

Seismic stratigraphy, some examples from Indian Ocean, interpretation of reflection data in interactive mode

K. S. Krishna

National Institute of Oceanography, Dona Paula, Goa-403 004.

krishna@nio.org

Seismic reflection method basically uses the source to propagate seismic waves and set of hydrophones to receive the reflected signals from various boundaries. The reflections are primarily originated from surfaces that are distinguishing the sedimentary layers on the basis of density-velocity contrasts. The surfaces may indicate unconformities or conformities. Eventually the method provides image of the sedimentary strata with internal surfaces and basaltic basement and occasionally its underneath along a profile. Earth scientists will interpret these images in terms of stratigraphy.

In simple terminology the seismic stratigraphy can be defined as a viewing of seismic reflection data with a

geological approach. Total sedimentary strata are divided into number of seismic sequences/ depositional sequences/ stratigraphic units on the basis of bounding unconformities and correlative conformities.

Depositional sequence

A depositional sequence is composed of a relatively conformable succession of genetically related strata and bounded its top and base by unconformities or their correlative conformities (Figure 1). The magnitude of depositional sequence ranges generally from tens to hundreds of meters thick. Occasionally the range may run for thousands of meters.

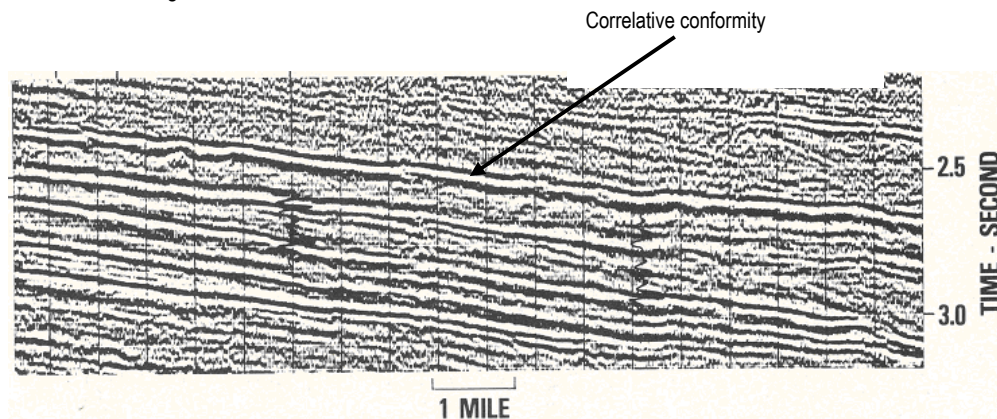


Fig. 1. Seismic section showing different depositional sequences and correlative conformities

Before proceeding to seismic stratigraphy work we must understand the type of boundaries that can bound the depositional sequences. Usually the boundaries are defined as unconformities and conformities.

Unconformities and conformities

An unconformity is a surface of erosion or non-deposition that separates younger strata from older rocks and represents a significant hiatus (Figure 2). Conformity is a surface that separates younger strata from older rocks, but along which there is no significant evidence of erosion and non-deposition (Figure 3).

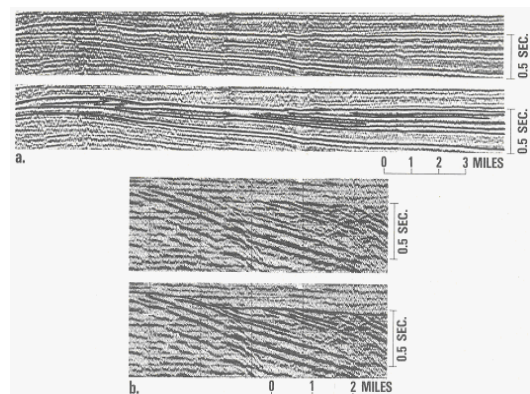


Fig. 2. Seismic reflection records show erosional truncations. Second section of each pair shows interpretation.

