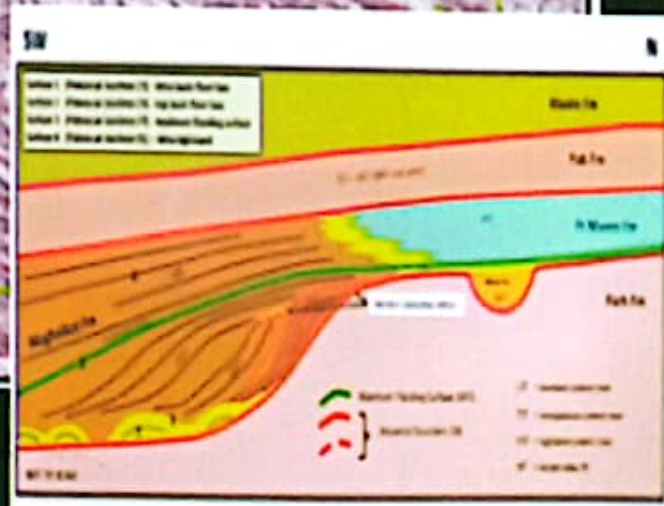
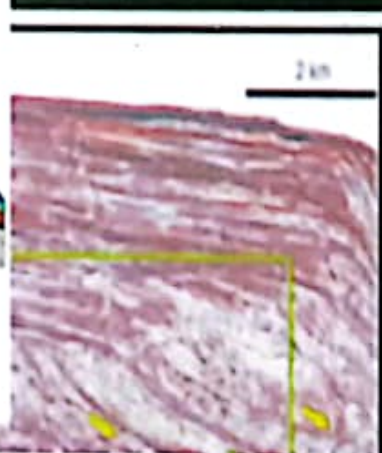
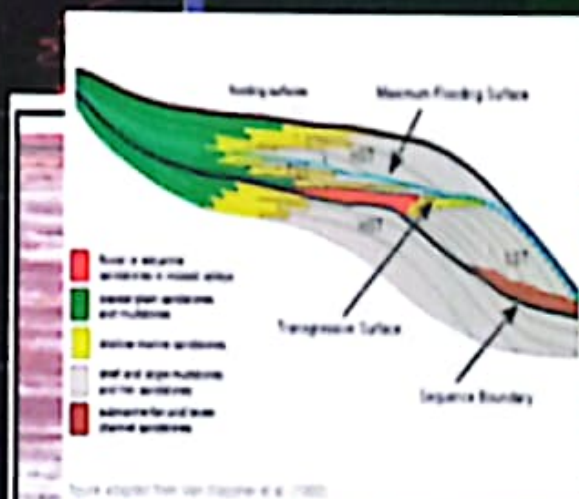
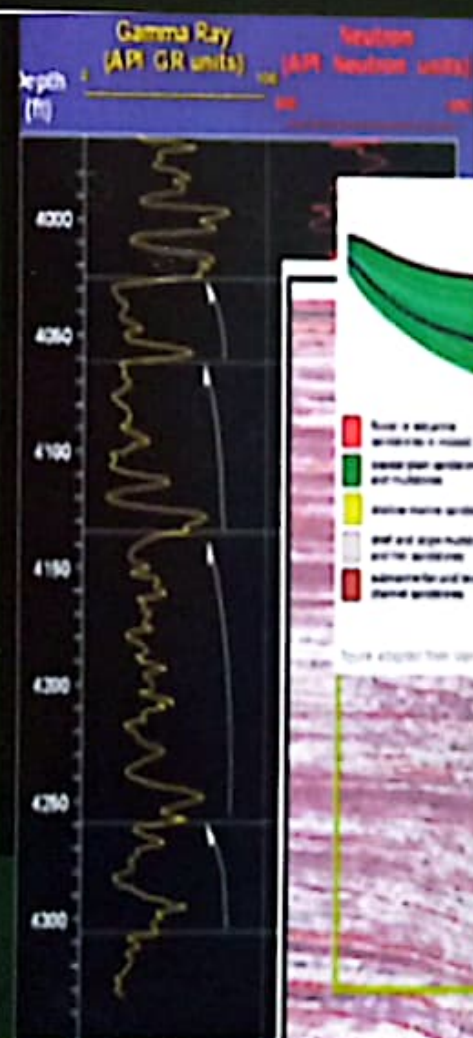


AN INTRODUCTORY APPROACH TO SEQUENCE STRATIGRAPHIC ANALYSIS

By MEPAIYEDA, SEYI
with sections by
ADEOYE TAIYE OLUSHOLA



AN INTRODUCTORY APPROACH TO SEQUENCE STRATIGRAPHIC ANALYSIS

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Foreword



Interest in the concept of stratigraphic interpretation continues to grow. More geologists and geophysicists are prospecting worldwide using stratigraphic concepts and models.

Because most new geologists come out of college with little understanding of some recent industry's primary tool and coupled with the fact that many experienced geologists encounter difficulties in interpretation due to several theories of stratigraphy, this book has introduced the concept of sequence stratigraphy in the simplest terms.

This book will serve as a training standard for industry, academia and can be used in a class environment or as a self-help program.

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South Africa

Preface



Sequence stratigraphy is an aspect of sedimentary geology that is currently one of the most active areas of research both in academic and industrial environments. More geologists and geophysicists are prospecting worldwide using stratigraphic concepts and methods. Sequence stratigraphy has evolved from an academic concept to a valuable tool for oil and gas exploration in the past two decades, but it is still underutilized. The predictions about reservoir potential based on sequence stratigraphy depend on understanding changes in global sea level, tectonic movements and how they affect lithologic facies and boundaries.

Learning how to evaluate and predict the flow-unit boundaries is the key to correct application of sequence stratigraphic models. Even though widely popular among all groups interested in analysis of sedimentary systems, it is yet a difficult undertaking due to the persistence of conflicting approaches to sequence stratigraphic analysis. This book provides an introductory approach with a view of providing a unifying platform for stratigraphic study. The book is addressed to anyone interested in the analysis of sedimentary systems from students to geologists, geophysicists and reservoir engineers. This book also offers a practical approach by demonstrating stratigraphic interpretations using real data sets. This is to help readers simulate a practical approach to stratigraphic interpretations in a localized environment. Readers can refer to the references for further study on this subject

Mepaiyeda S.
2019

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I am also grateful for all those who so kindly allowed us to use some of their illustrations in our book, specifically, Insole Allan of Univation, for providing practical illustrations used in this book. Nigeria. Every effort has been made to obtain permission to use copyrighted material and sincere apologies are rendered for any errors or omissions. The author would welcome these being brought to their attention. I also wish to thank professors, friends and colleagues, who through the years have shared their knowledge and expertise with us. The contributions of these people made this book possible.

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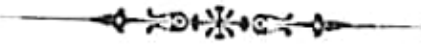
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CHAPTER ONE

AN OVERVIEW OF SEQUENCE STRATIGRAPHY



1.1 Introduction

Stratigraphy is the science of describing the vertical and lateral relationships of rocks. These relationships may be based on rock type, called lithostratigraphy, on age, in chronostratigraphy, on fossil content, labeled biostratigraphy, or on magnetic properties, named magnetostratigraphy. Sequence stratigraphy shows the stratigraphic succession of genetically related intervals of strata, bounded by discontinuities. Sequence stratigraphic large-scale, three-dimensional analysis of the rock formations combined with seismic interpretations can provide a powerful means of predictive modelling.

Sequence stratigraphy is the most recent revolutionary paradigm in the field of sedimentary geology. The concepts embodied by this discipline have resulted in a fundamental change in geological thinking and in particular, the methods of facies and stratigraphic analyses. Over the years, this approach has been embraced by geoscientists as the preferred style of stratigraphic analysis, which has served to tie together observations from many disciplines. In fact, a key aspect of the sequence stratigraphic approach is to encourage the integration of data sets and research methods. Blending insights from a range of disciplines invariably leads to more robust interpretations and consequently, scientific progress. Thus, the sequence

stratigraphic approach has led to improved understanding of how stratigraphic units, facies tracts, and depositional elements relate to each other in time and space within sedimentary basins (Fig. 1.1). The applications of sequence stratigraphy range widely, from predictive exploration for petroleum, coal, and placer deposits, to improved understanding of Earth's geological record of local to global changes. The conventional disciplines of process sedimentology and classical stratigraphy are particularly relevant to sequence stratigraphy

Sequence stratigraphy is commonly regarded as only one other type of stratigraphy, which focuses on changes in depositional trends and their correlation across a basin.

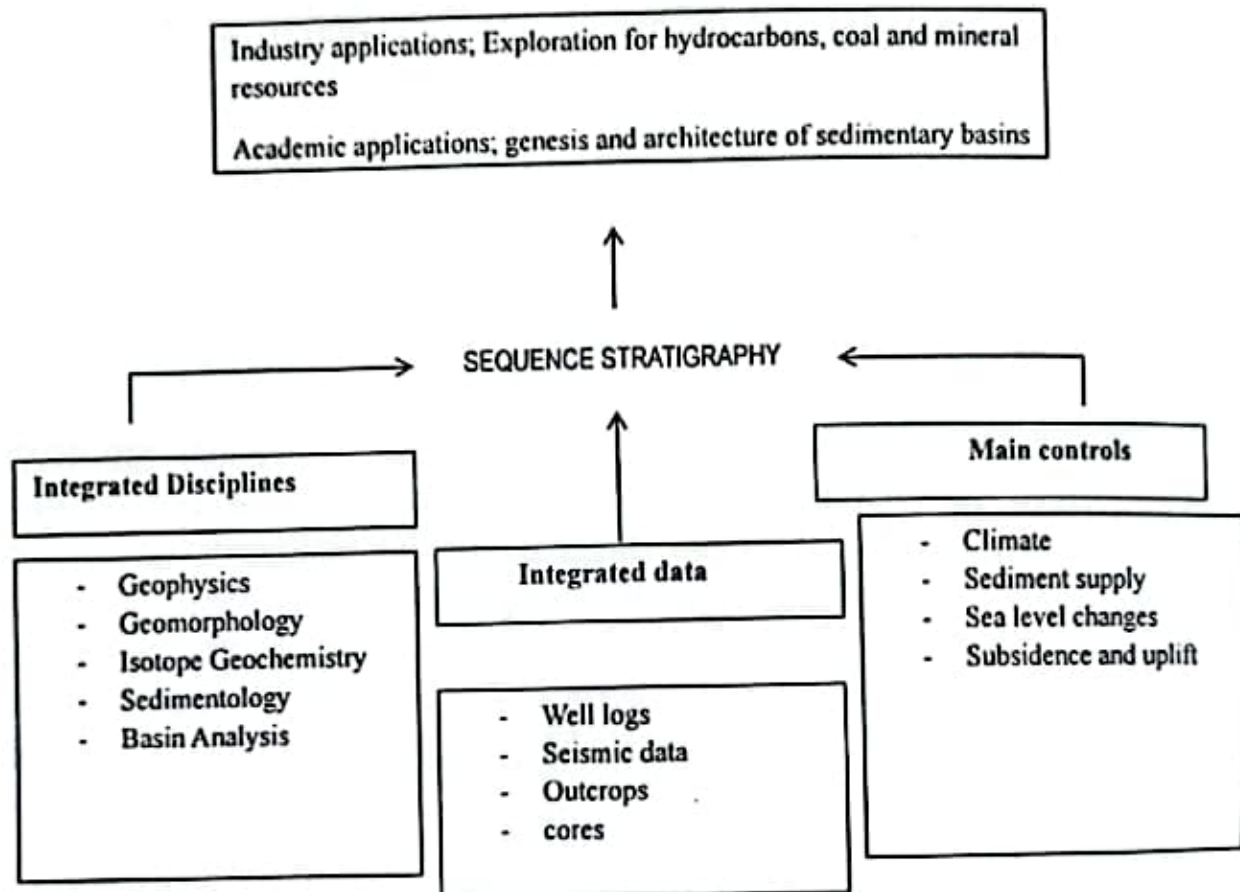


Figure 1.1; Sequence stratigraphy in the context of interdisciplinary research

Sequence stratigraphy is often confused with seismic stratigraphy, which represents only one of the tools of sequence stratigraphy. **Seismic stratigraphy can be defined as methods employed to determine the nature and geologic history of sedimentary rocks and their depositional environment from seismic evidence, in other words sequence stratigraphy is analysed on seismic data.** As an exploratory tool, sequence

stratigraphy is used to locate reservoir sands which are strong indicators of hydrocarbon accumulation. Reservoir dimensions are important factors that affect the quantity of hydrocarbons producible from a reservoir. The concepts that govern sequence stratigraphy must be understood before proper analysis can be done. First there must be the existence of a depositional sequence. This comprises of sediments deposited during one cycle of sea level fluctuation, by Exxon convention, starting at a low, going to high and then returning to low. These sequences are commonly referred to as time- stratigraphic surfaces as they are constrained by sequence boundaries and maximum flooding surfaces. Within each sequence identified, one tool for studying stratigraphy is the description of the parasequences. Van Wagoner (1988) defines a parasequence as a relatively conformable succession of genetically beds or bed sets bounded by marine flooding surface or their correlative surface. They are usually associated with distinct stacking patterns that can be described on the well logs. They are also seen on seismic sections as truncations and unconformities. All these are studied within the framework of system tracts. System tracts are depositional assemblages that have predictable stratigraphic order, character and contents. Each system tract exhibits characteristic log response and seismic signatures. System tracts are of three sub divisions within each sequence. They are lowstand, Transgressive and Highstand system tracts.

1.2 Historical perspective of sequence stratigraphy

Stratigraphy is the geological science dedicated to the study of rock strata, their succession, lithologies, fossil contents, distributions, and positions in time. Sedimentary rocks provide information on the geological environments and processes responsible for their deposition, since different depositional environments produce different sedimentary rocks. Being able to determine depositional environments from the sedimentary record is therefore of paramount importance to the petroleum explorationist, since some strata are more likely than others to generate hydrocarbons and to provide the seals and reservoirs necessary for hydrocarbon accumulation. A review of the theories and evolution of classical stratigraphy is given in Fig 1.2

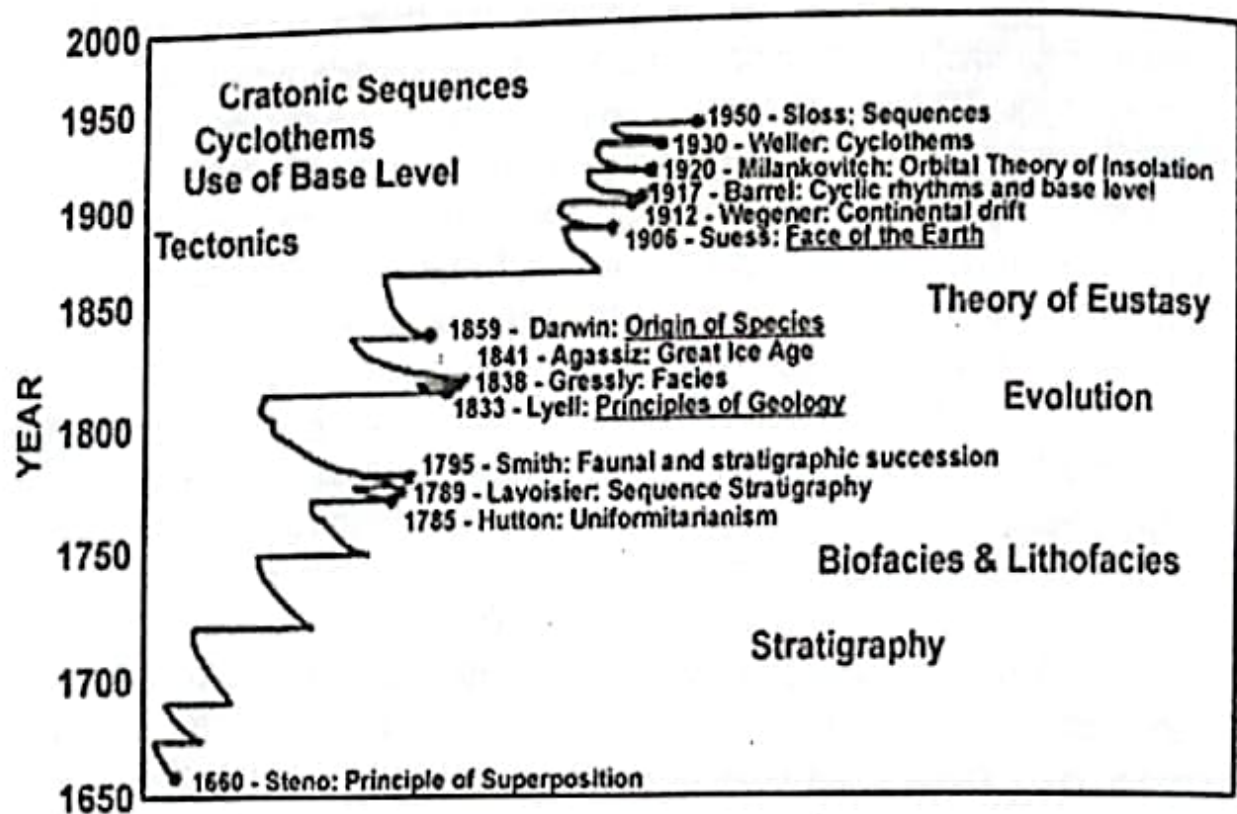


Figure 1.2 Theories and evolution of classical stratigraphy (*History of stratigraphy from 1650 to 1950, showing important contributors and their achievements*).

