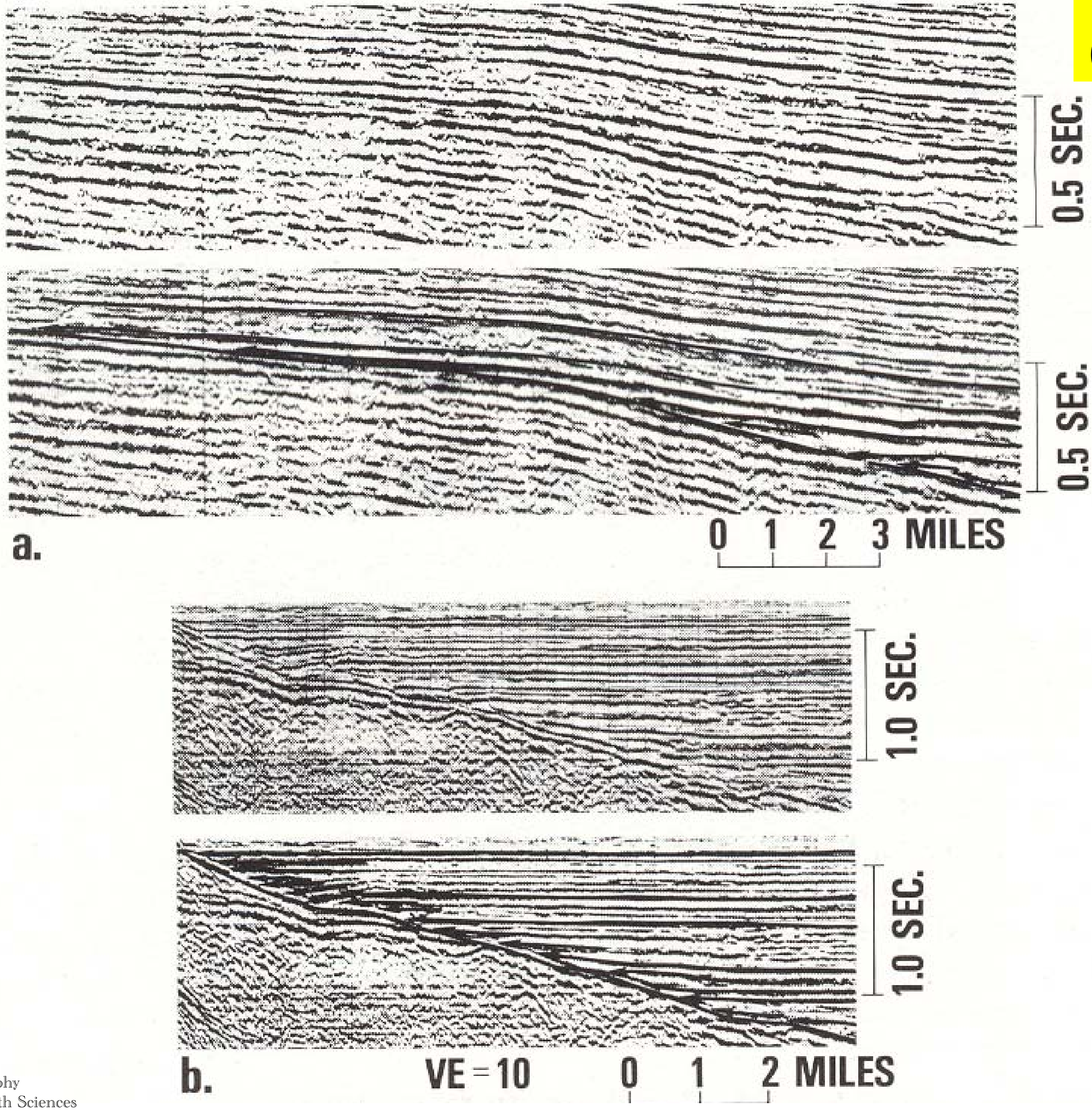
Clinoforms merging into toplap. Peru, a temperate water carbonate of Miocene age.

Examples of erosional truncation



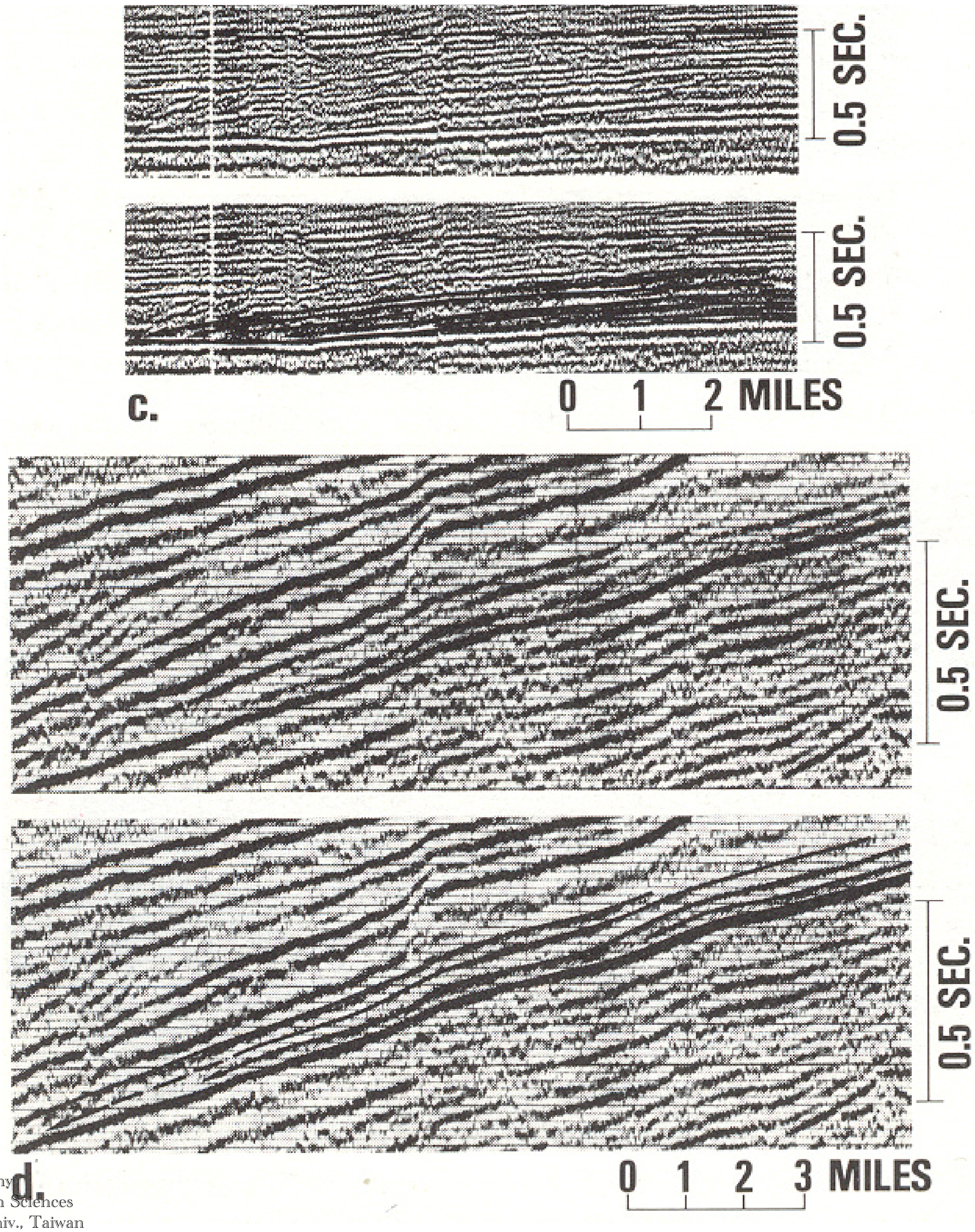
(Mitchum et al., 1977)

Examples of onlap (one kind of baselap)

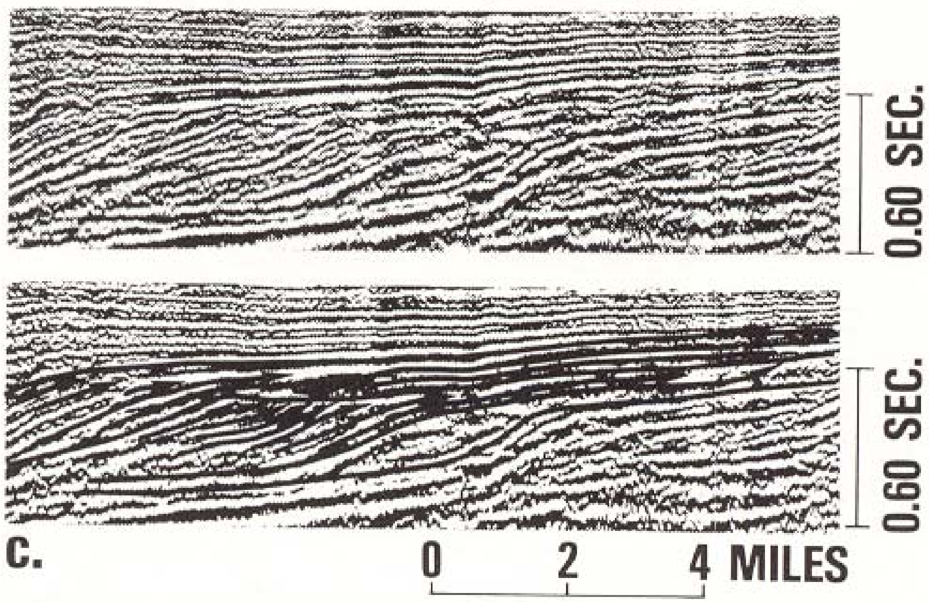


(Mitchum et al., 1977)

Examples of downlap (one kind of baselap)