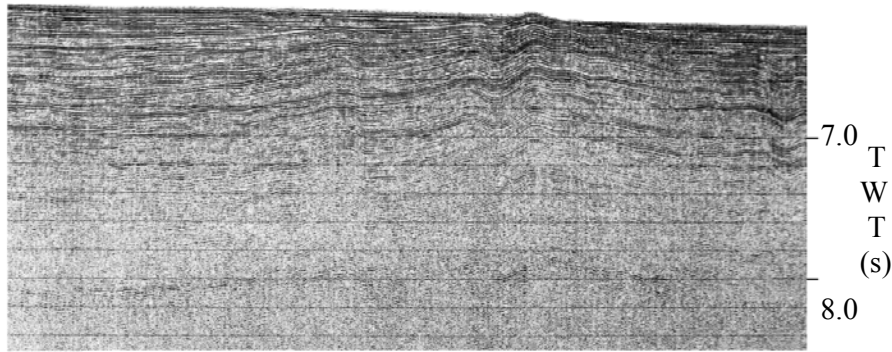


Fig. 3. Depositional sequences are separated by the conformities.

There is another type of unconformity called angular unconformity or structural unconformity occasionally found in the sedimentary strata without erosion and non-deposition (Figure 4). Horizontal compressional forces operated in typical geological setting make the sedimentary strata to undergo folded and/ or faulted, subsequently the younger sedimentary strata will be onlapped against the folded surface. The configuration or orientation of the seismic reflectors within the upper depositional sequences differs from that of seismic reflectors in the lower sequence, hence the boundary between the sequences is called angular unconformity. Sedimentary strata of the central Indian Ocean Basin associated with long-wavelength folding and faulting displays the classical angular unconformities at different geological ages.

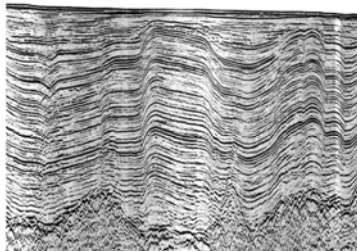


Fig. 4. Seismic section shows angular unconformity without erosion and non-deposition.

Hiatus

This is most frequently used term in seismic stratigraphy. A hiatus is the total interval of geologic time that is not represented by strata at a specific position along a stratigraphic surface. Hiatuses may be attributable either to erosion or to non-deposition or to both. If the hiatus encompasses a significant interval of geologic time, the stratigraphic surface is called non-deposition and erosional unconformity (Figure 1). We have recognized two prominent hiatuses of late Oligocene and early Eocene in Arabian Sea and in Bay of Bengal respectively.

Types of reflection patterns to depositional sequence boundaries

In seismic section boundaries are identified on the basis of termination of seismic reflectors against the surfaces. The following diagram (Figure 5) shows different type of reflection patterns such as onlap, downlap on lower depositional boundary and toplap, offlap, erosional truncation on upper depositional boundary.

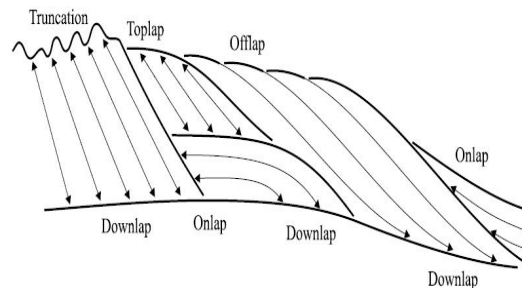


Fig. 5. Different type of reflection patterns against the depositional boundary.

Reflection patterns on lower sequence boundary

Onlap

This is a base-discordant relation. In which horizontal strata progressively terminate against an initially inclined surface (Figure 6a). The Central Indian Basin shows classical examples of angular unconformities, in which sedimentary layers are onlapped against initially folded sedimentary strata.

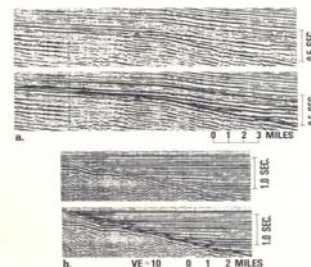


Fig. 6a. Seismic sections show onlap reflector patterns against boundaries.

Downlap

This is a base-discordant relation. In which inclined strata terminate downdip against an initially horizontal or inclined surface (Figure 6b). If onlap cannot be distinguished from downlap because of subsequent deformation, the more inclusive term baselap may be necessary.