In 1660, Nicolaus Steno, a Danish physician and geologist, developed the theory that younger sediments overlie older ones, establishing the *principle of superposition*.

- III James Hutton, a Scottish physician and geologist, is credited as the father of modern geology. In 1785, he formulated the *doctrine of uniformitarianism*, establishing the uniformity between past and present geological processes.
- III The concept of *sequence stratigraphy* was originally developed in 1789 by Antoine Lavoisier. While compiling a geologic map of France in 1766, Lavoisier developed an understanding of the relationship between sedimentary processes and their end products. In 1789, Lavoisier published his views on stratigraphy

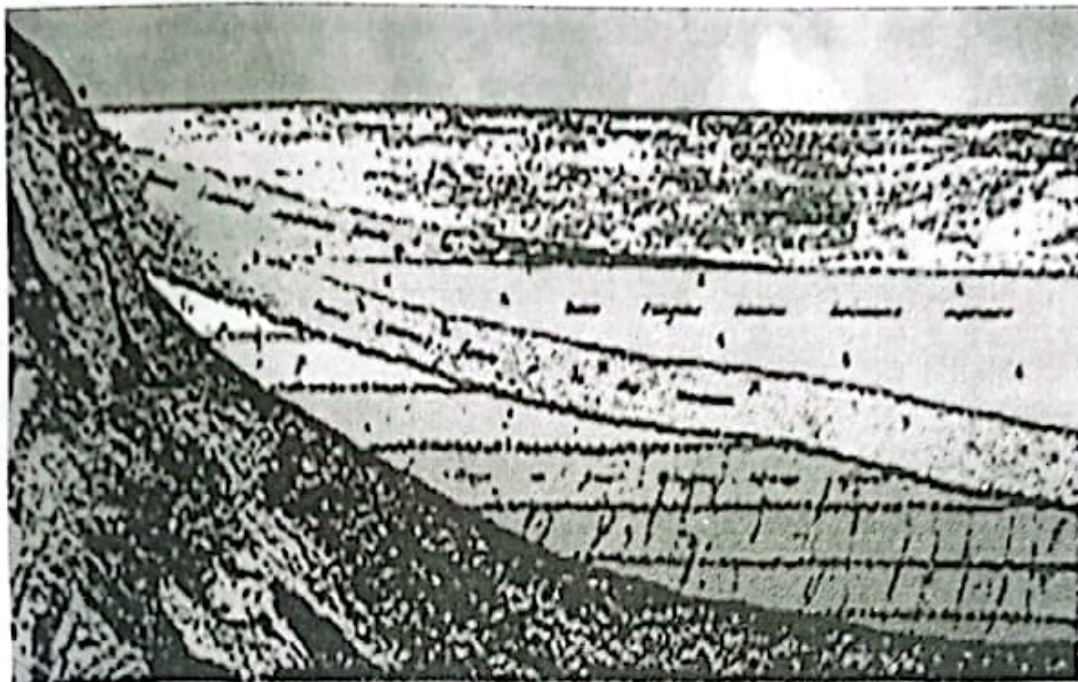


Figure 1.3; 1789 Lavoisier stratigraphic model

This figure is remarkably similar to the model developed nearly 200 years later at Exxon Production Research and which forms the basis of modern seismic sequence stratigraphy. Lavoisier eventually drifted away from the project, and is now better known as the father of modern chemistry. Lavoisier was sent to the guillotine following the French Revolution for having been a tax collector for personal profit — profits he used to finance his research.

- The principle of *faunal succession and stratigraphic correlation*, or what is now termed *biostratigraphy*, was established in 1795 by William Smith. As a canal engineer in England, he observed sedimentary strata and fossils, noting that the same succession of fossil faunas could be seen in different parts of the country. By recognizing the same fossil contents, he drew correlations between sedimentary layers in distant regions.
- *Principles of Geology* was published in 1833 by Charles Lyell. Strongly influenced by the work of Hutton and Smith, Lyell divided geologic time into 13 periods, based on fossil changes between one period and the next. Lyell's classification scheme has since undergone numerous changes and refinements.

In 1838, the Swiss geologist Armand Gressly developed the concept of *facies*. Based on his study of Jurassic outcrops in Switzerland, Gressly concluded that a facie represents the sum total of the sedimentology and paleontology of a layer or group of layers, and that different facies represent different depositional environments. His definition is still appropriate today.

- The theory of a *Great Ice Age* was developed in 1841 by Jean Louis Agassiz. At the time, his conclusion that erratic boulders, jumbled sediments and U-shaped valleys in the high Alps were the products of ice sheets that once covered large parts of the continents was startling. Attributing observed fossil extinctions to the action of ice, Agassiz missed the overwhelming importance of evolution. Agassiz later made important contributions to the earth sciences, and to glacial geology in particular.
- Charles Darwin published the *Origin of Species by Natural Selection* in 1859. On boarding the H.M.S. Beagle in 1831 for his famous voyage, Darwin was given a preliminary copy of Lyell's *Principles of Geology* by the ship's master, Captain Fitzroy.

While we generally attribute each of these achievements to an individual, it is pertinent to realize that many researchers made important contributions, culminating in the recognized individual's ability to synthesize past work into an elegant solution or statement.

Stratigraphy was the dominant subject for geologists during the first half of the nineteenth century and represented the tool for understanding the complex geology observed in outcrops around the world. Stratigraphy enabled geologists to impose order on sedimentary deposits which initially appeared chaotic, using the concepts of superposition, uniformitarianism and faunal succession. During the second half of the nineteenth century, studies of the deformation of Earth's crust led to an understanding of the importance of tectonics, but did not reach a consensus as to its causes. Preeminent among researchers at this time was Eduard Suess, a professor of paleontology at the University of Vienna. His analysis of mountain building and the origin of the Alps led to his treatise *The Face of the Earth* (1906). In this work, he developed the concept of global tectonics. He later proposed a theory of *eustasy*, or worldwide synchronous changes in sea level, to explain his observations of the stratigraphic record.

The basic concepts of modern sequence stratigraphy were in place by the early decades of the twentieth century. The next important steps included absolute dating techniques, reflection geophysics, plate tectonics and countless field observations.

An important breakthrough for stratigraphic geology was the discovery and use of radioisotopes in the absolute dating of geologic strata. The potential for radioactive isotopes to accurately date rocks had been realized soon after the turn of the century. But it was during the Manhattan Project (1942-1946) that refined mass spectrometry instrumentation was developed, permitting the routine analysis of isotopes. The technique provided an *absolute* chronology for geological events in Earth's history a quantum leap from the previous *relative* methods based solely on paleontology.

Petroleum was first discovered on land using the geophysical reflection method in 1924. By 1927, the method was routinely applied to petroleum exploration (Dobrin, 1976). Further developments following World War II produced the continuous seismic profiling method for marine reflection surveys. For the first time, these tools enabled geoscientists to examine the structure and stratigraphy of sediments underlying the world's oceans and continents. As technology improved, new geophysical tools were developed and quickly applied to deciphering Earth's history, particularly if these tools gave companies an economic advantage.

The development of new geophysical tools led to further investigation of several long-standing dilemmas, including plate tectonics. The idea that all of Earth's continents had split apart and moved was formally proposed by German meteorologist Alfred Wegener in 1912. His theory was quickly repudiated by fellow scientists, since Wegener lacked a mechanism to explain the movement of the continents.

Following World War II, geologists went to sea and began probing the shape and structure of the ocean floor using more sophisticated tools. A number of discoveries quickly followed, and by 1961 Harry Hess at Princeton and Robert Schmalz at Penn State independently suggested that Earth's mantle was convecting heat, that hot rocks were being spewed out along the axis of mid-ocean ridges, and that the ocean floor was spreading away from these ridges and plunging under the continents. Robert Dietz coined the term *sea-floor spreading* for this model. In 1967, Dan McKenzie of Cambridge University synthesized these disparate models into the

theory of plate tectonics. This theory provided an explanation for global tectonic events, and was essential to the study of stratigraphic sequences.

1.3 Sequence stratigraphy as a tool for explorationists

Sequence stratigraphy has evolved from an academic concept to a valuable tool for oil and gas exploration in the past two decades, but it is still under-utilized. The predictions about reservoir potential based on sequence stratigraphy depend on understanding changes in global sea level, tectonic movements and how they affect lithologic facies and boundaries. Learning how to evaluate and predict the flow-unit boundaries is the key to correct application of sequence stratigraphic models. Concepts of cyclic sedimentation have been used in geologic interpretation for decades. Cyclical sedimentation is defined by stacked shoaling-upward packages of marine sediment and stacked submarine fans. Sequence stratigraphy refines the old cyclic sedimentation concepts into specific 1st, 2nd, 3rd, 4th and 5th order sequences based on identification of unit boundaries. Identification of the stratigraphic sequences that make up the cycles is based on lithology and boundary changes. Seismic reflections are particularly useful in picking the sequence boundaries. The deposition of sequences is dependent on sea level change, sediment supply and subsidence. Interpretation of sedimentary strata based on sequence stratigraphy using correlated seismic, wireline and core data is important for hydrocarbon exploration.

1.4 Challenges and limitations of sequence stratigraphy

There are a number of approaches and theories on sequence stratigraphy. There may be confusion on whose theories to apply. The concepts have changed and evolved over time. Each theory has a multitude of terms that may be contradictory. The difficulties in interpreting cycles, parasequences and sequences can be solved by focusing on the basic principles. Using both logs and seismic data allows for better correlation of intervals and evaluation of the data. Analysis of global sea level changes and determining the order of sequences relies on interpretations of biostratigraphic and subaerial unconformities. Sequence stratigraphy has proven useful for petroleum exploration, but it is commonly misapplied. There is controversy over whether the technique can be applied to carbonate systems since it was

designed to explain sand-shale systems. Some experts maintain that sequence stratigraphy is easier in carbonates because carbonates are extremely sensitive to sea level change. There is unanimous agreement, however, that low sedimentation rates often pose special problems. When sedimentation rate is moderate to high, layers within a sequence are tens to hundreds of meters thick, comfortably within the resolving power of a typical seismic wave, but when sedimentation rate is low, several sequences might fit within a seismic wavelength. Sequence stratigraphy cannot be confidently applied here, but it has been done countless times. A useful interpretation in thinly-bedded regions requires abandoning small scale features and concentrating on larger scale, long term processes that control the generation of sequences.

CHAPTER TWO

THEORETICAL BASIS OF SEQUENCE STRATIGRAPHIC ANALYSIS

2.1 Elements of Stratigraphic analysis;

Sequence stratigraphy relates key physical surfaces, strata geometries, stacking patterns and lithofacies distribution to the various segments of an eustatic (sea level) curve. The stratigraphic intervals are organised into a hierarchy: laminae, beds, parasequences and systems tract sequences. The dividing stratigraphic surfaces are all placed within a rigid chronostratigraphic framework. Variations in coastal onlap around the world have been analysed stratigraphically. This research resulted in the production of a global cycle chart, which shows quantitatively the eustatic fluctuations during the Mesozoic and Cenozoic. The fluctuations in sea level are suggested to be the result of the interaction of two processes:

1. Climatic changes inducing formation and melting of polar ice caps.
2. Variations in the rate of formation of new oceanic crust at mid-ocean ridge
3. The theory considers that both these mechanisms affect the whole globe simultaneously.
4. The critical elements of a sequence stratigraphic study are:
5. Time control (refined biostratigraphy, magnetostratigraphy, radiometric dating).
6. Shifts in facies and depositional environments (sedimentological techniques, including facies analysis, lithofacies and isopach maps,

- palaeocurrent analyses, and paleoecological studies).
7. Stacking and lateral correlation parameters (lithostratigraphy, wireline logs, seismic)
 8. Geometry of sediment bodies (seismic).
 9. Identification of unconformity and condensation surfaces (lithostratigraphy, biostratigraphy, seismic).

2.2 Stratigraphic architecture

Stratigraphic architecture is the result of the interaction of tectonics, eustasy and climate. Tectonics and eustasy control the space available for sediment to accumulate (accommodation) and tectonics, eustasy and climate interact to control sediment supply and how much of the accommodation is filled. One of the most difficult problems which the sedimentary geologist faces when attempting to determine the mechanisms and processes that produced the stratigraphic architecture of a basin fill is the question of sea level changes. The vertical movements of sea level can only be determined from the stratigraphic record left on the Earth's crust. If the crust were static, there would be no problem. However, in reality, the crust experiences vertical movements at varying rates due to a variety of mantle and lithospheric processes. The position of a shoreline at any point in time will therefore be the product of the interaction between sea level changes on the one hand and crustal uplift and subsidence on the other. This means that there are no absolute reference markers for the calibration of sea level change. Sequence stratigraphy is the latest in a long line of strategies that geologists have evolved in an attempt to investigate and overcome this problem.

The Law of Superposition is one of the basic principles of sedimentary geology. It states that in any succession of strata the beds were deposited in a simple vertical order from base to top and sees sediments as more or less uniform sheets or wedges, although perhaps showing thickness or facies changes from one part of the basin to another. However, stratigraphic superposition is a complex process and it results in a diversity of styles of stratigraphic architecture. In many environments, lateral accretion of sediment is as important as vertical aggradation. Only in a few environments, such as carbonate platforms and evaporate basins, is sedimentation uniform and deposits stratigraphic units with a tabular geometry. In most environments, however, sediment distribution is constrained by factors, such as base level or wave base, and sediment accumulates laterally as well as, or instead of,

vertically. This means, for example, that on a prograding delta or shelf, time increments will be represented by thick clinoform units that may pass into a thin reworked zone or even a hiatus on the delta plain or the shelf platform, respectively. Additionally, the locus of progradation may switch laterally because of slope changes or channel diversion. Consequently, a clinoform set may be followed laterally by a hiatus with the main stratigraphic time sequence being developed elsewhere. Finally, sediment depocentres and stratigraphic relationships are greatly affected by subsidence and uplift and by changes in sea level. Many of the concepts and principles of sequence stratigraphy evolved from the observation from seismic data that prograding basin margin systems often have a consistent depositional geometry.

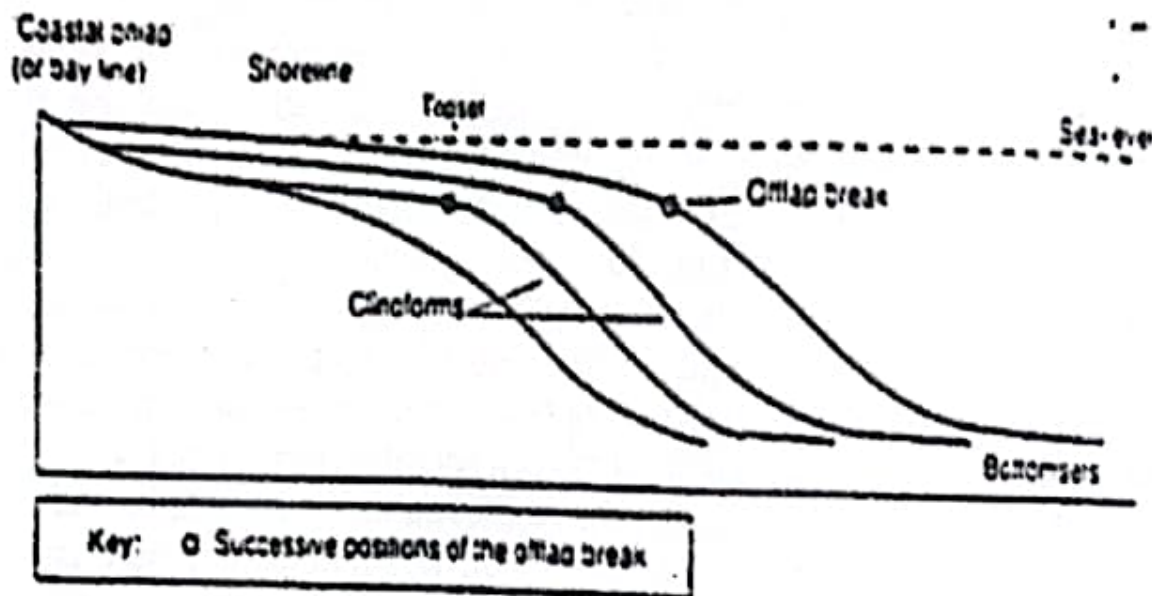


Fig 2.1 Typical profile of a prograding basin-margin unit, comprising topsets and clinoforms separated by a break in slope, the offlap break. Bottom sets may also be present.