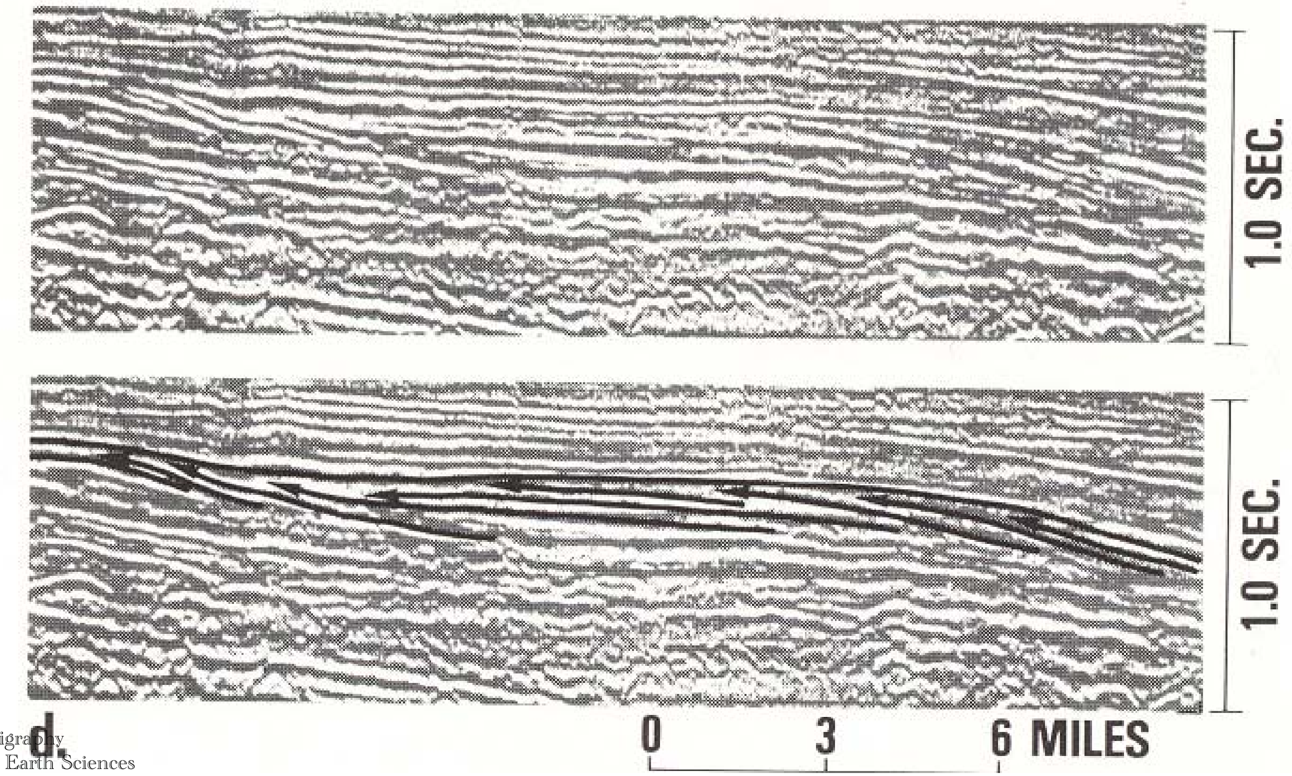


(Mitchum et al., 1977)



c.

Examples of toplap



d.

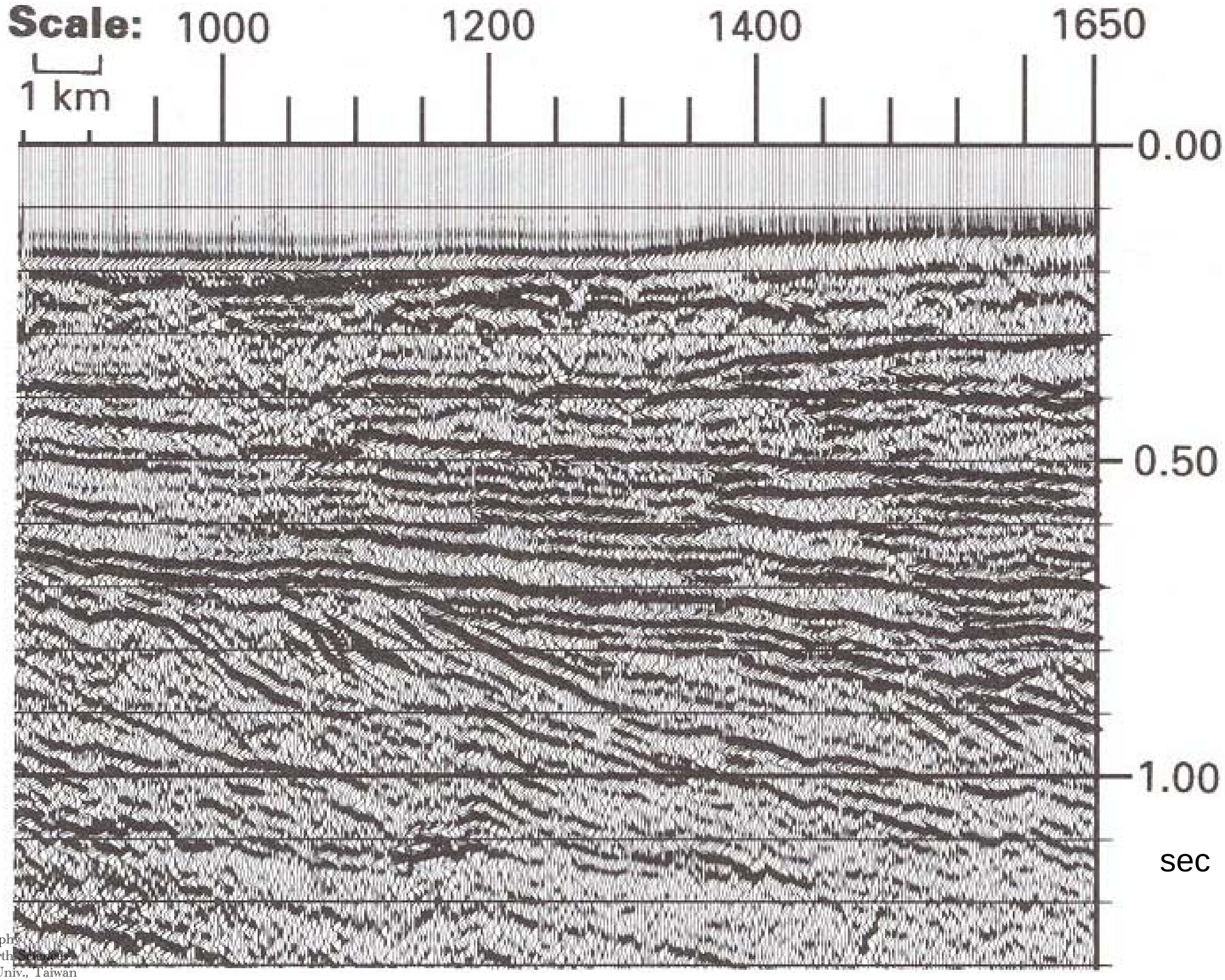
(Mitchum et al., 1977)

Steps in the <u>stratigraphic</u> interpretation of a seismic section

1. Determine the vertical and horizontal scale of the section.
2. Migrated section or not, marine or land data?
3. Identify multiples (e.g., water-bottom multiples, peg-leg multiples etc.) and mark them in light blue by convention.
4. Identify and mark reflection terminations or unconformities (e.g. onlap, downlap, truncation etc.) with arrowheads (by convention use a red pencil).
5. Identify *seismic surfaces* on the basis of reflection terminations (A seismic surface is a line on a seismic section where reflections terminate in a consistent manner.). In initial stages, mark seismic surfaces in yellow colour by convention. Then assign specific colour to individual seismic surface based on its type (e.g. sequence boundary, transgressive surface, maximum flooding surface etc.) or age in later stages of stratigraphic interpretation.
6. Identify sequence boundaries. Sequence boundaries are commonly marked by truncation or onlap, whereas maximum-flooding surfaces are commonly marked by downlap.
7. Carry out a similar exercise on other intersected seismic lines and tie the seismic surfaces and interpretation (i.e., ensure that the interpretation is consistent where lines cross) around the data set.
8. Mapping sequence units on the basis of thickness, geometry, orientation, or other features to see how each sequence relates to neighboring sequences.
9. Identify seismic facies for each sequence.
10. Interpretation of depositional environments and lithofacies.

Practical:
On the following figure, overlay a piece of tracing paper and do the following:
1. Pick reflection terminations;
2. Draw lines of seismic surfaces.

The seismic data is from the Outer Moray Firth, central North Sea, showing the seismic stratigraphy of the post-Palaeocene section. The surface at around 0.7 second is dated as close to the top of the Miocene, and the high-relief surfaces in the shallower section are interpreted as glacial lowstand surfaces in the Pliocene-Pleistocene.