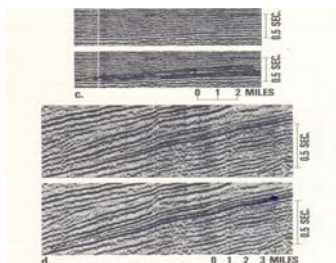


Fig. 6b. Seismic sections show downlap reflector patterns against boundaries.

Reflection patterns on upper sequence boundary

Toplap

It is termination of strata against an overlying surface. Initially the lower strata such as forest beds and clinoforms get inclined due to some tectonic movements. Sea level variations also form the toplap reflection patterns in shallow marine deposits, particularly in deltaic complexes.

Truncation

This implies the deposition of strata and their subsequent tilting and removal along an unconformity surface. This termination is the most reliable top-discordant criterion of a sequence boundary. Such truncation can also be caused by termination against erosional surface, as for instance a channel.

Offlap

Nonsystematic reflection terminations against other reflectors are commonly termed as offlaps. Internal convergence within depositional sequences boundaries should not be confused with terminations along sequence boundaries. Offlaps are commonly found in sedimentary basins, where reflection patterns are prograding into basins.

Seismic Facies Analysis

After seismic sequences are defined, characters of the reflectors within the sequences are interpreted from seismic and geologic data. Seismic facies analysis is the description and geologic interpretation of seismic reflection parameters, including configuration, continuity, amplitude, frequency and interval velocity. Each parameter provides considerable information on the geology of the subsurface (Table 1).

Seismic Parameter	Facies	Geologic Interpretation
Reflection configuration		Bedding patterns Depositional process Erosion and paleotopography Fluid contacts
Reflection continuity		Bedding continuity Depositional process
Reflection amplitude		Velocity-density contrast Bed spacing Fluid content
Reflection frequency		Bed thickness Fluid content
Interval velocity		Estimation of lithology Estimation of porosity Fluid content

Table 1. Seismic reflection parameters used in seismic stratigraphy, and their geological significance

Reflection Configuration

It is gross stratification patterns identified on seismic records. Four basic types of configurations (Figure 9) are recognized:

- 1. Parallel patterns:** It includes even or wavy patterns and is generated by strata that were probably deposited at uniform rates on a uniformly subsiding shelf or stable basin plain setting (Figure 7).
- 2. Divergent configurations:** It is characterized by a wedge-shaped unit in which lateral thickening of individual reflection subunits within the main unit (Figure 8). It signifies lateral variations in rates of deposition or progressive tilting of the sedimentary surface during deposition.
- 3. Prograding reflection configurations:** It is reflection patterns generated by strata that were deposited by lateral outbuilding or progradation to form gently sloping depositional surfaces called clinoforms (Figures 9a and 9b). Prograding reflection configurations may have a variety of patterns including sigmoid, oblique, or hummocky.
- 4. Chaotic reflection patterns:** It represent a disordered arrangement of reflection surfaces owing to soft-sediment deformation, or deposition of strata in a variable high-energy environment (Figure 10). Some chaotic reflections may also be related to over pressured zones. Reflection-free areas on seismic records may represent homogeneous, nonstratified units such as igneous masses or thick salt deposits.

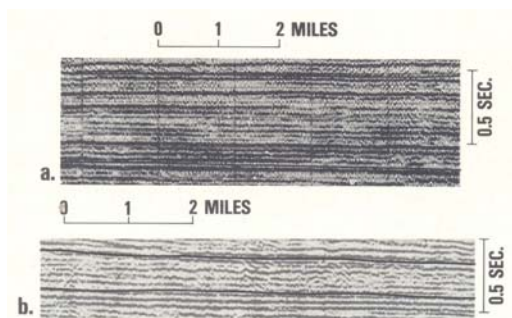


Fig. 7. Seismic sections show parallel and subparallel seismic reflection configurations: **a** is a parallel configuration with good continuity and high to medium amplitude; **b** is subparallel configuration with good to fair continuity and high to medium amplitude.