Topset is the term used to describe the proximal part of the basin-margin profile characterised by low gradients ($<0.1^\circ$). Topsets effectively appear flat on seismic data and generally contain fluvial, deltaic and shallow-marine depositional systems. The **shoreline** can be located at any point within the topset. It may coincide with the offlap break (see below) or it may occur hundreds of kilometres landward. The proximal termination of the topset is usually termed the point of **coastal onlap**, referring to the up-dip limit of coastal-plain or paralic facies.

- **Climoform** is used to describe the more steeply dipping portion of the basin margin profile (commonly $>1^\circ$) developed basinward of the topset.

Clinofolds generally contain deeper water depositional systems characteristic of the slope. The slope of the clinoform generally can be resolved on seismic data.

- **Bottomset** is a term sometimes used to describe the portion of the basin margin profile at the base of the clinoform characterised by low gradients. Bottomsets contain deep-water depositional systems. The main break in slope in the depositional profile occurs between topset and clinoform and is called the **offlap break (or depositional shoreline break)**. This is not the same as the **shelf break** which is the edge of the modern continental shelf and is usually a relict feature rather than a depositional one. The topset-clinoform profile is the result of the interplay between sediment supply and wave, storm and tidal energy in the basin. Sediment enters the proximal end of the profile through a river system. It is then distributed across the topset area by wave and/or current-related processes. These may include fluvial currents, tidal currents, storm currents, etc. These topset transport processes are only effective at relatively shallow depths (up to a few tens of metres). To move sediment into deeper water a slope must develop in order to allow sediment transportation by gravity processes. The clinoforms build up to the angle required to transport sediment at the required rate. Clinoform slope angle is strongly influenced by the nature of the sediment. Coarse-grained clastic sediments, with a higher angle of repose, will build up steeper slopes than fine-grained sediments. Carbonate systems generally build steeper depositional slopes (up to 35°) than fine grained clastic systems ($0.5 - 3^\circ$) because of their greater shear strength. Steeper slopes in clastic systems are generally either made up of coarser grade material or are zones of erosion and sediment bypass.

2.3 Basin-margin types

The importance of the offlap break on the depositional systems is most apparent during relative sea level fall. When relative sea level fall exposes the offlap break, rivers commonly incise in order to re-equilibrate to lowered **base level**. Consequently, the river becomes entrenched at its mouth. The response of the depositional system to this relative sea level fall depends on the nature of the basin margin (fig. 2.2):

1. **Shelf-break margins.** These are margins which have well-developed

depositional clinoforms. Fluvial entrenchment during sea level fall may result in focussing of the sediment load to discrete locations on the clinoform's slope. Large turbidity current and submarine fan deposits can be formed by slope failure of the sediment mass. Shelf-break margins are typical of passive continental margins at times of slow rise of relative sea level. At such times, the delta systems can easily prograde to the shelf edge.

2. **Ramp margins.** This type of margin is characterised by relatively shallow water depths, where storm and current processes can operate over much of the area of deposition. Depositional angles are generally less than 1° and seismic clinoforms (if resolved) are shingled with a dip of about 0.5° . The offlap break on a ramp margin is likely to be at the shoreline, where fluvial gradients pass into slightly steeper shelf or delta-front slopes. During a relative sea level fall, depositional systems will be translated basinward without significant slope bypass or basinal deposition. Consequently, unlike shelf-break margins, there will be none or very little deep-water turbidite deposition during lowstand. Any turbidites found on a siliciclastic ramp margin are likely to be delta-front turbidites rather than detached submarine fans. Many modern delta systems can be considered to form ramp margins, since they are generally shelf deltas prograding on to the drowned topsets of an earlier shelf-break margin.
3. **Rift margins.** Margins of this type typify actively extending basins. Extensional faults have a strong influence on both palaeogeography and sediment influx rates. The tectonics are a major control on the distribution of sediment accommodation within the rift. Subsidence rates generally increase from the margin to the centre of the rift, although each fault block will have its own pattern of sediment accommodation. The footwall crest will see the least subsidence and may suffer uplift and erosion. In contrast, the hanging wall will experience progressively greater subsidence rates towards the controlling fault. The depositional systems that develop will depend on whether the rift is marine or continental. Rift margins may have high topographic relief and relative sediment starvation because sediment is by-passed towards the rift centre. Basin-margin systems may build out into deep water with long clinoform slopes and relatively minor topsets. There is little potential for trapping coarse clastic material in the topsets and much of this may be by-passed to the basin.
4. **Foreland-basin margins.** These will vary depending on whether sediment is being fed axially along the basin or directly into the basin from the thrust

belt. In the latter case, the rate of tectonic subsidence increases towards the foreland thrust belt, the source of the sediment. In other words, sediment accommodation may be relatively high in proximal areas compared with the basin centre. This has a pronounced effect on strata geometries and may result in the aggradation of thick topset deposits with little opportunity for seismic-scale clinoforms to develop

5. **Growth-fault margins.** Margins of this type are characterised by gravity driven syn-sedimentary extensional faults. The subsidence rate is considerably greater on the hanging wall side of the growth fault and this result in an expanded sedimentary succession in that direction. The effect of the growth fault on the depositional system will depend on whether the fault had a topographic expression on the seabed. When the hanging wall is a topographic low relative to the footwall, facies differentiation occurs across the fault, with thicker, deeper water clastic deposits on the downthrown side.

2.4 Eustasy, relative sea level and Tectonics

In order to understand the controls on sequence development, it is necessary to define what is meant by eustasy, relative sea level and water depth.

Eustasy is measured between the sea-surface and a fixed datum, usually the centre of the Earth. Eustasy can vary by changing ocean-basin volume or by varying ocean water volume. The interpretation of eustatic changes from the rock record is a complex and often controversial topic. Eustatic sea level changes rise or fall. This will cause variations in the base level for erosion on a *global scale*, where base level is defined as the level above which deposition is temporary and erosion occurs.

Relative sea level is measured between sea-surface and a local moving datum, such as basement or a surface within the sediment pile. Tectonic movements of a basement datum, sediment compaction involving subsidence of a datum within the sediment pile and vertical eustatic movements of the sea-surface all contribute to relative sea level change. Relative sea level "rises" due to subsidence, compaction and/or eustatic sea level rise and "falls" due to tectonic uplift and/or eustatic sea level fall. The **equilibrium point** is the point on a depositional profile where the rate of relative sea level change is zero. The equilibrium point will separate, at any given time, the zone in the basin margin where relative sea level is falling from the zone where relative sea level is rising.

2.5 Accommodation

Eustasy and subsidence rate together control the amount of space available for sediment accumulation – this is conventionally termed accommodation.

Accommodation is the space available for sediment to accumulate at any point in time. It is controlled by base level because in order for sediments to accumulate, there must be space available below base level. The base level datum varies according to depositional setting (fig. 2.4). In alluvial environments, base level is controlled by the graded stream profile, which is graded to sea level or lake-level at its distal end. In deltaic and shoreline systems, base level is effectively equivalent to sea level. In shallow marine environments, also level is also ultimately sea level, although fair weather wave base can form a temporary base level in the form of a "graded shelf profile".

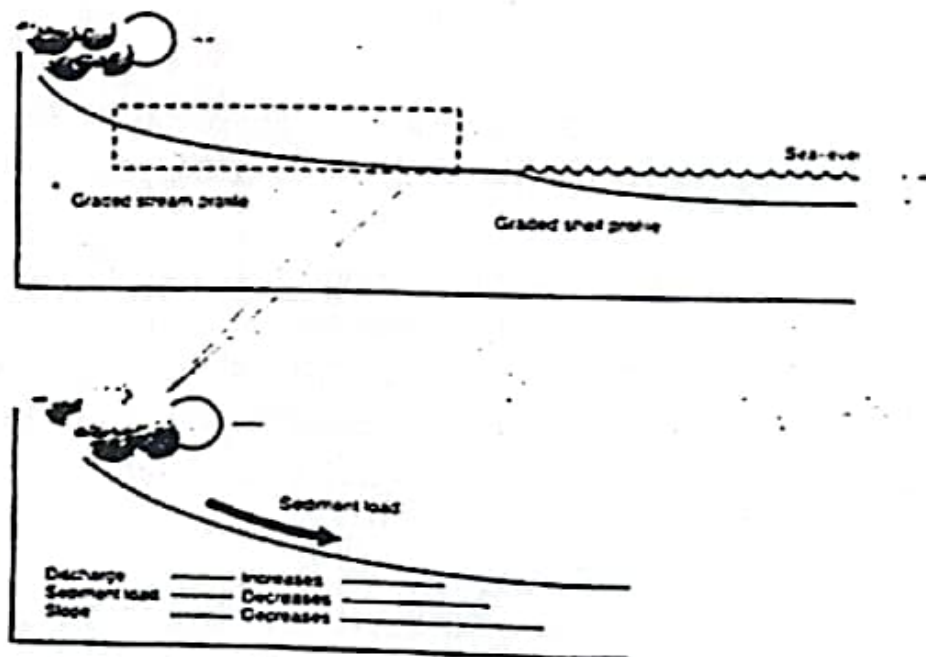


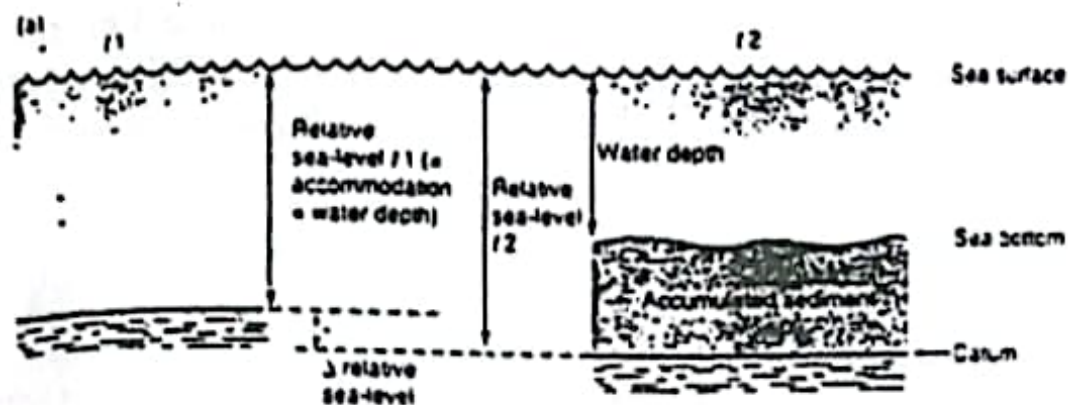
Figure 2.4, Definitions of base level in alluvial, shoreline and shelf environments

Sediment supply fills the accommodation created and controls water depth:

Accommodation = eustasy + subsidence + compaction

Sediment supply fills the available accommodation. If the rate of sediment supply exceeds the rate of creation of accommodation at a given point, water depths will decrease:

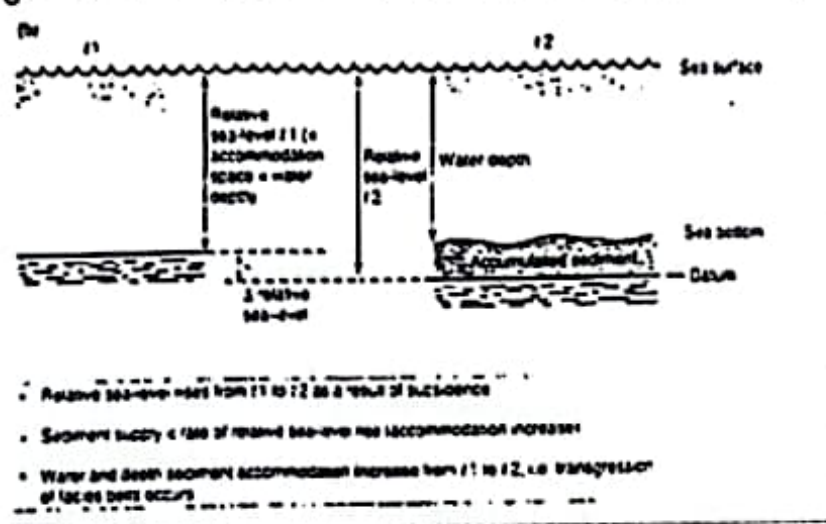
Water depth = eustasy + subsidence + compaction – sediment thickness deposited



- Relative sea-level rises from t1 to t2 as a result of subsidence
- Sediment supply > rate of relative sea-level rise (accommodation increase)
- Sediment accommodation increases from t1 to t2 but water depth decreases resulting in facies belt regression

Figure 2.5; Diagram illustrating how eustatic sea level rise/fall and subsidence/uplift can create/destroy accommodation. The rate at which sediment fills the space created controls water depth and whether progradation or retrogradation of facies belts is observed.

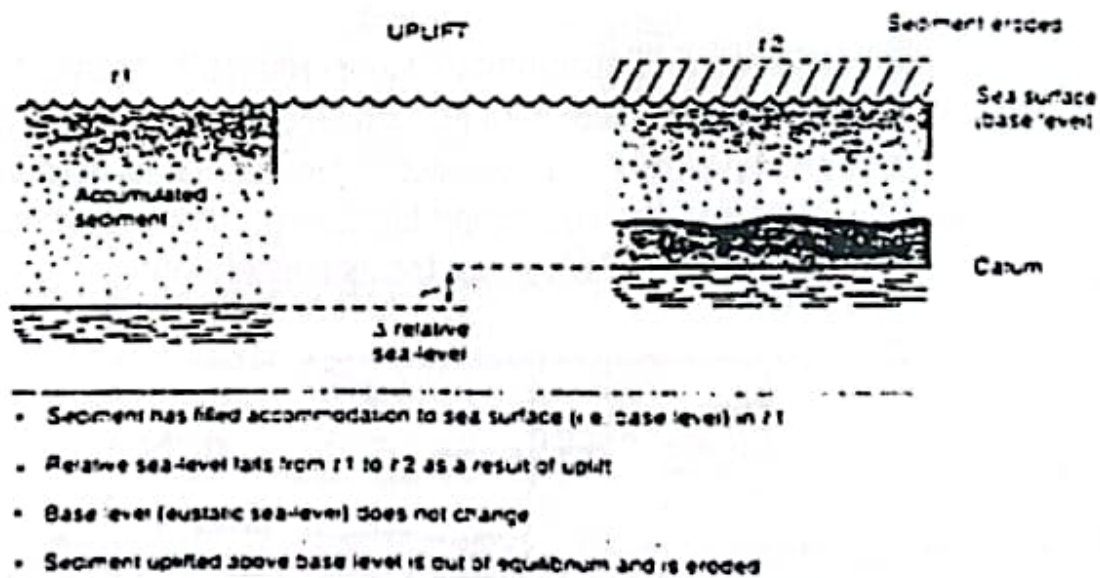
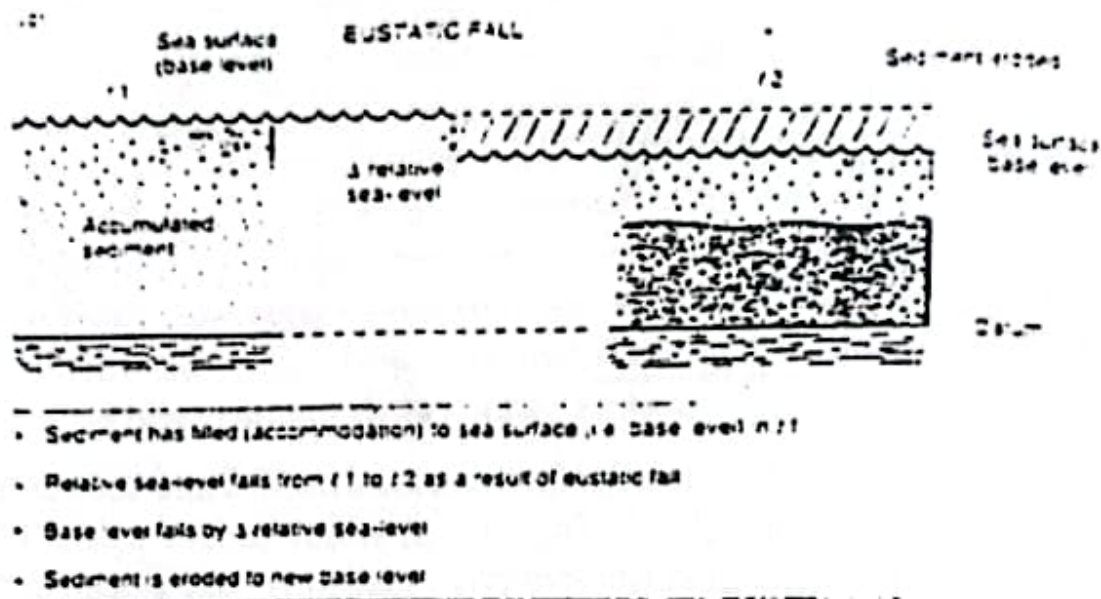
(a). Relative sea level rises and accommodation increases from time 1 to time 2 due to subsidence, but the rate of sediment accumulation at this point is greater than the rate of relative sea level rise and so water depth decreases from time 1 to time 2. In the depositional record, the interaction of these parameters would result in an overall regressive character to the vertical facies succession