Sequence Stratigraphy
Department of Earth Sciences
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10.5 Seismic facies analysis

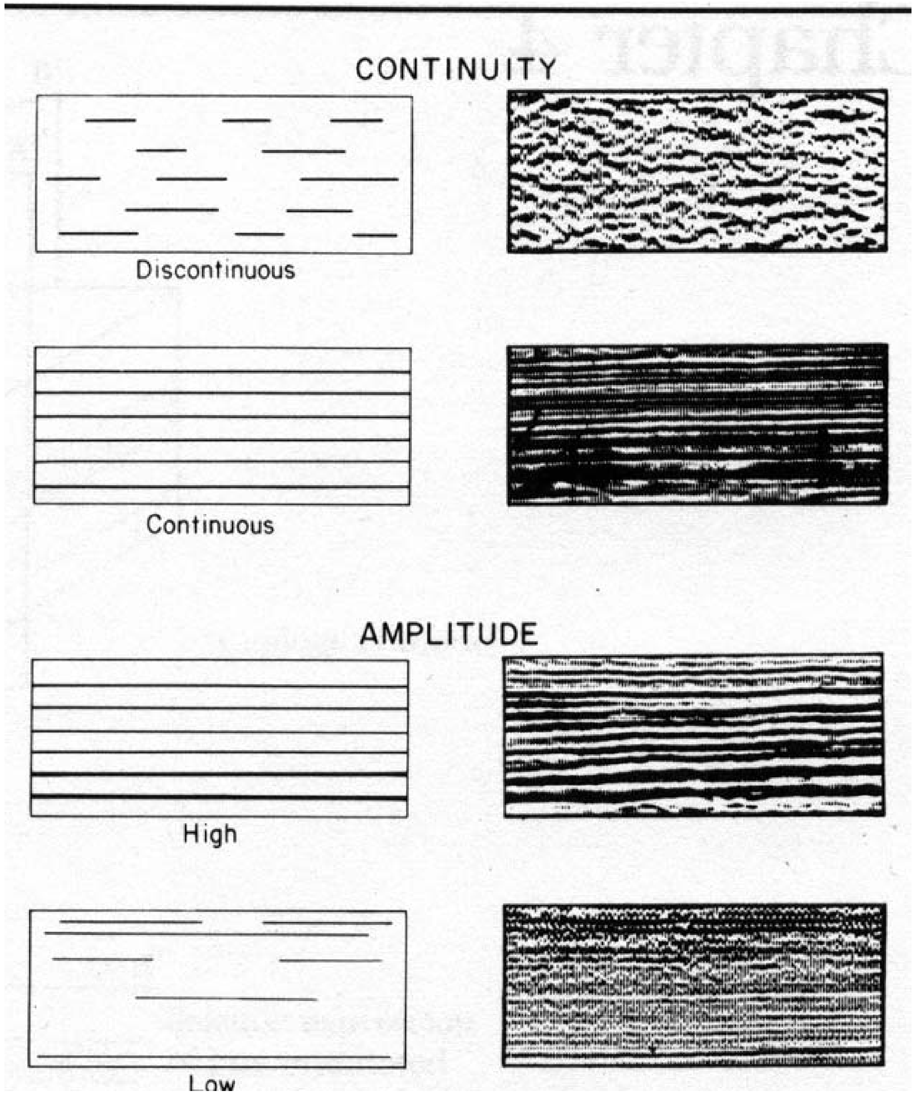
Seismic facies analysis takes the interpretation process one step beyond seismic sequence analysis by examining within sequences smaller reflection units that may be the seismic response to lithofacies.

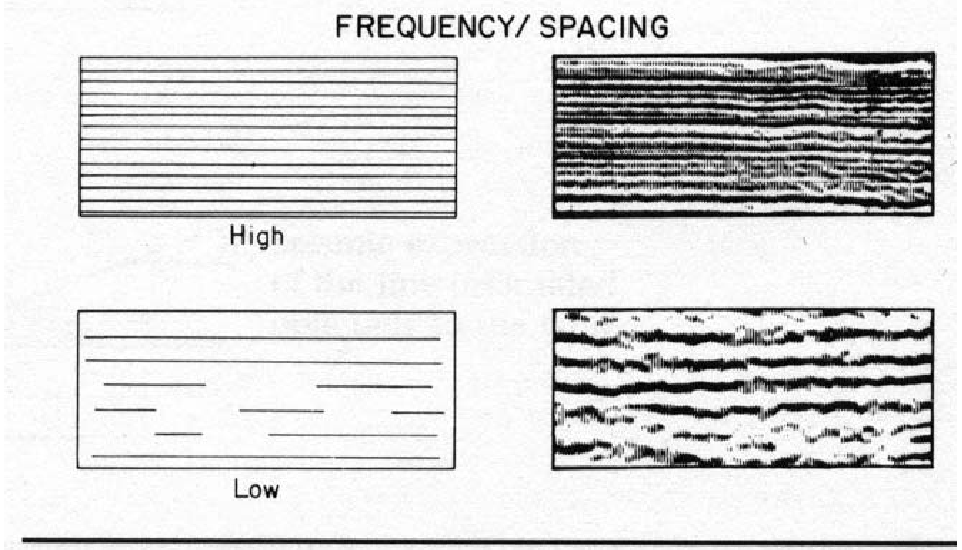
Seismic facies are packages of reflectors with a set of seismic characteristics differing from adjacent units (similar to definition of a “formation”-must be distinguishable from adjacent units and mappable on earth's surface).

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

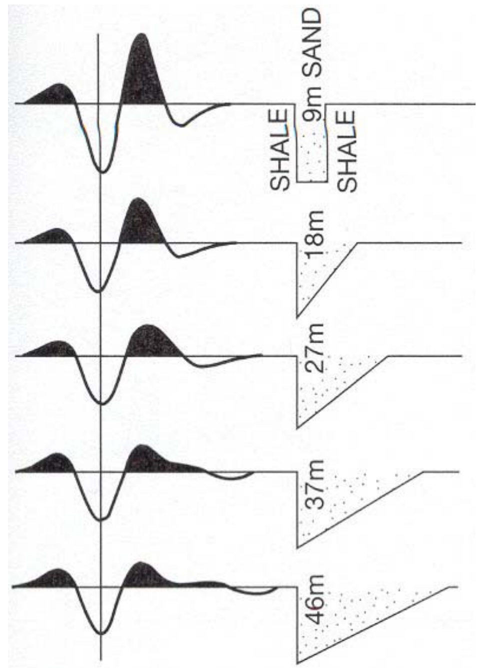
1. An understanding of the effects of lithology and bed spacing on reflection parameters: **amplitude, frequency, continuity of reflections**.

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)



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

Presence of gas may cause "bright spots" effect.

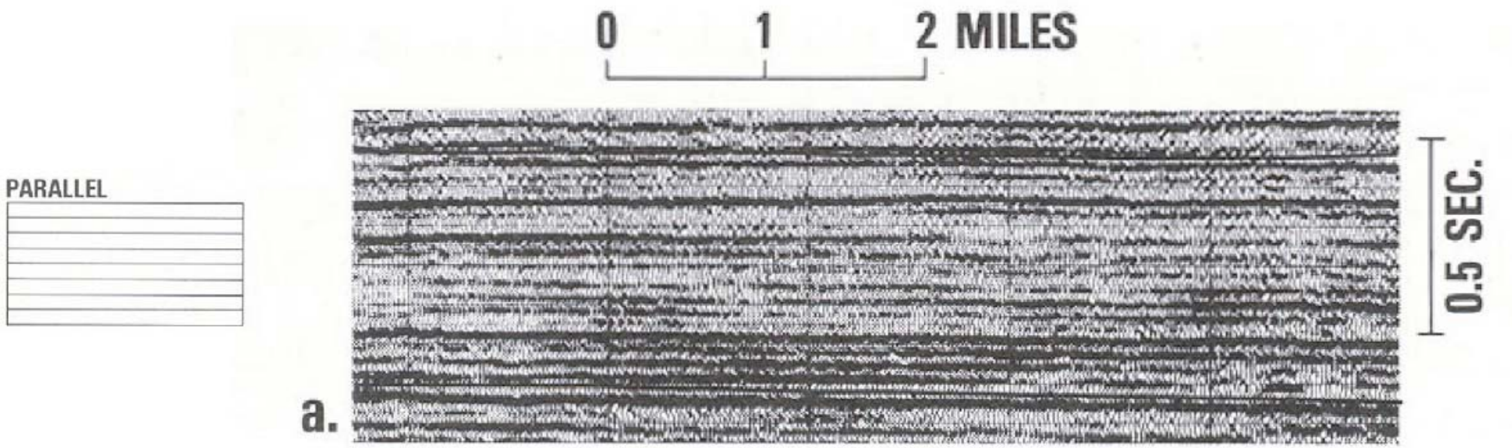
2. Parallelism of reflection cycles to gross bedding, and therefore, to physical surfaces that separate older from younger sediments : **Reflection configurations**.

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

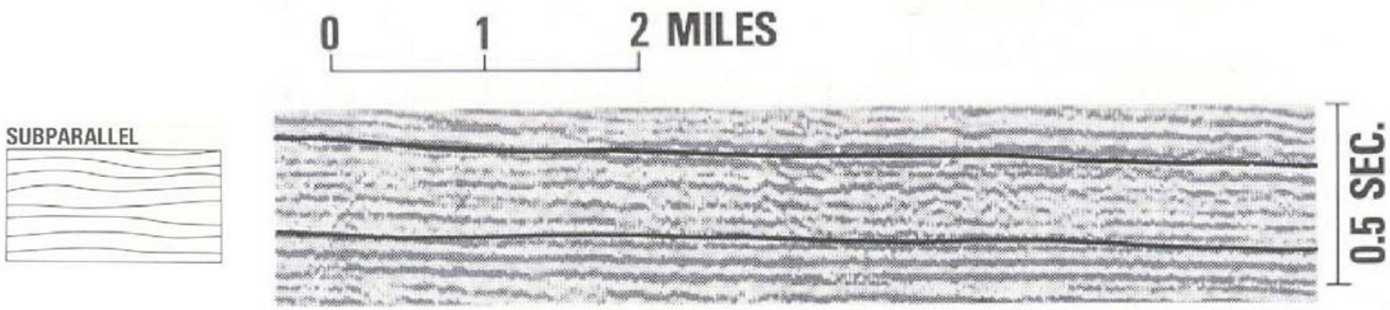
Feature of Reflectors	**Geological Interpretation** (Sangree Widmier, 1979)
Reflection Configuration (pattern)	Stratification patterns, Depositional processes, Erosion and paleotopography
External form and **areal association** of seismic facies units	Gross depositional environment, Sediment source,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