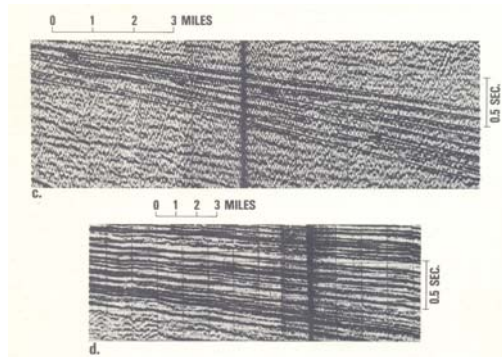


Fig. 8. Seismic sections show divergent reflection configurations with thickening of individual reflection cycles in direction of divergence. Nonsystematic reflection terminations occur in direction of thinning.

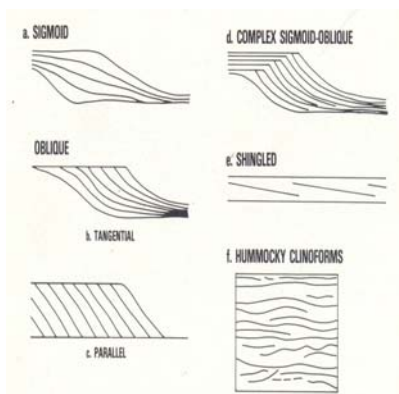


Fig. 9a. Various forms of seismic structures.

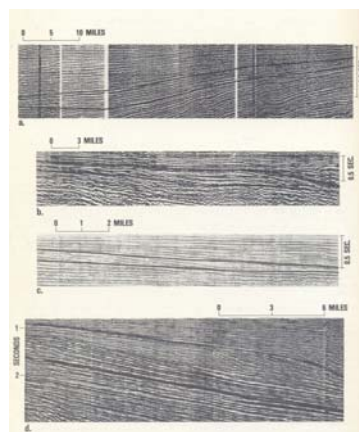


Fig. 9b. Examples of sigmoid-oblique and complex sigmoid-oblique seismic reflection configurations. **a** is sigmoid, **b** is mostly tangential oblique with some sigmoid, **c** is mostly parallel oblique, **d** is complex sigmoid oblique.

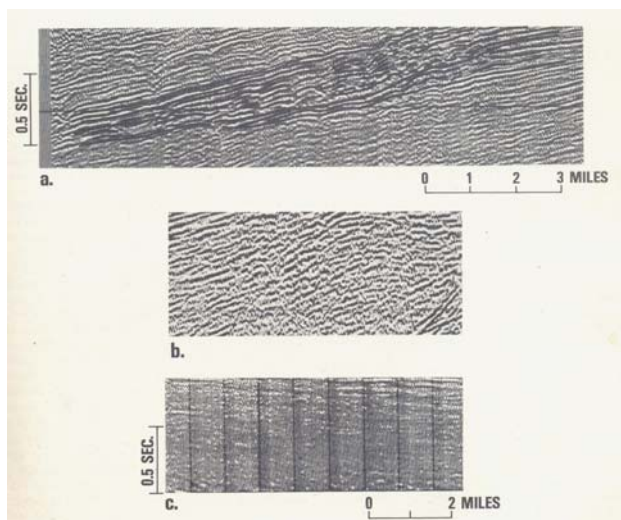


Fig. 10. Examples of chaotic and reflection free seismic configuration. In **a** reflection may be interpreted as contorted stratal surfaces; in **b** no stratal patterns may be reliably interpreted; **c** is largely reflection free, where no or very few reflections occur in seismically homogeneous shale.

Reflection Continuity

Reflection continuity depends upon the continuity of the density-velocity contrast along bedding surfaces. It provides information about depositional process and environment. In contrast to continuous reflectors, reflection patterns showing reflection terminations indicate stratigraphic relationships such as onlap, downlap, and toplap that occur in coastal regions in response to transgressions and regressions.

Reflection Amplitude

Reflection amplitude depends primarily on return of magnitude of seismic energy from the bedding reflectors. It is controlled principally by the velocity - density contrast along individual reflecting surfaces and increases with increasing velocity-density contrast. The amplitudes of reflected seismic waves can be affected also by fluid content of sedimentary beds or by accumulations of gas in the beds. The presence of hydrocarbons in the beds can produce a marked increase in amplitude of waves that shows up on seismic records as so-called "bright spots".

Reflection Frequency

The frequency of seismic waves affects both the depth of penetration of the waves into the subsurface and the resolution of the sedimentary strata. Lower frequencies give greater depth of penetration but less resolving power. The higher frequencies have more resolution power but gives shallow depth of penetration.