- Relative sea-level rises from t1 to t2 as a result of subsidence
- Sediment supply < rate of relative sea-level rise (accommodation increase)
- Water and depth sediment accommodation increases from t1 to t2, i.e. transgression of facies belts occurs

(b). Relative sea level rises and accommodation increases from time 1 to time 2 due to subsidence, but the rate of sediment accumulation is less than the rate of

relative sea level rise and so water depths increase from time 1 to time 2. In the depositional record this may be apparent as a transgressive vertical facies succession. The same patterns would occur for a relative sea level rise due to a eustatic rise of the same rate



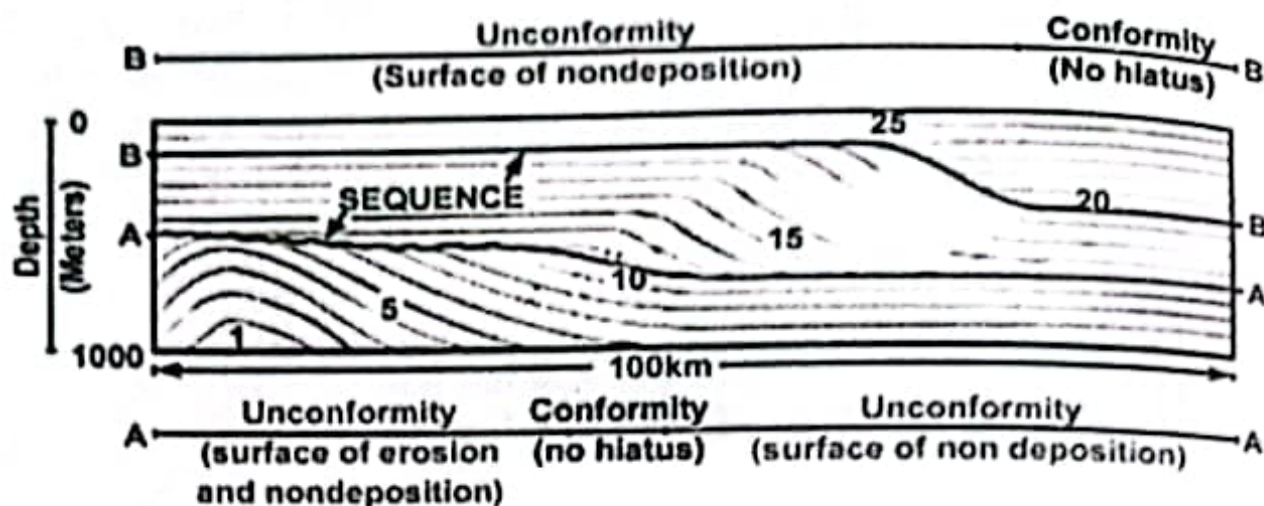
(c) Accommodation is destroyed by tectonic uplift (and more locally salt or mud diapirism) and/or eustatic sea level fall. Relative sea level fall at the basin margin (where accommodation space is limited) causes erosion while in the basin centre (where accommodation space is not limited) by an increase in sediment supply. The increase in sediment supply to the more basinal areas is due to both the erosion of previously deposited sediment and bypass of areas where accommodation space is now limited.

CHAPTER THREE

TOOLS USED IN SEQUENCE STRATIGRAPHIC INTERPRETATION

3.1 Depositional sequences

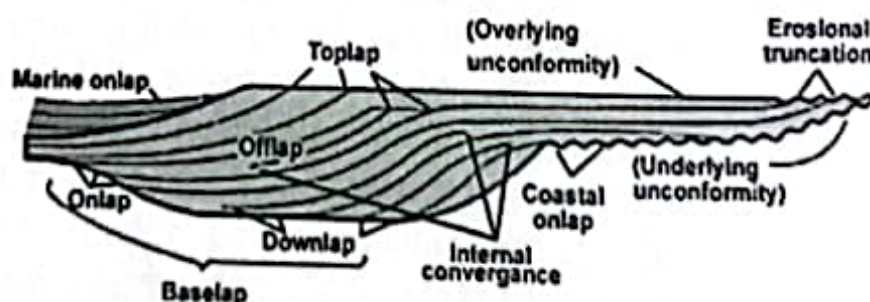
The fundamental medium-scale stratigraphic unit is the **depositional sequence**. This can be defined as a coherent packet of strata that are genetically related and which can be traced for considerable distances across the basin. The minimum stratigraphic unit that can be called a depositional sequence must have significance in the basin either in terms of thickness or in terms of geological time. Each depositional sequence is the result of the interaction of tectonics, thermal history, sea level change and sediment supply. Depositional sequences are recognised by bounding unconformities or laterally correlatable conformities at their bases and tops (fig. 3.1). These unconformities, recognised as erosional events, are by implication related to falls in relative sea level. It follows that, if the sequence bounding unconformities were created by relative lowering of sea level, then the depositional sequence must have been deposited during periods of relative sea level rise. A depositional sequence therefore represents a full eustatic cycle and should have a predictable succession of depositional settings related to the behaviour of relative sea level. It is this predictive element that potentially makes the technique useful.



(From Mitchum, Vail, Thompson, 1977; reprinted by permission AAPG)

Figure 3.1 A depositional sequence

The boundaries and stratigraphic terminations of depositional sequences are crucial to their definition and correlation. While terms such as nonconformity, angular unconformity, disconformity and para-conformity have been widely used to describe particular types of unconformity, in depositional sequence analysis it is the relationship of strata to the unconformity itself that is most important. Consequently, a range of new terms, including those derived from seismic reflection patterns, has evolved to describe the geometrical relationships between strata and a depositional sequence boundary or any other surface within a depositional sequence. These types of geometrical relationships not only help to define a depositional sequence boundary; they also provide clues to the origin of the unconformity. These terms can be defined as follows (fig. 3.2):



(From Vail et al. 1976)

Figure 3.2; Various unconformity boundaries of a depositional sequence

3.2 Depositional geometries of stratigraphic sequences

The geometries or patterns of strata, most frequently determined from seismic reflectors, provide the key to interpreting and analyzing systems tracts and sequence boundaries in seismic sequence stratigraphy. The most coarse internal elements of sequence systems tracts are parasequences. The balance between sediment supply and relative sea level controls overall depositional geometries, which fall into the following three major categories:

- progradational
- aggradational
- retrogradational

Progradational geometries result from a dominance of sediment supply over accommodation space. This surplus causes deposition to migrate basinward, where sediments have space. Progradation produces stratal clinoforms which display the outward migration of the offlap break. The *offlap break, or inflection point*, frequently represents the shelf edge, separating coastal plain topsets and neritic facies from upper slope (bathyal) foresets and basinal facies. Prograding complexes are characteristic of the shelf margin, highstand, and portions of the lowstand systems tracts, where internal strata (clinoforms) may represent either parasequences or low-order (i.e., fifth or sixth) cyclostratigraphic units. On well logs, an upward-coarsening profile of sedimentary components suggests progradation. This profile results from an upward shift from fine-grained, outer-neritic sediments to coarser-grained, shoreline-littoral depositional environments as sediments accumulate at a given location. *Aggradational* geometries occur when sediment supply matches the increase in accommodation space caused by either rising sea level or tectonic subsidence. This balance produces vertically stacked facies and an offlap inflection point that does not migrate. Electric logs generally show repetitive units, or parasequences, of upward-coarsening patterns or mixed components.

Retrogradational geometries result from either sediment starvation or a net increase in accommodation space, due to a relative sea level rise, over sediment supply. Facies patterns, including the shoreface, migrate landward. We see an upward shift from coarse-grained, inner-neritic deposits to deeper, pelagic depositional environments, as sea level rises and the shoreline migrates. Retrogradational

geometries are associated predominantly with transgressive systems tract deposition, and produce fining-upward electric log patterns. The transgressive systems tract geometry of (Figure 3.4) is the result of low sediment supply and/or a rapid rise in sea level, which frequently results in the erosion of the continental shelf

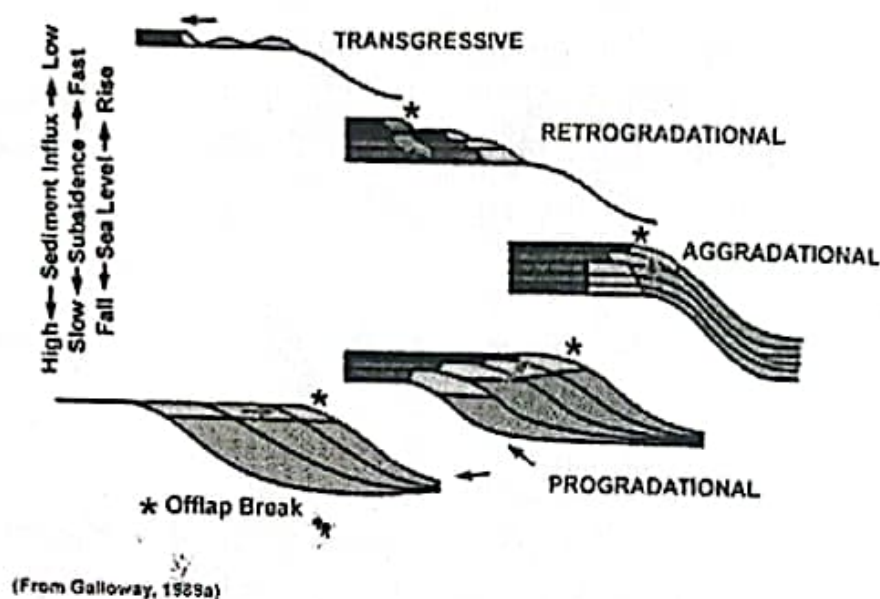


Figure 3.4 Depositional geometries

3.3 Depositional system and system tracts

A **depositional system** can be defined as the major three-dimensional assemblages of lithofacies enclosed within sequence boundaries and genetically linked by active (modern) or inferred (ancient) processes and environments. Depositional systems can be subdivided into smaller units of stratigraphy called **systems tracts**. These are defined as a three-dimensional unit of deposition comprising an associated group of contemporaneous depositional systems, each being defined by stratal geometries at bounding surfaces, position within the sequence and internal parasequence stacking patterns. Sequence stratigraphic theory maintains that, within each system tract, there is a *predictable* succession of these associated depositional systems (fluvial, deltaic, shelf, etc.). The location and nature of depositional systems has been related to relative sea level fluctuations. The current view is that it is the *rate of sea level change* that is the critical factor in determining stratigraphic response, especially in relation to the *rate of subsidence*.

3.4 System tracts/sea level cycle relationships (the Exxon model)

Systems tracts are recognised and defined by the nature of their boundaries and their internal geometry. Within any one relative sea level cycle, the original Exxon sequence model recognised three basic system tracts (lowstand, transgressive and highstand), which are laterally linked sets of environments related to specific parts of the relative sea level change curve (figures 3.5 and 3.6). The original scheme has since been modified by the recognition of other systems tracts and elements. It is very easy to become lost in the complexities of systems tract terminology. It is worth remembering the purpose of the recognition of systems tracts within stratigraphic successions. Each systems tract represents a fundamental mapping unit for stratigraphic prediction. It contains a set of depositional systems with consistent palaeogeography and depositional polarity. A single palaeogeographic map can be drawn for each systems tract.

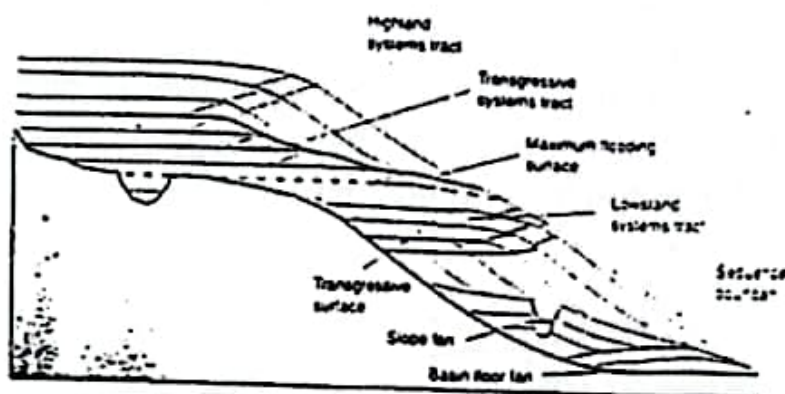


Figure 3.5; Strata geometries in a succession on a shelf-break margin. Five separate sedimentary packages are shown, traditionally assigned to three systems tracts: lowstand, transgressive and highstand

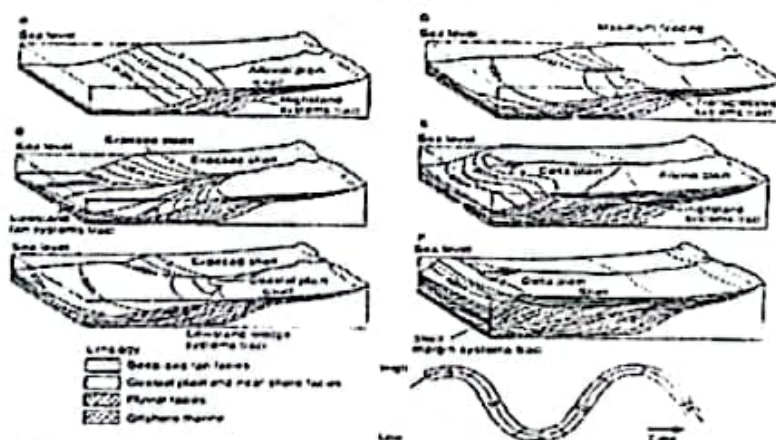


Figure 3.6; Characteristic systems tracts and their relation to the eustatic curve according to the Exxon group. These block diagrams are extremely idealised and have a strong vertical exaggeration.

3.4.1 Lowstand system tract

Lowstand systems tracts (LST) form the basal (i.e. stratigraphically oldest) systems tract in a depositional sequence. It is deposited when relative sea level fall is rapid and no space is available for further sedimentation. Falling relative sea level at the offlap break of a shelf-beak margin will have a pronounced effect on the rivers systems. Before the relative sea level fall, the rivers will have more-or-less maintained a graded river profile. When relative sea level falls at the offlap break, the river profile must adjust to the lowered base level. Consequently, the previously deposited topsets (alluvial plain, coastal plain and/or shelf deposits) of the previous sequence are incised by streams. The reworked sediments plus the fluvial load from the hinterland are transported basinward and sedimentation is transferred to the basin floor and basin slope. The lowstand deposits therefore directly overlie the highstand clinoforms of the earlier depositional sequence. Since the rivers are not free to avulse, the sediment is focused towards the same point on the slope. An inherently unstable situation therefore develops and sedimentary processes are dominated by large-scale slope failure, resulting in bypass of the slope and the formation of submarine fans in the basin. These processes continue while relative sea level falls and the river system is forced to incise.