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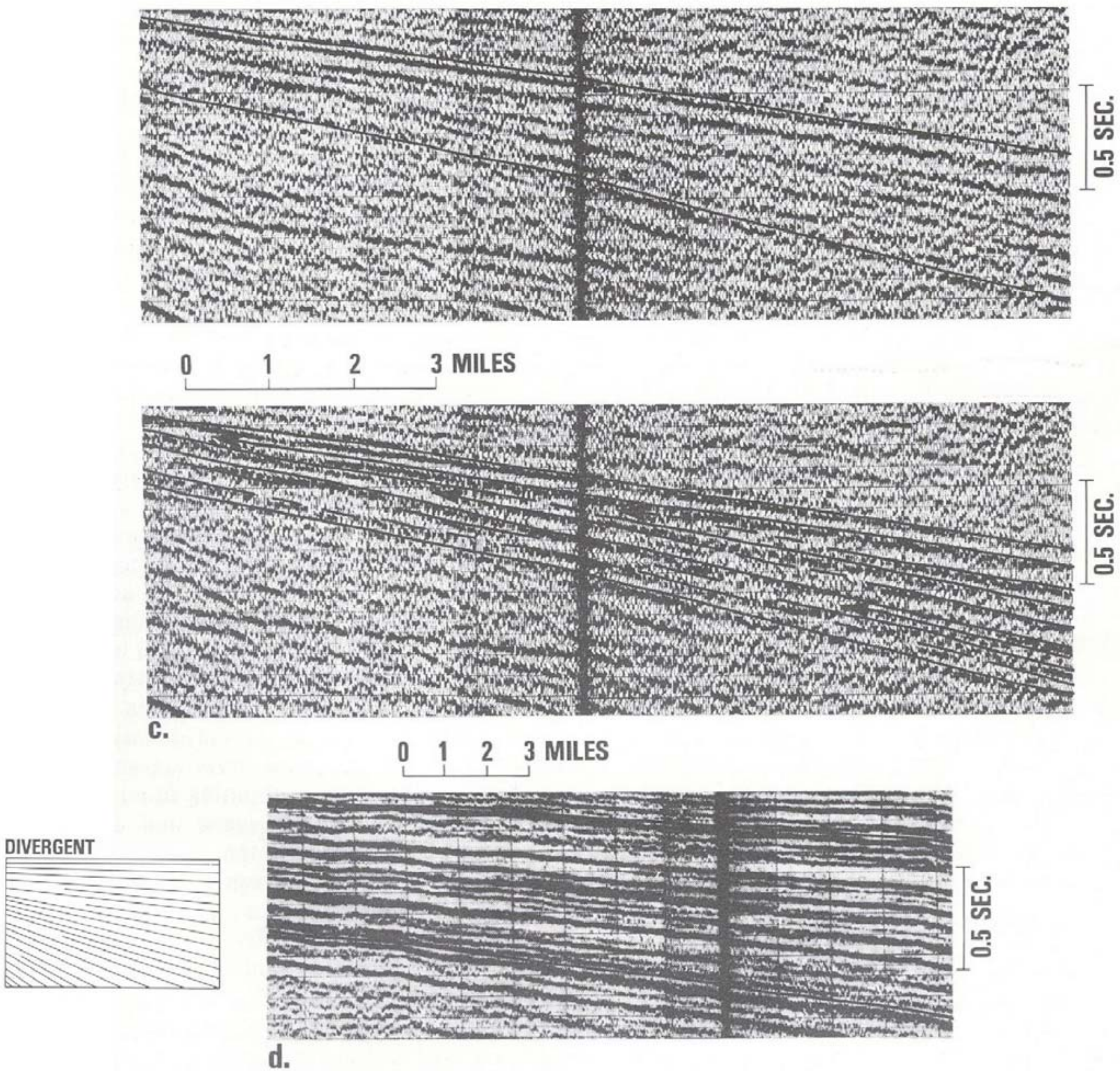


Divergent configurations, with thickening of individual reflection cycles in direction of divergence.

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.**

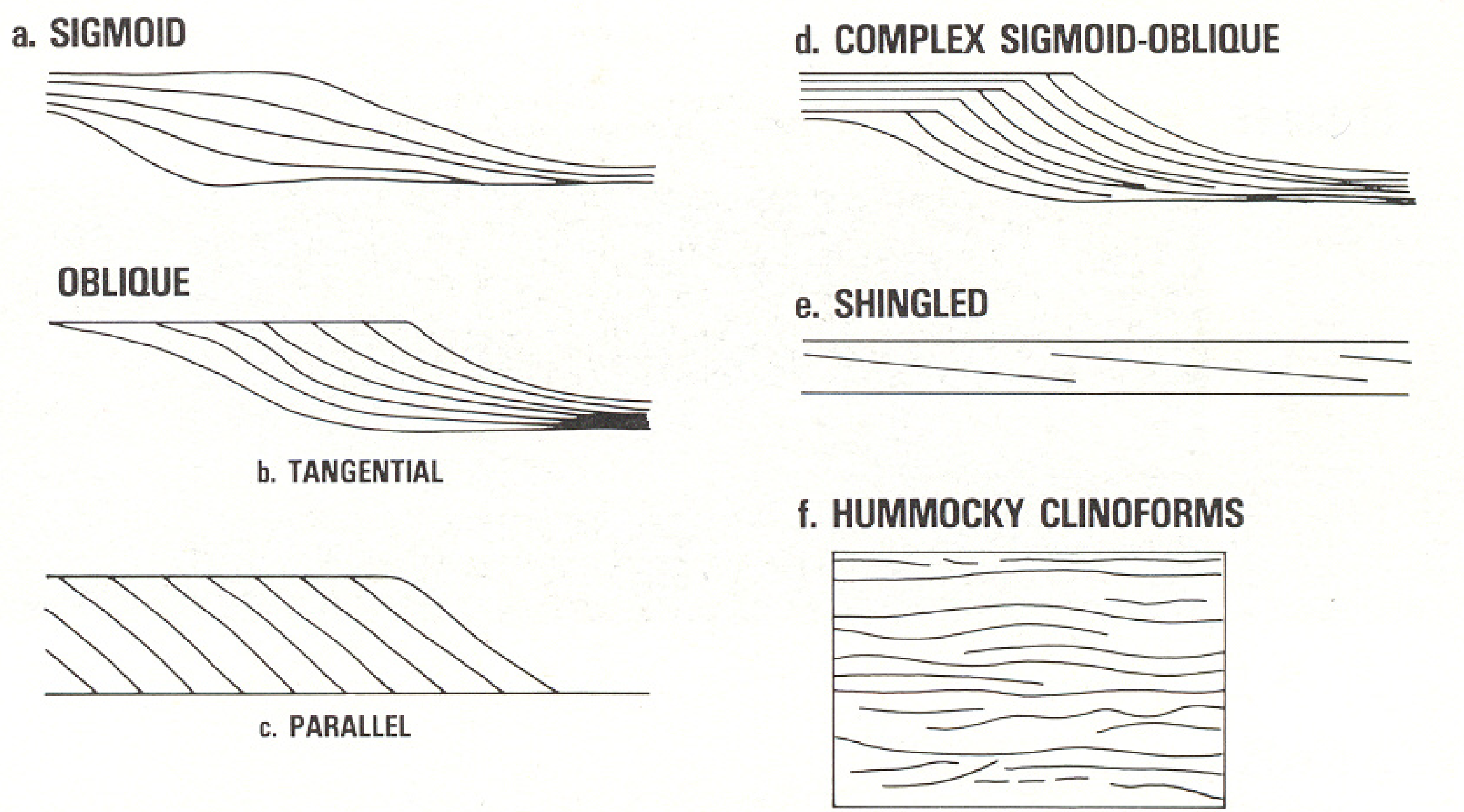
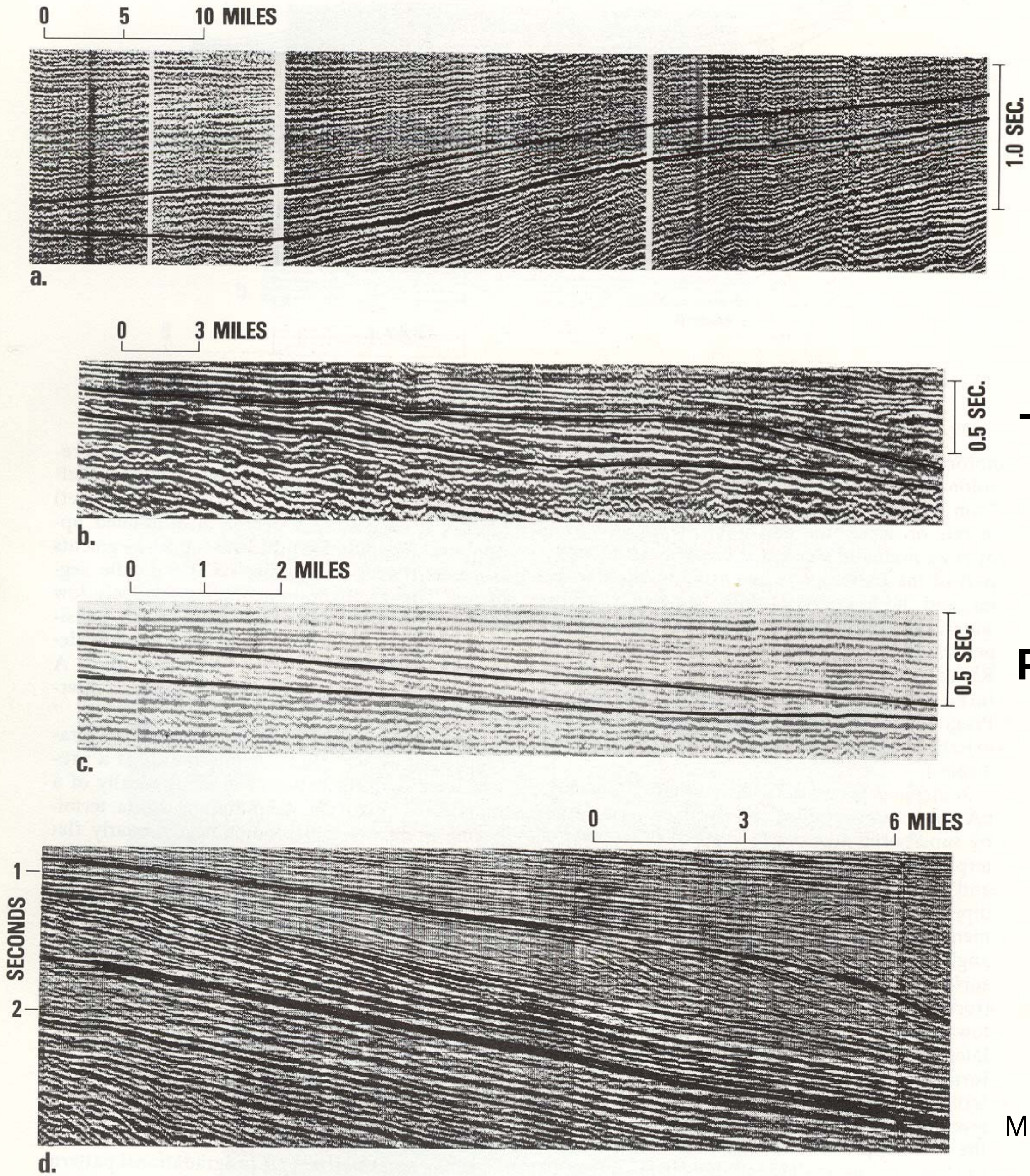