Interval (seismic-wave) velocity

Interval velocity refers to the average velocity of bedding reflectors within the seismic sequence. Velocity increases with density of the rock and with increasing overburden pressure. Velocity decreases with increasing porosity and also with increasing interstitial fluid pressure. The presence of gas at low saturations in the pore spaces of the rocks also causes a decrease in velocity.

Picking of Unconformities to Separate Seismic Sequences

The seismic section of the central Indian Ocean Basin is shown in Figure 11 for the purpose of identifying the seismic sequences along with unconformities.

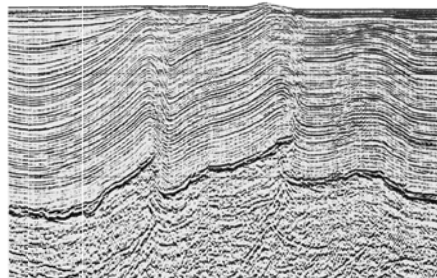


Fig. 11. Seismic reflection section of the central Indian Ocean Basin includes prominent structural unconformities

Three significant seismic boundaries in a sediment section above the lower Eocene unconformity are recognized based on criteria of equal thickness of sediments following the trend of folded and faulted basement, differences in topographic relief between the sets of seismic ref.

The section primarily shows two distinct patterns of seismic signatures: stratified layers (above) and discontinuous reflections (below). The patterns are separated by a boundary that indicates the oceanic basement. In this section oceanic basement is an irregular surface caused by the horizontal compressional forces. The basement is faulted probably some time after its formation, but the influence of the faults are marginally observed in near bottom sediments.

Four seismic sequences are identified in sediment column of the central Indian Ocean Basin that are separated by three regional structural unconformities. The lower unconformity is identified primarily from equal thickness of sediments between the basement and the boundary with a train of undulations and onlapping of sediment layers on the slope of the boundary. The oceanic basement and sediment section below the boundary are extremely crumpled at several locations in the form of tight folds and high angle faults, indicating the occurrence of intense deformation soon after the formation of the boundary. The upper two unconformities are identified on the basis of overlapping seismic reflectors.

The middle boundary is recognized primarily from the sediment pattern that separates the uniform thickness of sedimentary strata with undulations and onlapping of the strata on upper Miocene sediment structures at ODP Leg 116 Sites. To the northwest of the ODP Leg 116 Sites, sediments deform at the time of the formation of the middle boundary. It is interesting enough to note that the upper Miocene unconformity is absent and subsequent unconformities are present. These results suggest that the boundary is an unconformity, indicating the reoccurrence of deformation activity.

The upper boundary is mapped based on separation of flat-lying reflectors from underlying tilted or undulating reflectors and termination of sediment layers on the slope of the boundary. The boundary suggests the presence of another unconformity. The sediment layers above the boundary, in general, are sub-parallel except in the vicinity of exposed deformed structures. The unconformities are correlated to bio- and litho-stratigraphic results of ODP Leg 116 sites for the purpose of assigning ages to them. The oldest and youngest unconformities have ages of late Miocene (7.5-8.0 Ma) and late Pleistocene (0.8 Ma). The middle one would appear to be earliest Pliocene in age (4.0-5.0 Ma). Now that we can recognize three regional unconformities

and observe their stratigraphic relationship, it might be that the event at DSDP Site 218 is the lateral equivalent of the earliest Pliocene unconformity at ODP Leg 116 sites, and does indeed mark the onset of deformation in that area.

Steps followed to interpret a seismic section

1. Identify unconformities and correlative conformities along a profile and extend it to the entire area of study.
2. For identifying an unconformity, identify reflector terminations (e.g. onlap, downlap, toplap, truncation, offlap) with arrows
3. Assign the lithological properties of seismic sequences separated by the unconformities on the basis of interval velocity
4. Interpret the lithological changes in terms of depositional environments and in terms of sea level changes (wherever necessary)
5. Post drill well information (if available) to assign geological age to the unconformities.
6. Identify structural features and discontinuities (e.g. faults) in a section and establish their sub-surface continuity in the study area.

Interpret the seismic reflection record to understand tectonic history of the study area.