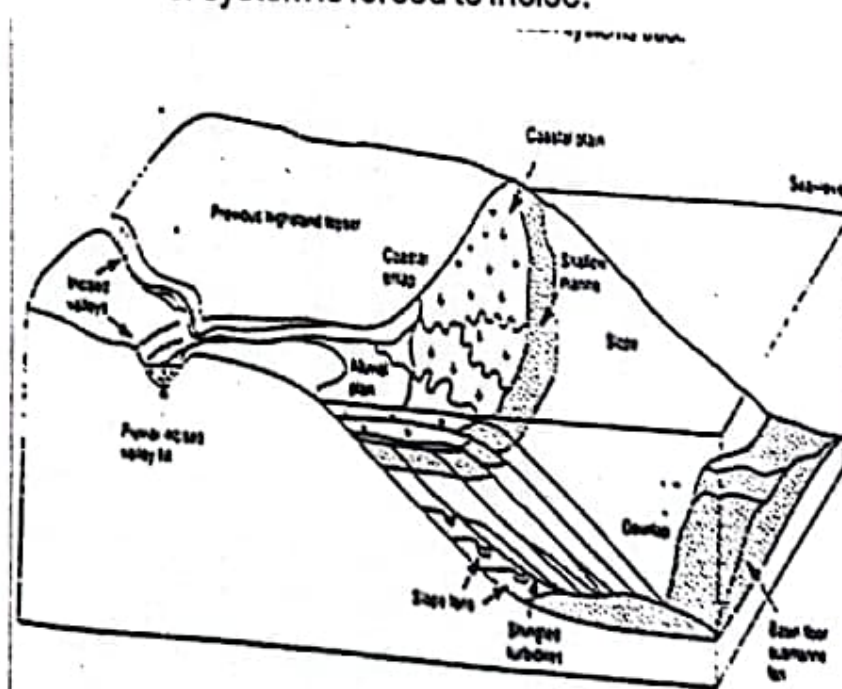


Figure 3.7; Components of the lowstand systems tract on a shelf-break margin. These include a basin-floor fan and a slope fan, but the diagram also shows the active systems of the lowstand wedge, namely valley fill, alluvial and coastal plain topsets, a

shallow marine belt and an active slope system, which in its early stages may contain shingled turbidites.

When the low point of relative sea level is reached, the river profile stabilises again and a prograding topset-clinoform system becomes established. The first topset of this system will onlap below the level of the previous offlap break. This is known as a *downward shift in coastal onlap below the level of the offlap break* and is indicative of a Type 1 sequence boundary. Lowstand systems tracts are thus always associated with an underlying Type 1 unconformity. After this point is reached in the sea level cycle, a rise in relative sea level begins. Initially the rate of rise of relative sea level is low and, together with the limited topset area of the prograding system, this results in a low rate of creation of topset accommodation. Sediment supply will therefore exceed accommodation, so that the system will prograde. However, the accelerating rate of accommodation creation may at some stage begin to outpace sediment supply. This will result in a change from progradation to aggradation and retrogradation and the onset of the next (transgressive) systems tract. It follows that lowstand systems tract consist of two elements:

1. A unit of submarine fans deposited during falling relative sea level (lowstand fans and slope fans)
2. A topset-clinoform system, initially progradational but becoming aggradational, deposited during a slow rise in sea level (lowstand wedge). These could be treated as separate and distinct systems tracts, because the fans and the topset-clinoform system never have been in depositional continuity. However, traditionally both are placed in a single lowstand systems tract on the basis that the boundary between the two may be gradational rather than distinct, with submarine fans forming much of the slope portion of the lowstand wedge.

Two distinct fan units can frequently be recognised within lowstand submarine fans:

Lowstand fans (or basin floor fan) are basin floor fan units detached from the foot of the slope. They are deposited at the base of the basin slope during the late relative sea level fall and early relative sea level rise. They are associated with the incision of fluvial valleys into the shelf and erosion of canyons in the slope. Sediment then bypasses the shelf and slope via valleys and canyons to feed the basin-floor fan. The base of the lowstand fan is coincident with the lowstand systems tract and is

correlated with the Type 1 sequence boundary.

The top of the fan may be a downlap surface to the subsequent lowstand prograding wedge, if it prograded far enough, or it may be a downlap surface for any overlying slope fans.

Slope fans (sometimes termed slope front fill) are deposited on the middle or base of the basin slope during late relative sea level fall or early relative sea level rise. They are characterised by turbidite and debris-flow deposition. Slope fans may be coeval with the basin-floor fans or with the early part of the lowstand wedge. The top of the slope fan may be a downlap surface for the middle and upper parts of the lowstand wedge. It is currently not clear whether these two distinct fan units can be distinguished in all successions in all basins. A two-fold division should not be forced on a submarine fan succession if the evidence does not suggest it. Some workers assign lowstand fan deposits to their own systems tract because they are formed not at lowstand but during the falling stage as a result of sediment bypass and reworking as the continental shelf is exposed to erosion. This has been termed the **lowstand prograding-wedge systems tract (LPWST)**. **Lowstand prograding wedges** are topset-clinoform systems deposited during the late relative sea level fall or early relative sea level rise at times of low but slowly changing sea level. Deposition is initially confined to the areas around the mouths of the incised rivers. Since little if any topset accommodation is created at this time, the sediment largely bypasses the topsets to be deposited on the clinoform slope. Slope instability and occasional fan deposition is likely to occur. The bottomsets of the early lowstand prograding wedge may therefore contain interbedded turbidites, which often have a characteristic "shingled" seismic facies. As relative sea level begins to rise, the incised fluvial valleys begin to be backfilled in their lower reaches with fluvial or estuarine deposits, while topsets of the prograding wedge begin to be deposited. As relative sea level accelerates, accommodation volume increases and this results in an upward increase in coals, overbank mudstones, lagoonal deposits and tidal influence. It also leads to a decrease in the connectivity of fluvial sand bodies. The transition to the overlying transgressive systems tract can be a gradational turnaround from progradation to retrogradation. Alternatively, when relative sea level rises above the level of the offlap break of the previous sequence, a huge increase in topset accommodation volume occurs (fig. 6.1) and the transition from lowstand wedge to transgressive systems tract is abrupt. This boundary may be called the **transgressive or flooding surface** (also sometimes termed the maximum progradation surface or top lowstand surface). It is marked by a change in

parasequence stacking geometry from progradational (in the lowstand wedge) to retrogradational (in the transgressive systems tract). The lowstand wedge deposits are often sandier than the preceding highstand systems tract deposits due to the recycling of sands from the highstand topsets. In a predominantly muddy system, sandy lowstand wedges can be bounded by the underlying shales of the highstand systems tract and the overlying shales of the transgressive systems tract, thus forming stratigraphic traps.

3.4.2 Transgressive system tracts

The transgressive systems tract (TST) is the middle systems tract in a sequence and overlies lowstand systems tract deposits. It is deposited at a time during the relative sea level rise cycle when topset accommodation volume is increasing faster than the rate of sediment supply. At the base of the transgressive systems tract is the **transgressive or flooding surface**, which marks a transgression caused by a rapid relative sea level rise. Transgressive systems tract deposits comprise topset parasequences with few associated clinoforms. The parasequences are retrogradational (i.e. they back-step onto the basin margin) with strong onlap in the landward direction and downlap onto the transgressive surface in a basinward direction.

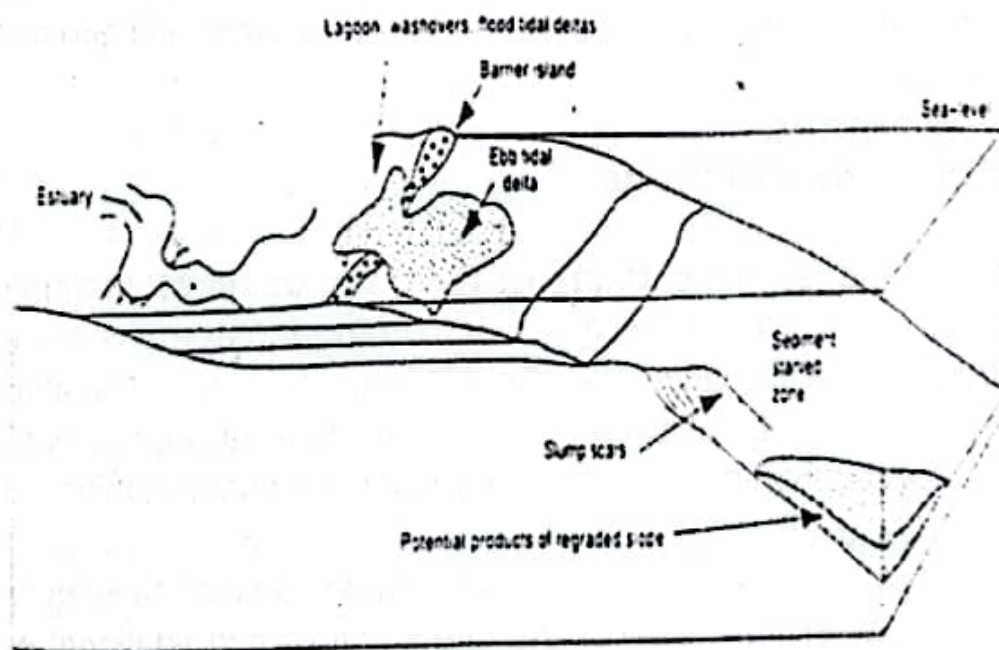


Figure 3.8; Components of the transgressive system tract. These are all topsets and are shown here to have significant tidal influence due to the wide shelfal area of the drowned lowstand topsets. Deposition includes estuarine, lagoonal, barrier and tidal depositional systems, which pass seaward into a shelfal condensed zone

Within transgressive systems tracts, the active depositional systems are topset systems, alluvial, paralic, coastal plain and shelfal. These depositional systems may exhibit evidence of an undersupply of sediment. They may be rich in coals, overbank deposits and lagoonal or lacustrine deposits. Drainage systems may be flooded to form estuaries, while any deltas will be shelf deltas. Transgressive systems tracts are characterised by wide shelf areas and tidal influence may be widespread. The transgressive systems tract passes distally into a **condensed sequence**. This is characterised by extremely low deposition rates and the development of very thin successions of facies such as glauconitic, organic-rich and/or phosphatic shales or pelagic carbonates.

The maximum rate of relative sea level rise occurs at some time within the transgressive systems tract. After this, the rate of relative sea level change decreases and therefore the rate of creation of topset accommodation decreases. When the rate of topset accommodation volume decreases to a point where it just matches sediment supply. At this point, the parasequence sets change from being retrogradational to being aggradational. The surface at which this change takes place is the **maximum flooding surface (MFS)**. Transgressive systems topsets tend to have a lower sand content than those of other systems tracts because little of the fine-grained clastic sediment bypasses the topsets. The transgressive systems tract therefore often contains sealing horizons for topset reservoirs and sometimes hosts source rocks.

3.4.3 Highstand system tracts

The **highstand systems tract (HST)** is the youngest systems tract in the depositional cycle. It forms after maximum flooding as the relative sea level rise slows down during the latest part of a relative sea level rise, comes to a standstill and then begins a slow fall in the early part of a relative sea level fall. At this time, the rate of creation of accommodation is less than the rate of sediment supply.

Highstand systems tract deposits are laid down at a time of decelerating relative sea level rise. This results initially in the deposition of aggradational parasequences overlain by progradational parasequences with clinoform geometries. These parasequences onlap onto the underlying sequence boundary in a landward direction. In a basinward direction, they downlap onto the top of the transgressive systems tract or lowstand systems tract deposits. There is therefore a prominent

downlap surface below a highstand systems tract sequence. Condensed sequences may develop during the early stages of a highstand systems tract before major progradation begins.

Highstand systems tract deposits comprise shelf to non-marine sediments. At first, the depositional systems may be similar to those in the transgressive systems tract.

However, the infill of shelf areas by progradation combined with the decrease the rate of relative sea level rise may lead to a decrease in tidal influence during a highstand systems tract and a decrease in the amount of coal, overbank mudstones and lacustrine/lagoonal shales. Highstand conditions offer the possibility of thick subaerial deposition of fluvial sediments. Initially, since a great deal of new space is added, rivers will aggrade with a vertical stacking pattern. As the final equilibrium or graded profile is reached, the rate of new space being added decreases. This encourages the formation of lateral stacking patterns. During this phase of the relative sea level cycle, channel sandbodies will become more common and more connected. Widespread fluvial deposition should cease at the inflection point of the falling limb of the relative sea level curve. Highstand systems tract deposits form the top of the depositional sequence. They may be considerably reduced in thickness due to erosion accompanying the next cycle fall in sea level.

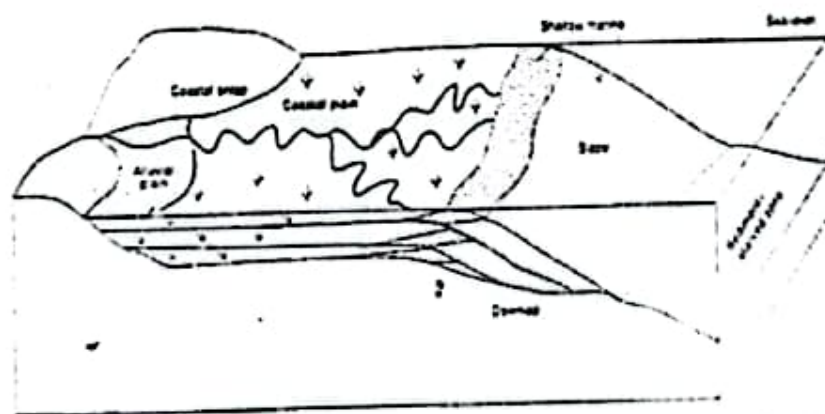


Figure 3.9; Components of the highstand systems tract on a shelf-break margin. These include topset (alluvial, coastal), shallow marine and slope systems.

3.5 Sequence boundaries

In the Exxon models, sequence boundaries are located at the unconformity surfaces.

Two types of unconformity are recognised (Fig 3.10).

1. **Type 1 unconformities** develop where sea level fall is rapid and is faster than tectonic subsidence. The coastline may move out close the shelf margin. Extensive sub-aerial erosion takes place. Fluvial valleys on the shelf become incised submarine canyons on the continental slope are deepened. These fluvial and canyon systems act as conduits down which clastic detritus is transported to the base of the continental slope, where extensive lowstand systems tracts develop. Type 1 unconformities represent a time when facies belts underwent a substantial basinward shift. Highstand deposits below the unconformity may be deeply eroded. Stratigraphic sequences across a Type 1 unconformity will exhibit a **facies dislocation**, that is, the superposition of a relatively proximal on a significantly more distal facies without the preservation of the intermediate facies.
2. **Type 2 unconformities** develop when relative sea level falls slowly. Consequently, there is a gradual basinward shift of facies tracts and only minor subaerial exposure and erosion. Type 2 unconformities are much more difficult to identify in both outcrop and seismic records since they are not accompanied by deep be recognised on seismic data by a downward shift in coastal onlap to a position landward of the offlap break, where topset reflections can be seen onlapping an older topset erosion or abrupt facies. The sequence boundary may be recognised on seismic data by a downward shift in coastal onlap to a position landward of the offlap break, where topset reflections can be seen onlapping an older topset

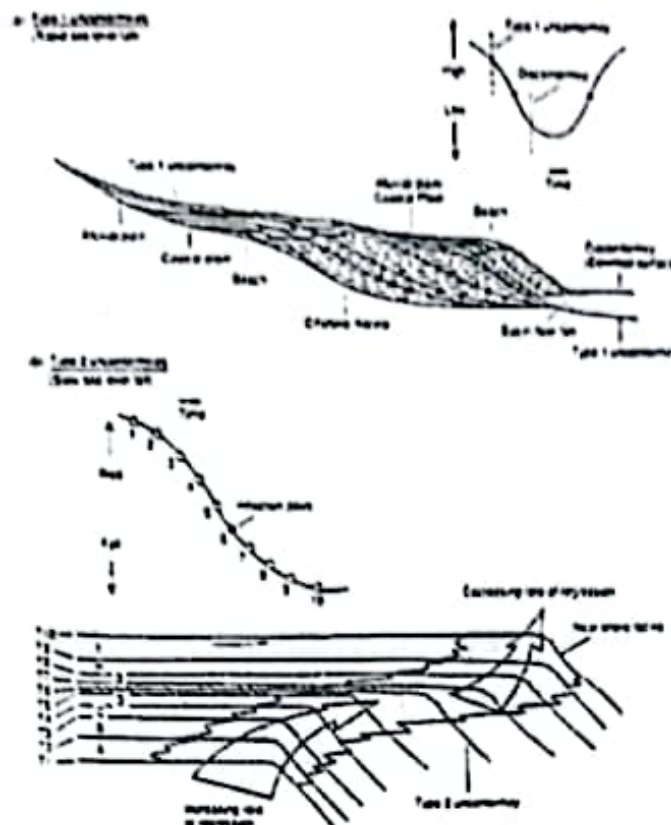


Figure 3.10; Type 1 and Type 2 unconformities. Type 1 unconformities (a) erode into the older shelf sediments and may underlie basin-floor fans. They are believed to be formed during a rapid sea level lowering. The sediments of the second depositional sequence downlap onto a disconformity or onlap the Type 1 unconformity.