FIG. 6—Seismic reflection patterns interpreted as prograding clinoforms.

Mitchum et al. (1977), p.125

Examples of prograding configuration pattern



Sigmoid

Tangential oblique

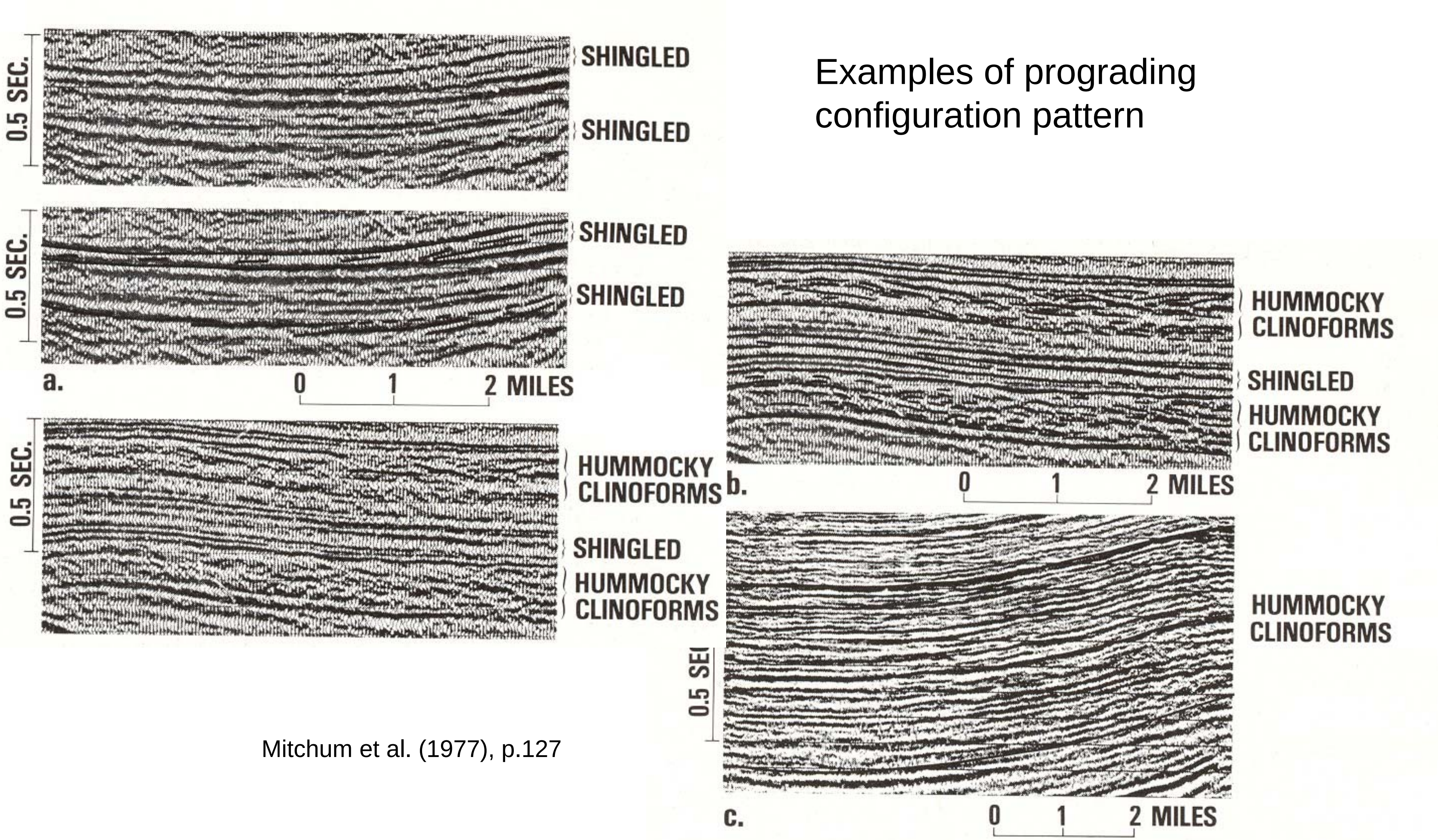
Parallel oblique

Complex sigmoid-oblique

Mitchum et al. (1977), p.126

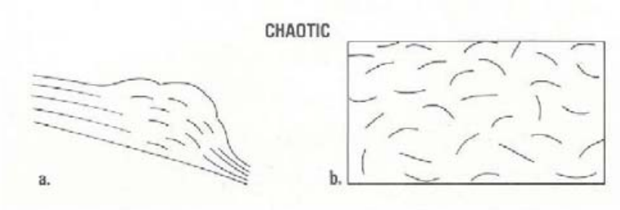
FIG. 7—Examples of sigmoid, oblique, and complex sigmoid-oblique seismic reflection configurations: **a** is sigmoid, **b** is mostly tangential oblique with some sigmoid, **c** is mostly parallel oblique, **d** is complex sigmoid-oblique.

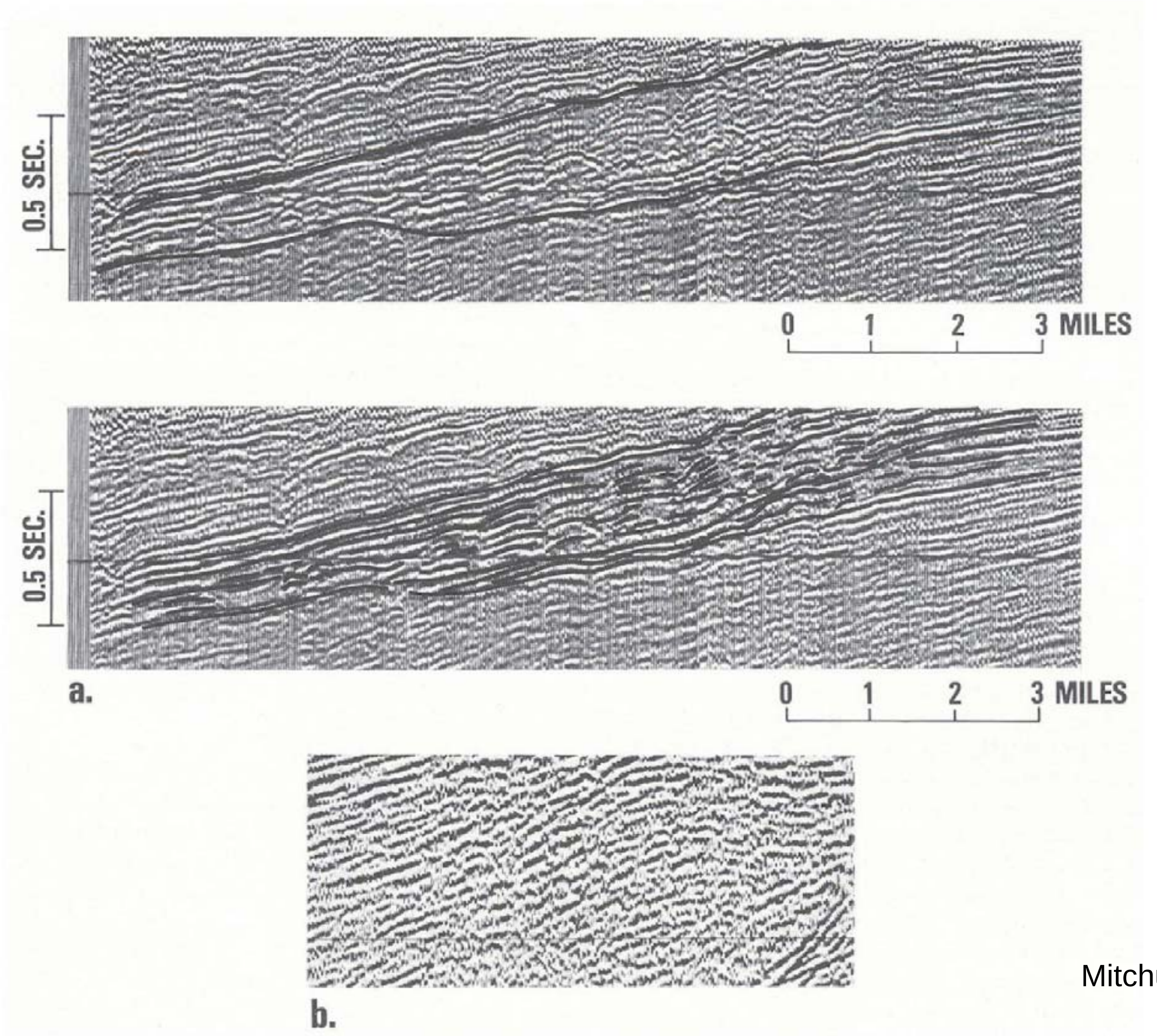
Examples of prograding configuration pattern



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.