- (b) Type 2 unconformities do not strongly erode the underlying depositional sequence, but signal a change from prominent progradation to aggradation as the rate of regression slows. Overlying sediments may onlap the Type 2 boundary landward of the shelf edge, although this is not illustrated above. Type 2 unconformities are interpreted to form at the inflection point of a slow relative sea level fall

Based on the nature of the basal bounding unconformity, the Exxon group subdivided depositional sequences into:

1. **Type 1 sequences**, which are bounded at the base by a Type 1 unconformity and are composed of lowstand, transgressive and highstand systems tracts.
2. **Type 2 sequences**, which are bounded at the base by a Type 2 unconformity and consist of shelf margin, transgressive and highstand systems tracts. This terminology has not been widely used outside the Exxon group. It

should be noted that, while sequence boundaries develop at times of lowest relative sea level, these may not be the same as the times when eustatic sea level is actually at its lowest. Sequence boundaries typically represent the time of maximum rate of fall in sea level. Where the eustatic curve approximates to a sine curve, as shown in most Exxon diagrams, the sequence boundary corresponds to the inflexion point in the falling curve. After this time, according to the Exxon model, tectonic subsidence outpaces and relative sea level rises. In practice, there will normally be an offset time between the inflection point and the time of lowest relative sea level. This will vary depending on the rate of sea level change and the rates of tectonic subsidence and sediment supply. These rates vary widely, depending on the nature of tectonic and eustatic controls. This observation becomes critical when attempts are made to use sequence boundaries to date eustatic sea level change and to derive global cycle charts.

3.6 Interpretation of 3D seismic data

The objective of seismic interpretation is to transform a stacked reflection seismic profile into a laterally continuous structural/geologic model of the subsurface. The interpretation of seismic is non-unique; there are infinite numbers of theoretically correct models. However the only reasonable models are those that are consistent with available ground truth, geologic principles and processes, and generally accepted seismic interpretation methodologies.

The test of a good interpretation is consistency rather than correctness. It is rare that the correctness or incorrectness of an interpretation can be ascertained because the geology is rarely ever known in adequate detail. Hence, it is always better to explore various possibilities, but usually only one is wanted and it is that which offers solution to the problem and offers the greatest possibilities for significant profitable hydrocarbon accumulation-the whole essence of interpretation. Two main approaches exist to the interpretation of seismic sections; structural analysis and stratigraphical analysis.

3.6.1 Structural analysis

The main application of structural analysis of seismic sections is in the search for structural traps containing hydrocarbons. Structural interpretations are best done on

migrated data where reflections are in their proper spatial locations and time-depth conversions are relatively straightforward if subsurface velocities are known. Most structural interpretation is carried out in units of two-way reflection time rather than depth, and time-structure maps are constructed to display reflection geometry events by means of contour of equal reflection time. The first step is usually reflection identification with bedding planes based on correlations with observations in boreholes, velocity information and synthetic seismograms or previous experience in the area.

Horizons are first mapped on cross sections and the sections are compared at line intersections to identify the same horizons on all lines. The horizons are carried along all lines in the prospect area to the extent that data quality permits. Maps such as structural contour maps can be prepared from the tracked horizons. Contour maps showing variation of reflection time interval between two reflectors, sometimes referred to as isochron maps, are also obtainable and these can be converted into isopach maps (useful in studying structural growth) by the conversion of reflection time intervals into thicknesses using appropriate interval velocity

3.6.2 Geologic structures sought in oil exploration

Over the period of more than four decades during which the reflection method has been used in exploration it has been possible to obtain useful information on many types of structural features which might be responsible for the entrapment of hydrocarbon. Corrected record sections, particularly those presenting data obtained with modern field and processing techniques, often make the presence of such structures obvious to the eye.

The most common structural targets associated with oil entrapment are anticlines and faults. Anticlines are generally easy to see on record sections, and faults are more than marginal displacement should be discernible, although some types are more readily recognizable than others.

3.6.3 Anticline

Anticlines can easily be mapped by reflection if the data are of good quality and if the closure is greater than spurious irregularities in apparent structure such as are caused by lateral velocity changes. Anticlines are observable where reflections dip

down both ways from a high point. They are not necessarily oil traps. To form a trap, the anticline must be closed, with dip downward in all directions, not just the two directions on the line, to prevent the escape of oil. Oil-bearing anticlinal structures may be associated with tectonic forces as well as with deformations due to the upward push of diapiric features underneath.

A closed contour on a map, that is, a contour that curve around to meet itself, indicates a closure, either a closed high or a closed low. Low closed features are not prospective, so they do not attract much attention unlike the high ones. An anticline with very steep dip can be difficult to interpret because sound must be reflected perpendicularly to return to its source, steeply dipping reflections can be recorded only from some distance away from that feature.

3.6.4 Faults

Faults detection on seismic section can be quite easy under favourable circumstances. Often, however, the indications are subtle, and the identification and delineation of such features can be quite challenging. Because of the role faults often play in the entrapment of hydrocarbons, the techniques for finding and mapping have considerable practical importance

The practical indications of faulting on seismic sections are the following:

- 1) Discontinuities in reflections falling along an essentially linear pattern
- 2) Misclosures in tying reflection around loops
- 3) Divergences in dip not related to stratigraphy
- 4) Diffraction patterns, particularly those with vertices which line up in a manner consistent with local faulting
- 5) Distortion or disappearance of reflections below suspected fault lines

Where discontinuities are well defined, the position of the fault trace may be evident on the record sections even to someone entirely inexperienced in seismic interpretation.

CHAPTER **FOUR**

HOW TO APPLY SEISMIC STRATIGRAPHY TO THE INTERPRETATION OF DEPOSITIONAL ENVIRONMENTS

4.1 Depositional Environments

A depositional environment is a **geomorphic unit** in which deposition takes places. It is a geomorphic unit that has certain distinctive chemical, biological, and physical characteristics that is different from adjacent depositional areas. There are different types of depositional environments:

4.1.1 Types of depositional environment:

Depositional settings may be classified into three broad categories, as follows Continental (beyond the reach of marine flooding), shallow marine/marginal marine/transitional (intermittently flooded by marine water), and marine environment (permanently covered by marine water).

Continental, including alluvial fans, fluvial plains, sandy deserts, lakes, and glacial regions. It is dominated by the process of erosion, transport and deposition:

Transitional /marginal marine/shallow marine, including deltas, estuaries, barrier island complexes, and glacial marine environments. It is dominated by the process of transport and deposition;

Marine/deep marine, including terrigenous shelves or shallow seas, carbonate shelves or platforms, continental slopes, continental rises, basin plains, ocean ridges, and ocean trenches. Dominated by the process of transport and deposition.

We will now discuss each of these depositional environments in detail:

4.1.2 Continental Environment

The different sub environments under the continental environment classification are discussed in detail in this section:

Alluvial Environment

Alluvium (from the Latin, *alluvius*, from *alluere*, "to wash against") is loose, unconsolidated soil or sediments, which has been eroded, reshaped by water in some form, and redeposited in a non-marine setting. Alluvium is typically made up of a variety of materials, including fine particles of silt and clay and larger particles of sand and gravel. When this loose alluvial material is deposited or cemented into a lithological unit or lithified, it would be called an alluvial deposit.

Aeolian Environment

Aeolian processes, also spelled eolian, or æolian, pertain to wind activity, and specifically to the wind's ability to shape the surface of the Earth (or other planets). Winds may erode, transport, and deposit materials, and are effective agents in regions with sparse vegetation and a large supply of unconsolidated sediments. Although water is a much more powerful eroding force than wind, aeolian processes are important in arid environments such as deserts.

Fluvial Environment

Fluvial involves sediments that are formed by activities of river, stream, and associated with gravity flow process. There are two kinds of environmental settings from fluvial deposits. They are alluvial fans and river systems. Fluvial processes include the motion of sediment and erosion or deposition on the river bed.

Alluvial deposits have gross – cone-like shape and form a convex-up construction in cross section. These deposits consist of abundant gravel-sand detritus on mostly

fairly steep depositional slope. They are poorly sorted and are common from the base of mountain range with many sediment supplies.

River systems- There are three major kinds of river based on the sinuosity channels, bars, and the number of channels. They are meandering (single-channel), braided (multiple-channel), and anastomosing rivers. Some meandering rivers will form a characteristic morphology, called oxbow lake. In braided river, deposition of sand and gravel grain sizes happens around the channel.

4.1.3 Shallow Marine Environment.

The most prominent depositional environment under the shallow marine section is the deltaic environment:

Deltaic Environment

A delta is a landform that is formed at the mouth of a river, where the river flows into an ocean, sea, estuary or lake. Deltas are formed from the deposition of the sediment carried by the river as the flow leaves the mouth of the river. Nowadays, although Delta doesn't form a perfect triangle, the term Delta is still used to describe the subaerial or subaqueous deposition of fluvial processes into a body of water like sea.

4.1.4 Deep Water Marine Environment

Deep water depositional environments are those where sediment accumulated in water deeper than about 200 m (e.g., off the edge of the shelf).

Near shorelines, it is usually siliciclastic in composition because of the proximity to beaches, deltas and rivers. Further offshore, you might run into bioclastic sediment that is the product of biologically-influenced chemical sedimentation.

Examples include:

A. Pelagic sediments- fine-grained sediments deposited far from land influence by slowly settling particles suspended in the water column. These include:

Carbonate ooze - carbonate shells of tiny planktonic organisms (foraminifera, coccolithoforids)

Silica ooze - silica shells of tiny planktonic organisms (radiolarian, diatoms)

Red clay - clay-sized particles of continental origin (mostly transported by wind). Very high Fe and Mn contents produce the coloration, and frequently Mn pavements, crusts and nodules are found in this environment.

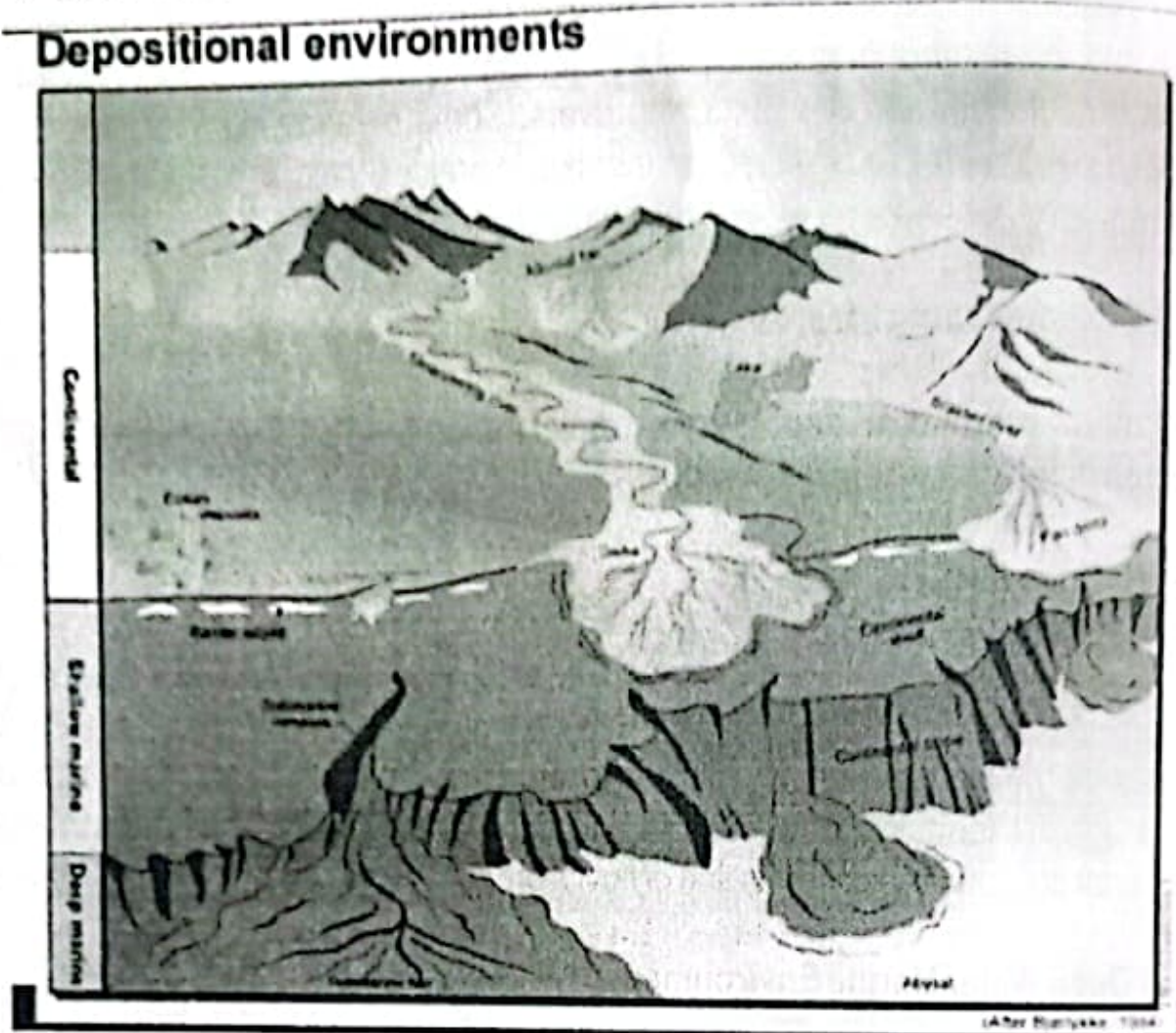


Figure 4.1: Classification of Depositional Environments.

B. Turbidites - fining-upward deposits that were transported seaward in deep-sea channels and canyons by high-density, sediment laden currents. In map view, turbidites form fans that spread outward on the sea floor from the mouths of the canyons.

4.2 Background to Seismic Stratigraphic Interpretation

Individual sedimentary reflections can be considered **timelines**. i.e. they are representing a short time interval of continuous sedimentation conditions (Veeken, 2008). This timeline concept signifies that seismic reflections tend to cross laterally

through different depositional environments and therefore they can incorporate various lithofacies units. In Figure 3.2 (Hinz 1983), it is seen that, if a specific seismic loop (reflection) is followed from the left to the right, it goes from a sub-parallel topset into a gently dipping foreset and finally it is transitioned into a sub-parallel bottomset. This two-way travel time geometrical relationship can be translated in terms of depositional environments:

We can say it goes from a sand-prone shelf (proximal = closer to source area of sediments), into a shale-prone slope (further from the source and thus finer-grained) and ending up in the distal shale-prone deeper basinal environment (distal = far from sediment source).

Being able to determine depositional environments from the seismic record is of paramount importance to the petroleum explorationist because some depositional environments are more likely than others to generate hydrocarbons or to provide seals and reservoirs necessary for hydrocarbon accumulation. This is the basis for interpreting depositional environments on the seismic record.