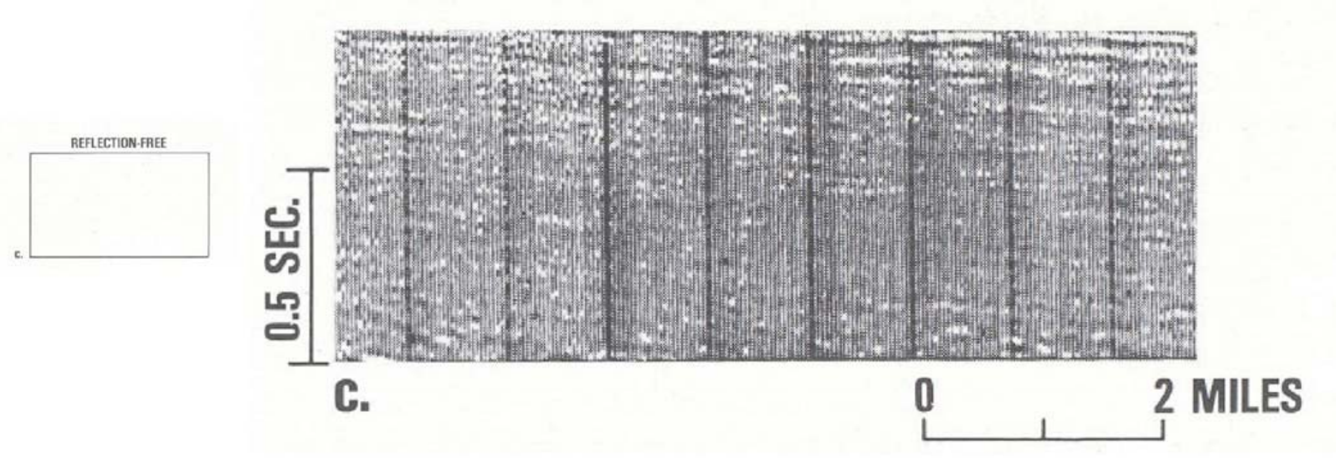




Chaotic seismic configuration. In (a) reflections may be interpreted as contorted stratal surfaces; in (b) no stratal patterns may be reliably interpreted.

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

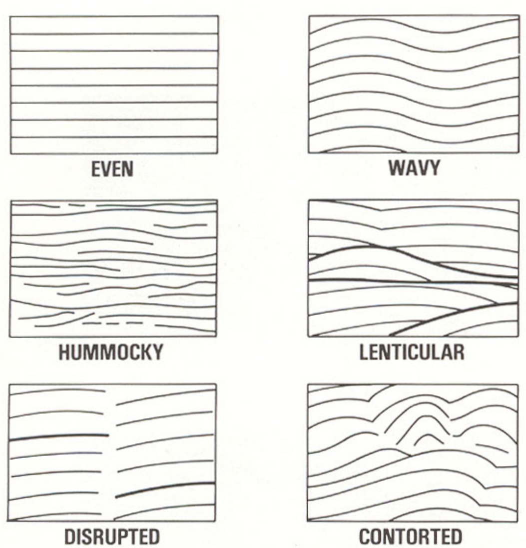
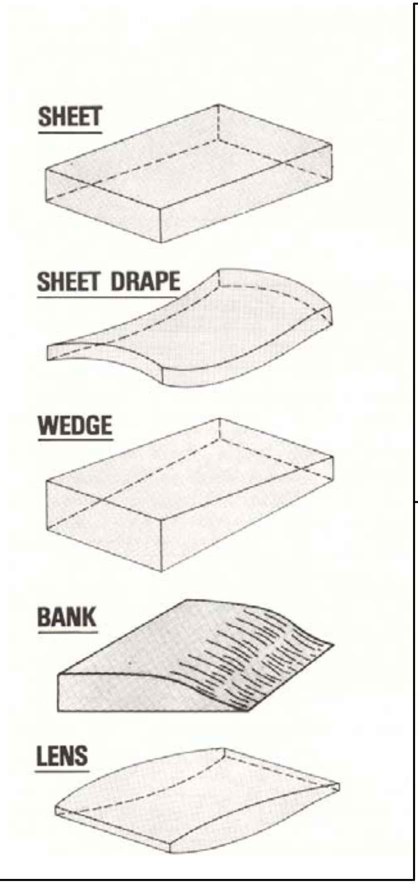
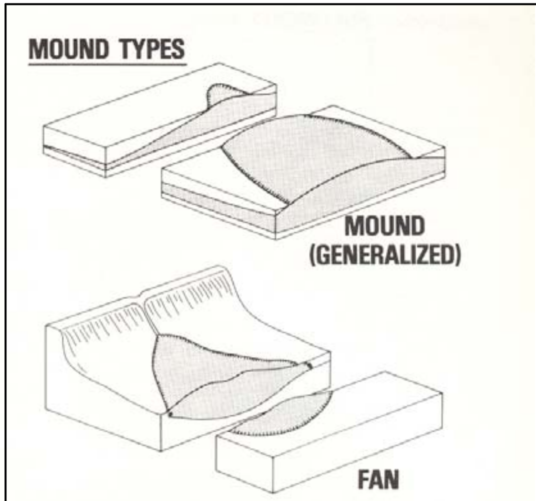


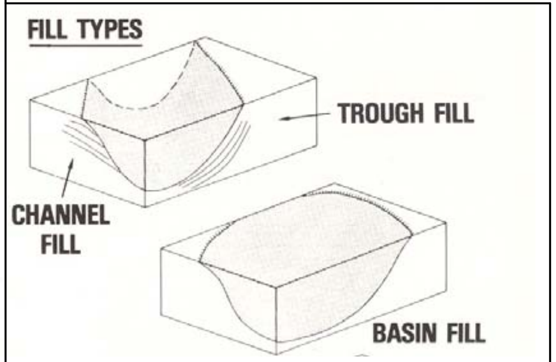
FIG. 11—Some modifying seismic reflection configurations.

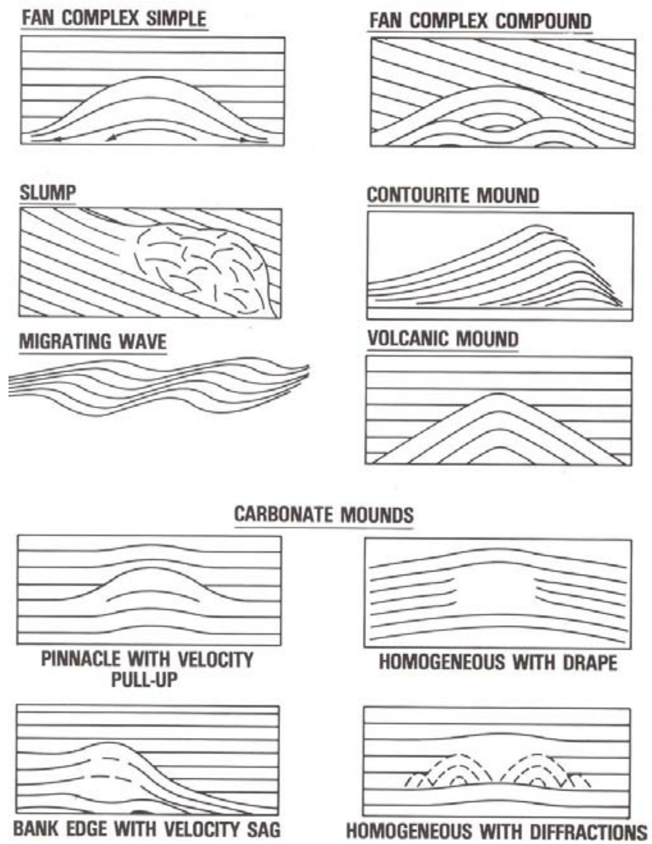
Mitchum et al. (1977), p.130

External forms of seismic facies units



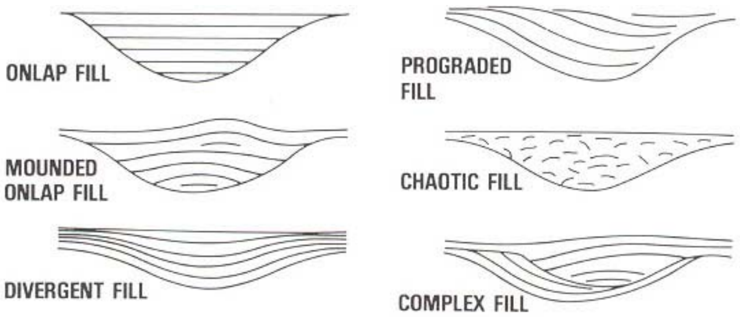






Sediment waves

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



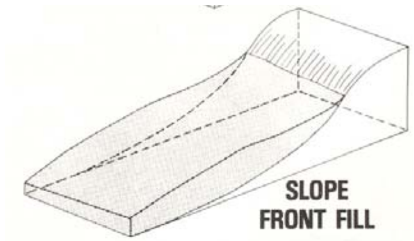


FIG. 15—Some fill seismic facies units.