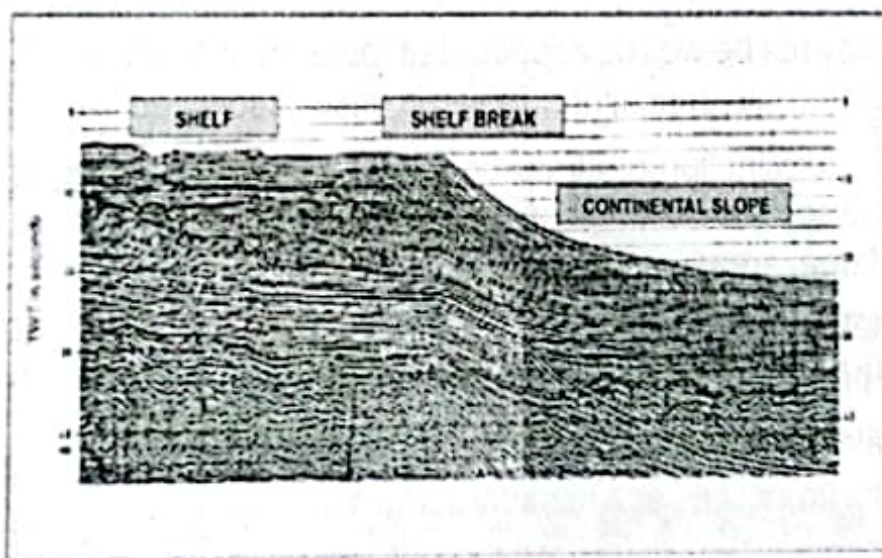


Figure 4.2: Seismic reflections passing continuously from a top-, fore-, to a bottomset configuration (Adapted from Veeken 2007).

4.3 Interpretation Steps

The first phase in seismic stratigraphic studies of a basin fill is to delineate genetically related units, which can be traced for considerable distance across the basin, called **Depositional Sequences** (Mitchum et al. 1977). These sequences are further

subdivided into individual **system tracts** (VanWagoner et al. 1987).

It is to be noted that depositional sequences are bounded by unconformities or correlative conformities, mostly represented on the seismic sections as upper and lower boundaries of the sequence.

So, the geometries of seismic reflectors are the key to interpreting sequence boundaries. To extract sequence bounding surfaces, we mark reflector terminations such as erosional truncation, toplap, offlap, downlap, onlap or concordance stratigraphic surfaces. The upper boundary of a sequence is determined by interpreting either erosional truncation, toplap or concordance reflections while the lower boundary of a sequence is interpreted by looking for onlap, downlap or concordance reflections. For the sake of simplicity, each of these terms are defined once again below:

A toplap: is a termination of inclined strata, or seismic reflection, against an overlying surface mainly as a result of non-deposition and/or minor erosion. In a toplap, the unconformity may not be well developed..but there are indications of minor erosion. Toplap may develop into truncation. Toplap is often associated with shelf breaks.

Truncation: is a termination of strata or seismic reflections along an unconformity surface. It is associated with strong erosion. Older sediments are eroded and removed over larger areas.

Onlap: termination of strata against a steeper stratigraphic surface. Younger sediments are progressively overstepping each other.

Downlap: a relationship in which seismic reflections of inclined strata terminate downlap against an inclined or horizontal surface.

Concordance: if the overlying sediments show the same deformation as the separating interface and the underlying unit. Refer to Figure 4.3 for the diagrams of these surfaces above.

After the sedimentary sequence has been defined on the seismic section, it is important to know the building blocks of such sequence. The component of depositional sequences are called system tracts (Type 1 sequence boundary- i.e. NOT Exxon Model):

Within a sequence, system tracts are depositional groups that have a predictable stratigraphic order and shape. These must also be defined:

LST- Low stand system tract signifying low sea level.

TST- Transgressive system tract as shorelines move landward

HST- High stand system tract at high relative sea level.

It should be mentioned that a Type 1 sequence consists of three systems tracts — the lowstand, transgressive and highstand systems tracts — but does not contain a shelf margin systems tract. Type 1 sequences and sequence boundaries are the most commonly observed.

The Type 2 sequence boundary lacks the strong erosional features associated with the Type 1 boundary, and the basinward shift of coastal facies, because the sea level in this case doesn't fall below the shelf edge. This type of sequence is, however; considered rare within clastic depositional sequences.

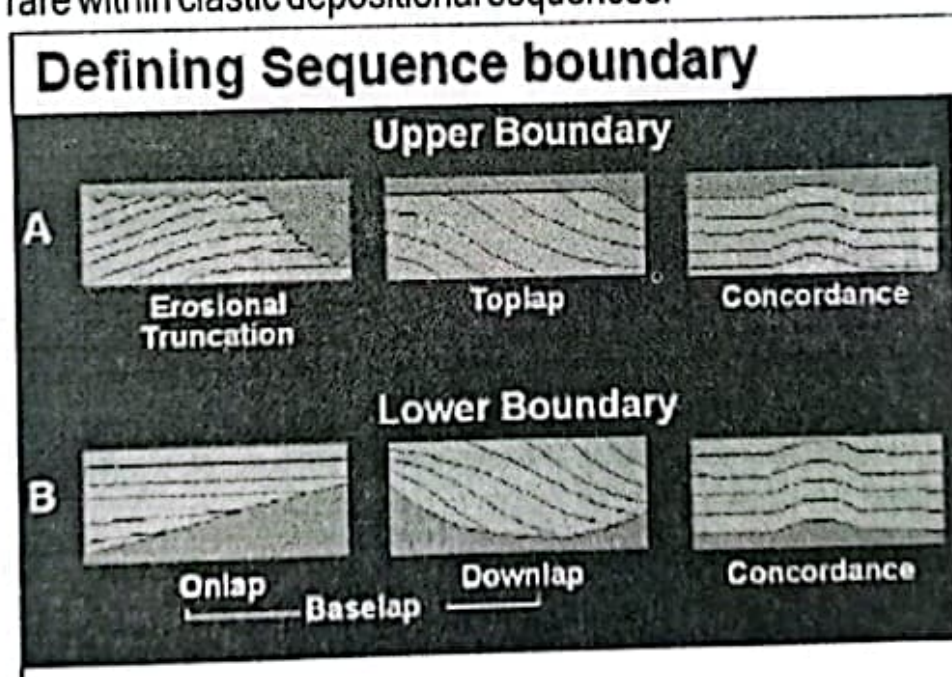


Figure 4.3: Diagram showing different types of reflection terminations employed in the mapping of sequence boundaries.

4.3.1 How to recognize system tracts on the seismic record.

Systems tracts are recognized and defined by the nature of their boundaries and their internal geometry. In other words, each system tract is in an unambiguous manner characterized by specific stratal stacking patterns and position within the framework of sequence stratigraphic surfaces.

Stratal pattern is determined by tracing seismic reflections to their terminations. This is achieved by mapping onlap, downlap and any other stratigraphic terminations that may be present within a sequence. In terms of position, the high stand system tract is most of the times, usually above the transgressive systems tract and the lowstand tract is usually found at the far right position, below the transgressive system tract (Fig 4.4). In addition each system tracts exhibits a characteristic log response and paleontological finger print.

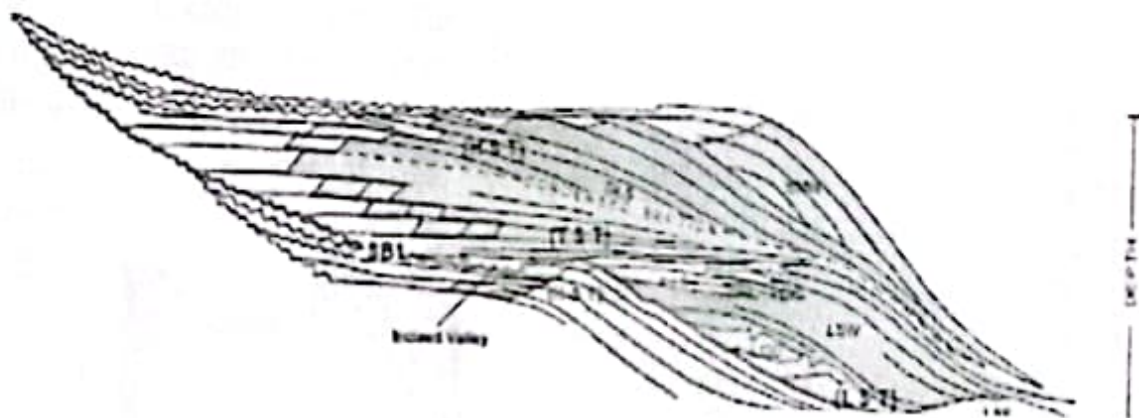


Figure 4.4: Diagram showing how specific stratal pattern and position is used to define the various system tracts.

4.3.1.1 Low Stand System Tract

Lowstand systems tracts (LST) form the basal (i.e. stratigraphically oldest) systems tract in a depositional sequence. It is deposited when relative sea level fall is rapid and no space is available for further sedimentation.

The lowstand systems tracts consist of two elements:

- a 'lowstand fan,' (a unit of submarine fans deposited during falling relative sea level). The lowstand fan systems tract consists of deposits that are

formed where they are originated and gravity-flow (slope and basin-floor fans) facies.

- 'lowstand wedge'. (deposited during a slow rise in sea level).

The lowstand wedge systems tract includes aggradational fill of incised valleys, and a progradational wedge which may downlap onto the basin-floor fan (Posamentier and Vail, 1988).

Economic Potential of the (LST)

The petroleum plays of the lowstand systems tract are diverse. The entire dip profile of the basin offers exploration opportunities within this systems tract.

The basin floor complex typically contains excellent reservoir quality sands. The basin floor complex (bfc) sands frequently have high permeabilities and porosities, limited continuity, and excellent seals when capped by pelagic shales.

The *slope fan complex* (sfc) generally grades upwards from pelagic shales into channel transport complexes, which may or may not contain overbank levee deposits. Sands of good reservoir potential are found within channel axes, and as sheet sands on the levee flanks. These sands, however, may be restricted laterally.

4.3.1.2 Highstand Systems Tract (HST)

The highstand systems tract forms during the late stage of base-level rise, when the rates of rise drop below the sedimentation rates, generating a normal regression of the shoreline. Consequently, depositional trends and stacking patterns are dominated by a combination of aggradation and progradation processes.

The highstand systems tract is bounded by the maximum flooding surface at the base.

The highstand sedimentary wedge is generally expected to include the entire suite of depositional systems, from fluvial to coastal, shallow-marine and deep-marine deposits (Catanaeu, 2009). Nevertheless, the bulk of the 'highstand prism' consists of fluvial, coastal, and shoreface deposits. However, the late highstand may be characterized by laterally interconnected, amalgamated channel and meander belt systems.

Economic Potential of the HST

The best potential reservoirs of the highstand stage tend to be associated with the shoreline to shoreface depositional systems, which concentrate the largest amounts of sand. These reservoirs are usually few meters to tens of meters thick and may display very good lateral continuity along the strike of the basin.

4.3.1.3 Transgressive Systems Tract (TST)

The transgressive systems tract represents sedimentation during a rapid rise in sea level. The shoreline retreats landward depriving the basin of sediment. The top of the TST is the limit of marine invasion and is called the maximum flooding surface. It is associated with wide spread shale deposition called condensed section. This condensed section provides seals for the reservoirs. The transgressive systems tract is commonly expected to include the entire range of depositional systems from fluvial to coastal, shallow-marine and deep-marine sediments.

Economic Potential

Basal transgressive sands derived from reworked lowstand sands can be excellent reservoirs, except where shell fragments may later cements the sands.

4.4 Facie Analysis

The next step in the seismic stratigraphic analysis is the delineation of individual seismic facies units. The aim of facies studies is to further categorize the environment of deposition by relating them to litho facies.

The following features are therefore used:

Internal Reflection Configuration

Several principal reflection configurations are recognized. Each of them are interpreted in terms of depositional environment and lithofacies distribution (Mitchum et al. 1977). The following geometries are distinguished:

A). Parallel to wavy reflection configurations

The parallel to wavy reflection are generated by strata that were probably deposited at uniform rates on a uniformly subsiding shelf. This parallel geometry can occur in both shallow and deepwater, reflecting a topset or a bottomset situation.

It is used for describing shelf environment (prograding shelf/slope systems) and delta complexes.

B) Divergent reflection configurations

Divergent reflection geometries are found in wedge-shaped sediment bodies where the sediment thickness distribution is irregular. Divergent geometry indicates syn-depositional differential tectonic movements. It suggest lateral variations in the rate of deposition OR progressive tilting of the depositional surface.

C) Clinoforms or foresets

Clinoforms are large dipping surfaces. Clinoforms reflection configurations originate from prograding (lateral out building or advance towards the sea as a result of the accumulation of waterborne sediment) slope systems in standing bodies of water. Clinoforms can occur in a topset, foreset or bottomset situation.

There are different types namely:

- i) **Sigmoidal clinoforms** tend to have low depositional dips, typically less than 1 degree. This geometry also might point to deposition from suspension (partial sediment drape). It represents therefore a lower-energy slope system.
- ii) **Oblique clinoforms**- may show depositional dips up to 10 degrees.

D) Hummocky reflection configuration

This hummocky reflection configuration consists of irregular, discontinuous reflections with variable amplitudes.

It is characterized by little systematic reflection terminations. It can occur both in top- and foreset positions e.g. pro-delta facies (part of the river that is farthest from the

shore & in which deposition is slowest). It indicates the presence of cut-and-fill geometries and/or contorted bedding. Most of the time the cut-and-fill is interpreted as channelised deposits.

Hummocky strata may also represent discontinuous point bars and crevasse splays.

E) Chaotic reflection configuration

Chaotic reflection configurations are composed of discontinuous discordant reflections of variable amplitude and frequency. The discontinuous character suggests a highly disordered internal organization of the deposits. **Chaotic** seismic reflections may reflect those with abundant channels or cut-and-fill structures. It occurs in all kind of depositional environments and may represent:

- Channel fills in a proximal fan.
- Slumped deposits on a slope.
- Overpressured shales
- Volcanic rocks
- Mobile salt deposits

F). Lenticular seismic reflections are most likely to appear in sections oriented perpendicular to depositional dip. They represent the depositional lobes of deltas or submarine fans. The overall geometry of a seismic facie unit consists of the external form and the internal reflection configuration of the unit. Both must be described to understand the geometric interrelation and depositional setting of the facies units. However, initial analysis always starts in the two-dimensional mode of a single seismic section.

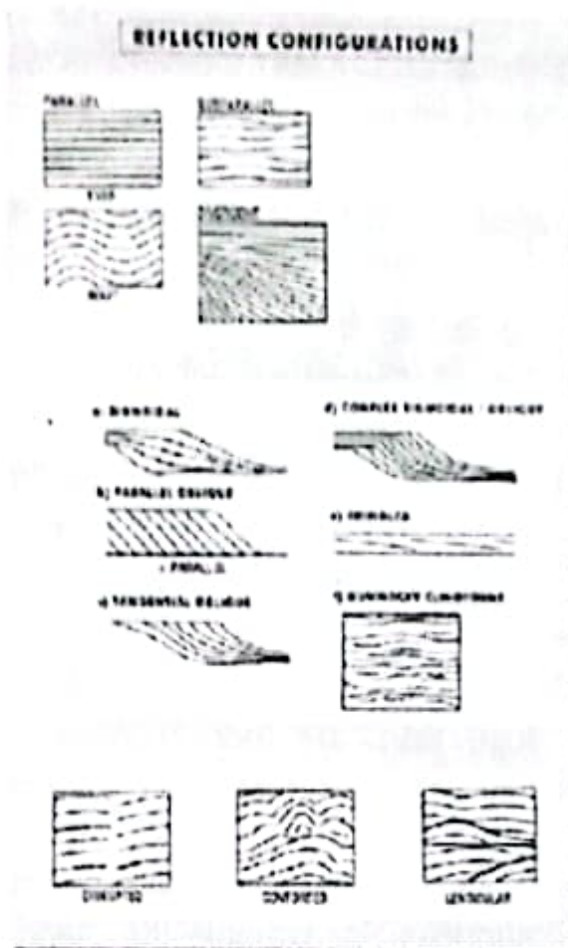


Figure 4.5: Various reflection configurations and their interpretation (Mitchum et al 1977).