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

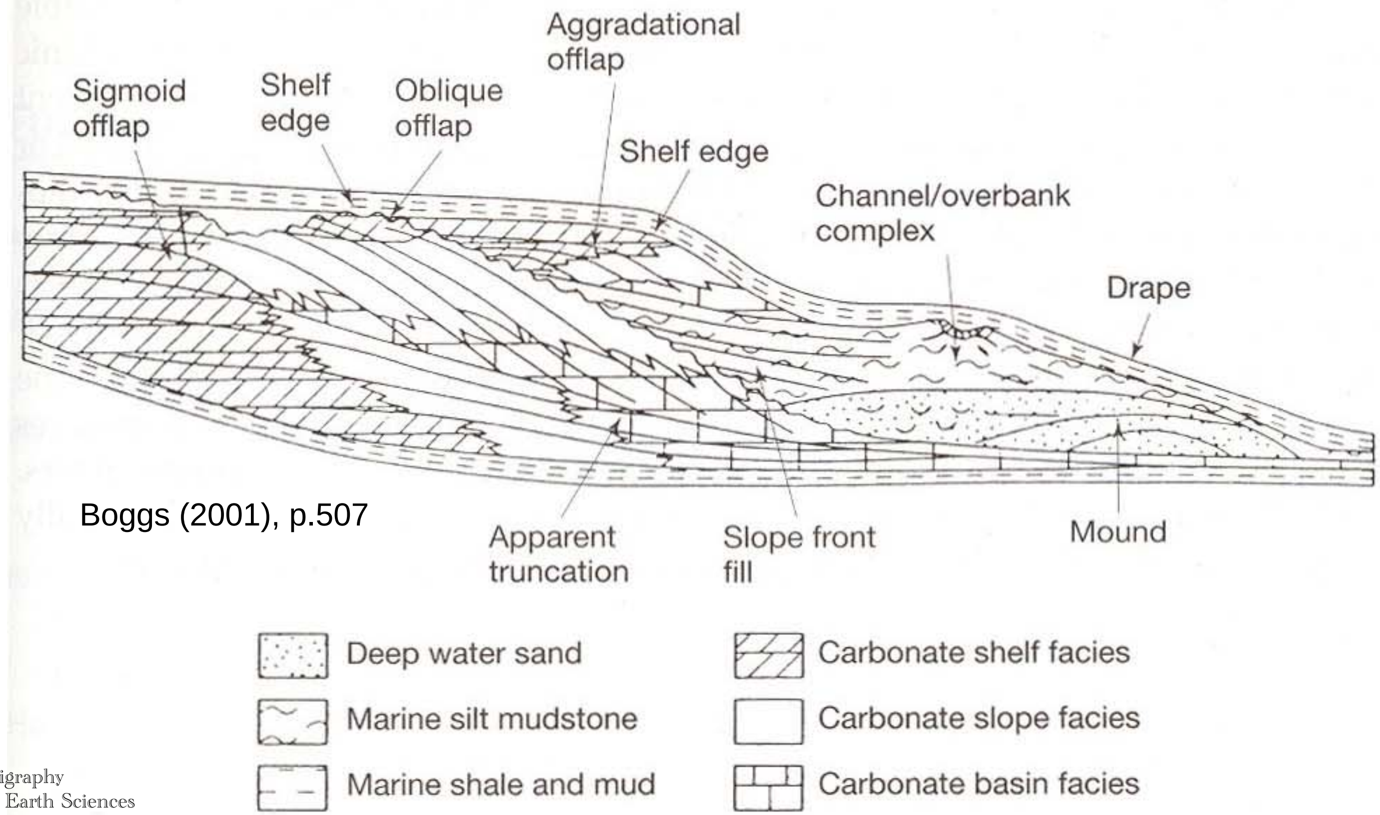
Mitchum et al. (1977), p.118

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:

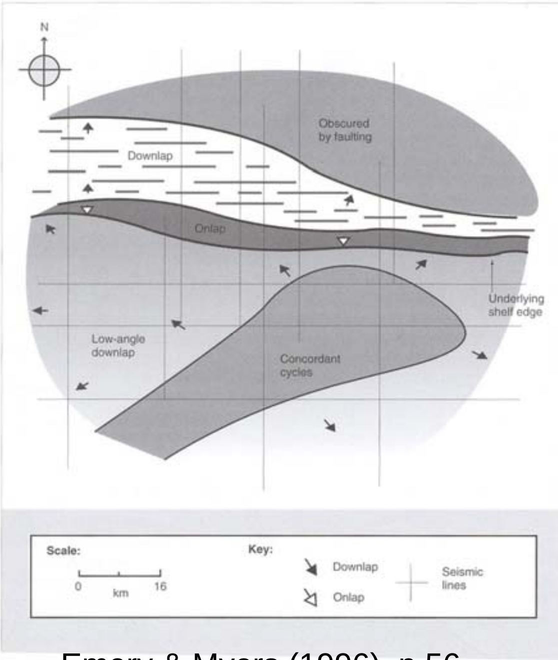


Fig. 3.11 An example of a seismic facies map (from Mitchum and Vail, 1977). This map shows reflection terminations at the base of a Lower Cretaceous package, offshore western Africa

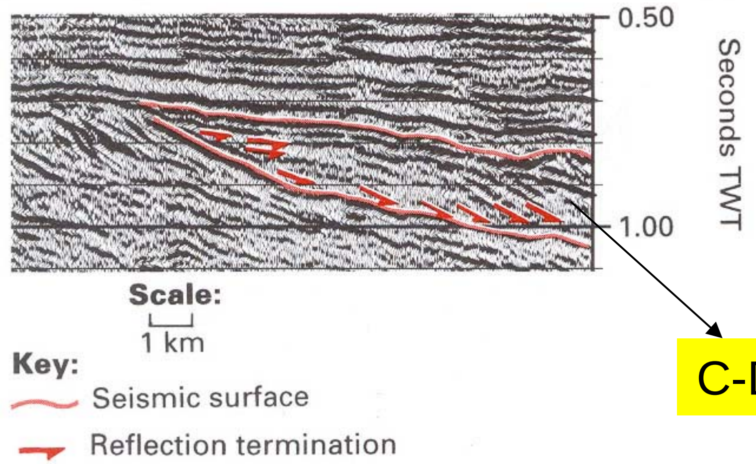
Emery & Myers (1996), p.56

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



C-Dwn/Ob

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

Summary of seismic facies characterized by parallel and divergent reflection configurations

Properties of seismic facies	Depositional environments/Settings: Shelf/Platform	Delta platform: DELTA FRONT/DELTA PLAIN	Alluvial plain/ Distal fan delta	Basinal plain
Reflection configuration	Parallel/slightly divergent; highly divergent near rare growth faults	Parallel/slightly divergent on shelf; highly divergent near growth faults in deep-water deltas	Parallel, generally grades basinward into delta plain or into shelf/platform facies	Parallel/slightly divergent; may grade laterally into divergent fills or mounds
Lithofacies and composition	Alternating neritic limestone and shale; rare sandstone; undaform deposits	Shallow marine delta front sandstone/ shale grading upward into subaerial delta plain shale, coal, sandstone channels; prodelta facies excluded except where toplap is absent; undaform deposits	Meanderbelt and channel-fill sandstone and floodbasin mudstone; marine reworked fan delta sandstones/profan shale; undaform deposits	Alternating hemipelagic clays and siltstone; calcareous and terrigenous composition; fondoform deposits
Geometry and structure	Sheetlike to wedge-shaped or tabular; very stable setting; uniform subsidence	Sheetlike to wedge-shaped or tabular on shelf-prismatic to lenticular basinward of subjacent shelf edge with growth faults and roll-over anticlines; relatively stable, uniform subsidence on shelf; rapid subsidence and faulting in deep-water delta	Sheetlike to wedge-shaped (individually elongate ribbons or lobes), commonly tilted and eroded	Sheetlike to wedge-shaped; may be slightly wavy or draped over subjacent mounds; generally stable to uniform subsidence; may grade laterally into active structural areas
Lateral relationships	May grade landward into coastal facies and basinward into shelf-margin carbonate facies; local carbonate mounds	May grade landward into alluvial systems and basinward into prodelta/ slope clinoforms (on shelf) or growth-faulted prodelta/slope facies (deep-water setting)	Grade landward into reflection-free, high sandstone facies; alluvial facies grade basinward into upper delta plain; fan delta facies grade basinward into shelf/platform or into slope clinoforms	Commonly grades shelfward into mounded turbidites, or slope clinoforms; may grade laterally into deep-water mounds or fills
Nature of upper/lower boundaries	Concordant, coastal onlap and/or baselap over upper surface; upper surface may be eroded by submarine canyons; basal surface concordant, low-angle baselap or (rare) toplapped by subjacent clinoforms	Normally concordant at top but may be rarely onlapped or baselapped; upper surface may be eroded by submarine canyons; basal surface generally toplapped by prodelta/ slope clinoforms (on shelf); rarely concordant with prodelta on shelf but common in deep-water, roll-over anticlines	Upper surface may be onlapped by coastal facies; top may be angular unconformity; base in generally concordant; fan deltas rarely overlie clinoforms (toplap)	Generally concordant at top and base; may onlap eroded slope clinoforms or eroded mounds; upper surface rarely eroded
Amplitude	High	High in delta front and coal/lignite or marine transgressive facies within delta plain; low/moderate in most delta plain and in prodelta where in continuity with delta front	Variable—low/high	Low to moderate
Continuity	High	High in delta front, coal/lignite and marine transgressive facies; low/ moderate in remainder of delta plain and prodelta where in lateral continuity with delta front	Discontinuous; continuity decreases landward	High
Frequency (cycle breadth)	Broad or moderate; little variability	Variable; broader in delta front; coal/ lignite and marine transgressive facies moderate; narrower in other delta plain and prodelta where in continuity with delta front	Variable; generally narrower cycles than shelf/platform	Generally narrower than shelf/platform; commonly very uniform breadth throughout

From Badley (1985) adapted from Vail et al. (1977).

Properties of seismic facies	Depositional environments/Settings	
	Slope: ASSOCIATED WITH PROGRADING SHELF/PLATFORM	Prodelta/Slope: ASSOCIATED WITH PROGRADING SHELF DELTA OR SHELF-MARGIN DELTA; OR Slope: ASSOCIATED WITH PROGRADING NERITIC SHELF SUPPLIED PERIODICALLY BY SHELF DELTA/FAN DELTA
Reflection configuration	Sigmoid clinoforms Progradational in dip profile; parallel to disrupted and mounded in strike profile	Oblique clinoforms Progradational in dip profile; hummocky, progradational to mounded in strike profile; mounds more common in deep-water slope than in prodelta/slope on shelf
Lithofacies and composition	Hemipelagic slope facies in upper/mid-clinoform; submarine fans common in lower clinoform; generally calcareous clay, silt and some sand (base of clinoform); clinoform deposited in deep water beyond shelf edge	*On shelf*: prodelta (upper) and shallow slope facies (mid-clinoform and lower clinoform); deposited on submerged shelf; composition generally terrigenous clay, silt and sand; sand concentrated in submarine fans at base of clinoform *Beyond shelf edge:* (1) prodelta and deep-water slope associated with shelf-margin delta; may be growth-faulted; clay, silt and sand (in basal submarine fans); and (2) deep-water slope associated with prograding neritic shelf supplied periodically by shelf deltas/fan deltas; clay, silt and sand (in basal submarine fans)
Geometry and structure	Lens-shaped slope system; poorly defined individual submarine fans and point sources; strike profile may intersect facies to define parallel to slightly mounded configurations; rarely affected by growth faults; represents low rate of sedimentation under relatively uniform sea level rise and/or subsidence rate	Complex fan geometry with apices at shelf-edge point sources; each submarine fan resembles a bisected cone; total slope system lens- to wedge-shaped; strike profiles intersect fans or cones to display complex mounds; seismic facies deposited rapidly relative to subsidence and/or sea level rise; highly unstable slopes associated with deep-water deltas (growth faults, roll-over anticlines)
Lateral relationships	Grades updip through shelf/platform edge facies into parallel/divergent shelf/platform (undaform) reflections; may grade downdip into basinal plain (fondoform) or mound/drape seismic facies; grades along strike to similar facies; may change landward to oblique facies	Terminates updip against base of delta platform or shelf/platform (undaform) facies and may grade downdip into basinal plain (fondoform), or mound/drape facies; may change basinward into sigmoid facies; grade along strike into mounded facies and locally submarine canyon-fill facies
Nature of upper/lower boundaries	Generally concordant at top and downlap (baselap) terminations at base; upper surface of outer or distal sigmoids may be eroded by submarine erosion and submarine canyons; eroded surface commonly onlapped by continental rise facies	Toplap termination at top and downlap (baselap) termination at base; may contain local or minor submarine erosion/onlap sequences; outer or distal oblique clinoforms commonly eroded by submarine erosion and submarine canyon cutting; eroded surface generally onlapped by continental rise facies
Amplitude	Moderate to high; uniform	Moderate to high in upper clinoform; moderate to low in lower clinoform; highly variable
Continuity	Generally continuous	Generally continuous in upper clinoform; discontinuous in mid-clinoform and lower clinoform; may exhibit better continuity near base
Frequency (cycle breadth)	Broadest in mid-clinoform where beds thickest; uniform along strike	Broadest at top and generally decreases downdip as beds thin; variable along strike

Summary of seismic facies characterized by progradational reflection configurations

From Badley (1985) adapted from Vail et al. (1977).

Properties of seismic facies	Depositional environments/Settings		
	Reefs and banks: SHELF/PLATFORM MARGIN, BACK SHELF PATCH REEFS AND PINNACLE/BARRIER REEFS	Submarine canyon and lower slope: PROXIMAL TURBIDITIES, SLUMPED CLASTICS	Hemipelagic clastics: PROXIMAL BASIN AND LOWER SLOPE
Reflection configuration	Mounded, chaotic, or reflector-free; pull-up or pull-down common	Mounded; complex and variable	Parallel; mirrors underlying surface
Lithofacies and composition	Shallow-water carbonate biogenic buildups; may or may not exhibit reef-forming framework	Sand and shale submarine fans; complex gravity-failure fans or mounds; turbidity flow; other grain flows, submarine landslides/debris flows; clinoform/fondoform deposits	Terrigenous and calcareous clays (commonly alternating); pelagic oozes; deposition from suspension plumes and nepheloid clouds; fondoform deposits
Geometry and structure	Elongate lens-shaped (shelf/platform edge and barrier reefs); elongate to subcircular lens-shaped (patch and pinnacle reefs/banks); form on stable structural elements	Irregular fan-shaped to mounded geometry; common but not restricted to unstable basins	Sheet to blanket geometry exhibiting drape over underlying surface; common in deep, subsiding basins
Lateral relationships	Shelf/platform edge facies grade updip into parallel/divergent shelf/platform facies; grade downdip into talus and sigmoid clinoform facies; patch reef/bank facies grade updip and downdip into parallel/divergent shelf/platform facies; pinnacle and barrier facies grade downdip into talus clinoforms and to basinal plain (fondoform) facies	May grade shelfward into progradational clinoforms (normally oblique), canyon onlap fill, or pinch out against eroded slope; may grade basinward and laterally into basinal plain (fondoform); onlap fills or drapes	Commonly grades laterally or basinward into basinal plain (fondoform) facies; may grade shelfward into submarine canyon onlap fill; may onlap eroded slope
Nature of upper/lower boundaries	Upper surface concordant or may be onlapped by flank reflections; basal surface concordant, baselapping, or may overlie clinoform toplap; pull-up or pull-down of basal surface common	Upper surface commonly erosional and onlapped, baselapped, or concordant (with drape); basal surface irregularly baselapping; may appear concordant (low resolution), or may onlap (mounded onlap fill)	Upper surface commonly concordant, but may be onlapped or baselapped; basal surface generally concordant but may onlap eroded mound or slope
Amplitude	High along boundaries; may be moderate to low internally; commonly reflector-free	Variable; generally low; some higher internal amplitudes may be thin hemipelagic drapes	Low to moderate; some high-amplitude reflections (well defined on high-frequency, shallow data)
Continuity	High along boundaries; internally discontinuous to reflector-free	Discontinuous to chaotic	High
Frequency (cycle breadth)	Broad; cycle may diverge into massively bedded buildup	Highly variable; commonly narrow	Narrow, uniform

Summary of seismic facies characterized by mounded and draped reflection configurations

From Badley (1985) adapted from Vail et al. (1977).

Summary of seismic facies characterized by onlap and fill reflection configurations

Properties of seismic facies	Depositional environments/Settings: Coastal (paralic) onlap facies	Continental rise: SLOPE-FRONT FILL AND ONLAP CLASTICS	Submarine canyon-fill deposits	Other deep-water fill deposits: MOUNDED, CHAOTIC, STRUCTURALLY ACTIVE BASINS
Reflection configuration	Parallel; coastal onlap	Parallel/divergent; platform or shelfward onlap	Parallel/divergent; landward and lateral onlap	Parallel/divergent; chaotic, mounded onlap
Lithofacies and composition	Delta/alluvial plain and medial fan delta sands and shales; supratidal clastic/carbonate facies; rarely beach/shoreface clastic facies	Sand and shale deposited in submarine fans by turbidity flows; hemipelagic terrigenous/calcareous clays; distal pelagic oozes	Sand and shale deposited by turbidity flow in submarine fans near base; hemipelagic and neritic shale/calcareous clays in middle and upper sequence, respectively; locally may contain coarse proximal turbidites	Sand and shale deposited by turbidity flow in submarine fans; hemipelagic terrigenous/calcareous clays; pelagic oozes; locally proximal turbidites
Geometry and structure	Sheetlike or tabular; uniform subsidence during deposition; periodic tilting and erosion; deposited near basinal hinge-line during subsidence and/or sea level rise	Wedge-shaped lens; may be fan-shaped or lobate in plan view; slow subsidence	Elongate; lens-shaped in transverse section; may bifurcate updip; pinches out updip; slow subsidence	Variable lens-shaped; commonly irregular; reflects bathymetric configuration of structural depression; slow to rapid subsidence
Lateral relationships	Pinches out landward; grades basinward into lower delta plain, distal fan-delta, or shelf/platform facies; may grade laterally into marine embayment facies	Pinches out updip; grades basinward into basinal plain or hemipelagic drape facies; continuous laterally for tens of kilometers	Pinches out updip and laterally; grades downdip into continental rise mounded turbidites, or large submarine fans	Pinches out in every direction
Nature of upper/lower boundaries	Upper surface commonly tilted, eroded, and onlapped by similar deposits; base of facies onlaps unconformity, commonly angular	Upper surface commonly baselapped by prograding clinoforms; basal surface onlaps updip against eroded slope (and commonly outer shelf); may show baselap basinward against mounds or bathymetric highs	Upper surface may be concordant with overlying shelf or platform reflections or commonly baselapped by prograding prodelta and slope facies; basal surface onlaps updip and laterally; baselap onto basin floor rarely observed	Upper surface may be concordant with hemipelagic drape or baselapped by prograding clinoforms; basal surface onlaps in all directions
Amplitude	Variable; locally high but normally low to moderate	Variable; hemipelagic facies moderate to high; clastics low to moderate	Variable; generally low to moderate	Variable; generally low to moderate
Continuity	Low in clastics; higher in carbonate facies; decreases landward	Moderate to high; continuous reflections in response to hemipelagic facies	Variable; generally low to moderate	Variable; poor in chaotic or mounded fill; high in low-density turbidites and hemipelagics
Frequency (cycle breadth)	Variable; generally moderate to narrow	Narrow; uniform	Variable but generally narrow	Variable; commonly narrow; may increase breadth toward axis of fill

From Badley (1985) adapted from Vail et al. (1977).