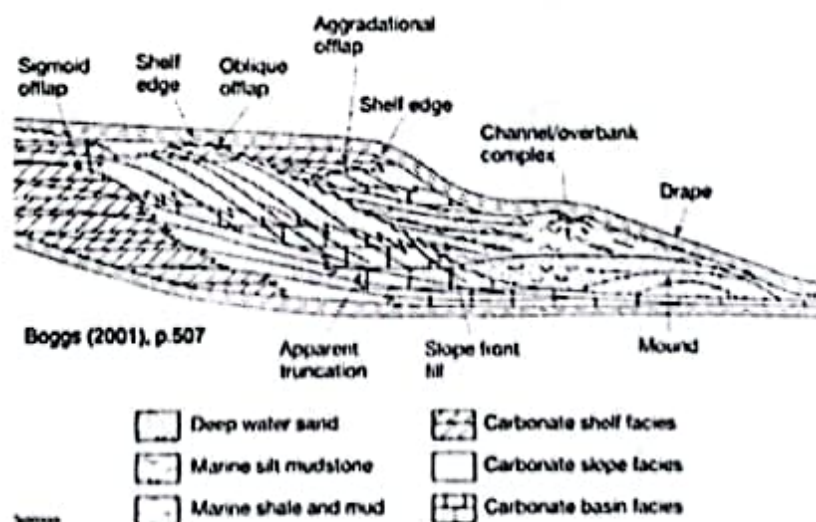


Figure 4.6: Different depositional environments interpreted on the basis of reflection configurations (Boggs, 2001).

After depositional environments and facies modelling have been carried out, the next set of steps are undertaken to integrate any available data.

4.4.1 Integrate with logs, cores, and biostratigraphic information:

- **Logs:** Stacking patterns, log motifs, and lithology are keys to the intermediate scale of correlation which should support the seismic correlations. Infact, the best log correlations are established when the seismic data is used as a guide to extending stratigraphic surfaces from well to well. While seismic data does not often capture the high-resolution stratigraphic correlations possible in a log cross-section, it usually displays gross geometries (e.g., dipping clinoforms) which should be followed in log correlation. For example, experience has shown that clinoform parasequences or stacked sequence architectures can be missed in log correlation if not first identified on seismic.
Stacking patterns seen on logs (and outcrops sections) are often indicative of key stratigraphic surfaces. For example, the change from retrogradational to progradational stacking often is associated with a maximum flooding surface, which can be checked against both seismic and biostratigraphic data.
Log motif interpretation of systems tracts is particularly well defined (e.g., Mitchum et al., 1994). These are not discussed here. Stacking patterns, log curve shape, vertical trends in sand content, and relationship to over- and underlying surfaces are keys to identifying the systems tracts.
- **Cores:** The best evidence for identification and validation of important stratigraphic surfaces often comes from cores. Sequence boundaries can be associated with basal lags or paleosols (on the interfluvial of incised valley-fills (ivf's)). Parasequence boundaries (PSB's) can be associated with burrowed, wave rippled surfaces.
- **Biostratigraphic data:** It is important when using biostratigraphic data to look for concentration/dilution cycles. In general terms, concentration cycles, zones where large numbers of microfauna and flora are condensed over short intervals, are often associated with maximum flooding surfaces (MFS). By contrast, dilution cycles are often associated with sequence boundaries. Keep in mind the potential for depressed fauna and displaced (transported) fauna. Be careful where data comes from wells with thin

stratigraphic sections on structural or paleogeographic highs. Sequence boundaries sometimes are associated with high numbers of reworked older fauna, usually due to updip or local erosion of older strata. Biofacies and paleoclimatic inferences from paleontologic data should also be considered in this integration because latitude variations in faunal and floral content can also occur (Armentrout et al., 1991).

CHAPTER FIVE

CASE STUDIES

5.1 Turbidites Characterization from Seismic Stratigraphy Analysis: Application to the Netherlands Offshore F3 Block

5.1.1 Introduction

Sequence stratigraphy is considered a revolutionary paradigm in the field of sedimentary geology (Catuneanu, 2006). From the beginning, this discipline generated controversy and long arguments among geoscientist trying to define the conceptual basis of this technique. In this context, throughout history several models have been proposed in an effort to best explain and reconstruct the depositional environment of an area of interest (Donovan, 2001), as it is shown in Figure 1. Now, the different point of view of the authors listed in Figure 1 generated variations on the original depositional sequence model theme proposed by Vail (1977), which resulted in several publications of slightly modified versions (Figure 2). For this particular application the sequence model found under the Depositional Sequence IV in Figure 2 will be followed to generate all the sequence stratigraphic analysis and to build system tracts model.

Extended exploratory projects have remarkably improved the understanding of offshore basins such as the North Sea (Back et al., 2011), which have been explored

over the past few decades in order to find the most profitable plays. Recently, many techniques for both geophysical and geological interpretation of seismic and well log data have been generated (Chopra, 2008; Catuneanu, 2006.), which have allowed geoscientist the identification of key features that can lead to the discovery of new fields. Now, by using these techniques both seismic and well log information can be converted to the basic input data to generate a reliable geological model of the subsurface. Nevertheless, despite all the information that can be obtained by using these interpretation techniques, using them separately diminish their potential. Rather than using them separately, it is recommended to combine them with classical methods of geological interpretation such as core analysis, outcrop analogs and regional geological knowledge (Brouwer, 2008).

The scope of this article is to show how the integration of different advanced techniques of geological and geophysical data interpretation led to the generation of a robust sequence stratigraphy model that accounts for the characterization of the turbidites found in the F3 Block North Sea prograding Tertiary delta complex.

5.1.2 Data and Methodology

The principal data of this study is a high-quality 3D PSTM from the block F3, located in the North Sea Offshore of Netherlands (Figure 3, left) presenting relevant large-scale sigmoidal bedding. The dataset consists of seven wells with the right well logs for the application, core and cuttings description, time to depth tables for the seismic well tie process and the seismic volume mentioned before (Figure 3, right). Figure 4 shows the workflow applied to the dataset to get the final model. All steps and partial results are illustrated and briefly described in the following sections. It is worth mentioning that both the seismic survey and well information in the interval related to this study do not have any importance for hydrocarbon exploration. Nevertheless, this methodology may be applied to an analog survey that shows similar geological features where it might be suitable for play definition.

5.1.3 Regional Geological Setting

The study area is located in the North Sea in part of the offshore of Netherlands (Figure 5). The basic structural framework of the North Sea is mainly the result of extensional tectonics due to a failed rifting during the Latest Jurassic and Earliest Cretaceous and are fundamental to the understanding of oil and gas traps in the North

Sea (Brooks, 1987; Pegrum, 1990). According to these events, the geological setting is subdivided into three parts with respect to the main episode of rifting (Gautier, 2005). The first episode marked is by events and processes prior to rifting (pre-rift). Those events and processes that took place during the rifting event are called syn-rift and the depositional processes and structural events subsequent to the Late Jurassic/Earliest Cretaceous are considered post-rift.

Rifting in the North Sea had largely ceased by the end of Early Cretaceous time (Ziegler, 1990). Steep geothermal gradients associated with the extensional tectonics decayed, and the regional pattern became one of gradual cooling and associated subsidence, especially near the axis of the abandoned rift where post-rift sediments accumulated to their greatest thickness. Late Cretaceous to Earliest Paleocene post-rift rocks are dominated by fine-grained pelagic carbonates (chalks) (Hancock, 1975). The Tertiary sedimentary sequences are mainly marine mudstones with locally significant submarine fans. Fans deposited during the Paleocene and Eocene are particularly significant (Reynolds, 1994).

Subsidence and sedimentation have continued in many areas throughout the Tertiary and Quaternary. The great isostatic differences resulting from erosion of uplifted blocks and accompanying rapid sedimentation in sub-basins and half-graben probably initiated salt tectonics in the Central Graben (Bain, 1993).

5.1.4 Seismic Image Conditioning and Input Data for Sequence Stratigraphic Interpretation

Right after performing the seismic-well tie process, the interpretation of the 3D seismic data started by conditioning the seismic image. This process included relative dip reflector interpretation and the enhancement of both reflectors continuity and faults. Based on the reflector dip attribute called Dip Steering (which was calculated using Opendtect) a set of about 1400 horizons were tracked which follow nicely the reflectors and therefore represent time lines that will be used in the following steps. It is worth mentioning that these horizons are truncated if they approach each other up to a certain distance defined by the interpreter, therefore making even easier the interpretation of stratigraphic features such as subaerial unconformities.

This 3D horizons framework along with time attributes such as the variation of

thickness calculated from the horizons framework allows the assessment definition of time attributes of bounding surfaces. Using the 3D horizons framework and the bounding surfaces defined from this last dataset a Wheeler diagram was then built, which led to the interpretation of the system tracts. In this context, both the conditioned seismic data and the 3D horizons framework were flattened using the Wheeler transform, in which time slices are equivalent to chrono-stratigraphic horizons. In these time slices it is possible to interpret the paleo-geomorphology of the entire seismic volume and identify stratigraphic features such as erosional events, non-depositional hiatuses (De Bruin et al., 2006), submarine channels, debris flows and most importantly turbidites. Figure 9 illustrates the conditioned seismic image and the corresponding 3D horizons framework for an Inline of the seismic survey. One may see on this Inline the prograding delta deposited during the Late Miocene and Pliocene (Archard, 1987), which is nicely followed by the horizons framework generated in this study.

5.1.5 Sequence Stratigraphic Interpretation

In this context, based on the horizons framework and the reflectors terminations associated with them a complete set of stratigraphic surfaces was defined which were later used to interpret the systems tracts (Figure 10). From Figure 10 it can be seen from bottom to top that the segment bounded by the light blue and the first light green surface shows retrograding para-sequence which can also be seen in the Wheeler domain (Figure 11). Based on the para-sequences, reflectors terminations and Electrofacies defined in the correlation wells, this interval was interpreted as a Transgressive System Tract [TST] (Figure 12) and therefore the light green surface represents the end of the transgression and so a maximum flooding surface [MFS]. The next package corresponds to a set of very steep prograding clinoforms that downlap the maximum flooding surface and present the typical toplap reflectors terminations of a normal regression of the coastline preceded by a transgression. According to the para-sequences and all the features listed before, this package is interpreted as a Highstand System Tract [HST] (Figure 12). This package is bounded at the bottom by the maximum flooding surface and at the top by both the subaerial unconformity [SU] and the basal surface of forced regression [BSFR] (Figure 10 and Figure 12).

Going forward, the following package is characterized by offlap reflectors terminations of a prograding set of clinoforms overlying the concave up BSFR. One

can see that the clinoforms that overly the BSFR have a clear trend of decreasing height seaward and are commonly found as products of the early stages of a forced regression of the coastline. These prograding clinoforms are then overlaid by a set of reflectors with onlap termination, which are one of the particular products of the late stage of a forced regression of the coastline. This package was interpreted as a Falling Stage System Tract [FSST] and is bounded at the bottom by the BSFR and at the top by the last part of the SU and the Correlative Conformity [CC] (Figure 12).

The next package consists of a set of reflectors that exhibit prograding and aggrading para-sequences, which combined result in a normal regression of the coastline that according to the Depositional Sequence IV proposed by Hunt and Tucker (1992, 1995) is characteristic of a Lowstand System Tract [LST]. This fact is an indicator of two important changes in the base level which are the end of base level fall and the beginning of the base level rise. During the early stages of base level rise the accommodation space is utterly consumed by the sedimentation rate thus creating a regression of the coastline and aggradation of fluvial and nearshore facies.

Now, in this particular case the LST is not followed by a transgression as in a normal base-level cycle. It can be seen in the Wheeler domain (Figure 11) that the clinoforms start prograding again instead of retrograding and attached to the surface that indicates the onset of progradation of the clinoforms one can find truncation and offlap reflectors terminations, which means that the base-level is falling again. This package was interpreted as a FSST based on the characterization mentioned before followed by a normal regression marked by a LST (Figure 11 and Figure 12). The last package interpreted in this section corresponds to a retrograding set with onlap reflectors terminations and a particular convex shape. Based on the description previously listed this package was interpreted as a TST.

5.1.6 Turbidites Geobodies Extraction

Based on not only the 3D horizons framework generated from the seismic data but also the 3D systems tracts interpreted, it was possible to extract the geobodies that represent the turbidite deposits that were generated during the FSST and subsequently preserved (Catuneanu, 2006). The main turbidites geobodies interpreted were found right after the last prograding off-lapping lobe where, according to Catuneanu (2006), it is most likely to find high density turbidite deposits associated with mounded geometries. Figure 13 illustrates the two horizons used to

extract one of the geobodies interpreted as a turbidite. The main input used to interpret all of the 3D model of the turbidite (Figure 14) were the 3D horizons framework, a thickness attribute estimated from the 3D horizons framework and the geometric attributes estimated during the seismic image conditioning phase. This particular turbidite corresponds to a high density turbidite deposit (Catuneanu, 2006) which most distal package was drilled by some of the correlation wells as it can be observed in Figure 15 where the gamma ray log clearly decreases once it reaches the top of the turbidite body.

It is then concluded that the distal portion of this turbidite has a lower sand-to-mud ratio, whereas the proximal portion has a higher sand-to-mud ratio. This conclusion is of paramount importance when designing an exploration strategy, since this body is overlying a MFS, which might represent a potential source rock and it is overlain by the late stage of a FSST that might have generated a potential seal layer. This interpretation has significant impact when defining a new play in a basin that is just being explored.

5.1.7 Conclusions

The definition of a 1D litho-types model using neural networks has proven to be a suitable method which has to be calibrated using core descriptions and sedimentological models built for the interval of interest. The generation of a 3D horizons framework based on the reflector dip is of paramount importance for seismic stratigraphy analysis, since it provides the main input data for the Wheeler transform.

Defining stratigraphic features such as reflectors terminations, boundary surfaces and electrofacies allows one to accurately interpret the depositional environment of an interval. The integrated interpretation of geological information (seismic, well log, drilling core and regional geology) presented in this article shows the relevance of using different sources of information to utterly understand the area of interest and properly define exploration strategies.

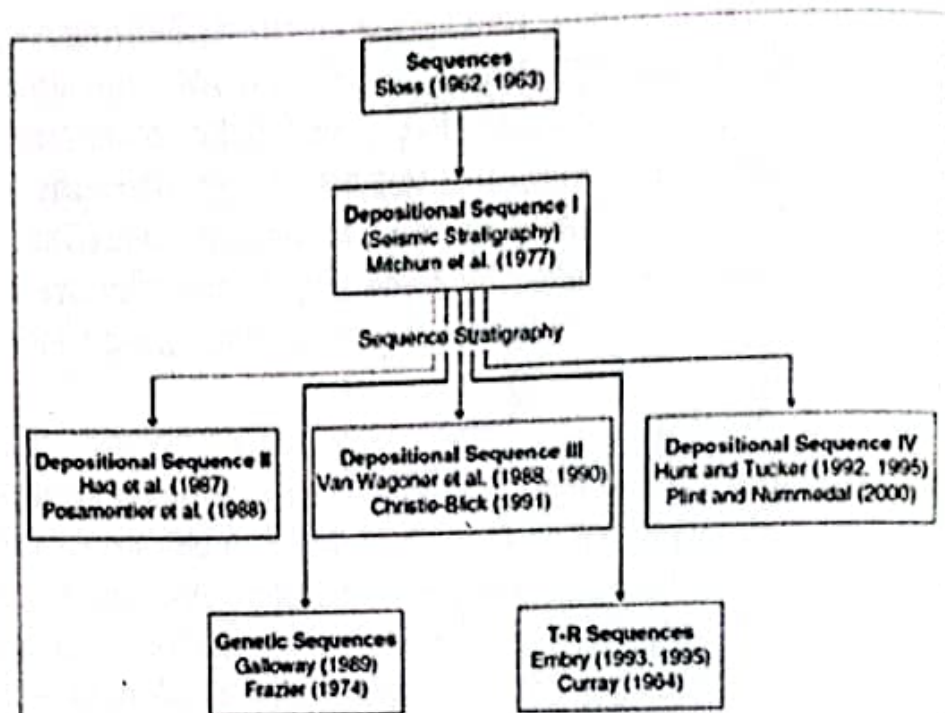


Figure 1. Family tree of sequence stratigraphy (modified from Donovan, 2001).

Sequence model	Depositional Sequence II	Depositional Sequence III	Depositional Sequence IV	Genetic Sequence	T-R Sequence
Events					
end of transgression	HGT	early HGT	HGT	HGT	RST
end of regression	TST	TST	TST	TST	TST
end of base-level fall	late LST (wedge)	LST	LST	late LST (wedge)	RST
onset of base-level fall	early LST (fan)	late HST (fan)	FSST	early LST (fan)	
	HST	early HGT (wedge)	HGT	HST	

Figure 2. Timing of system tracts and sequence boundaries for the sequence models currently in use (modified from Catuneanu, 2002)

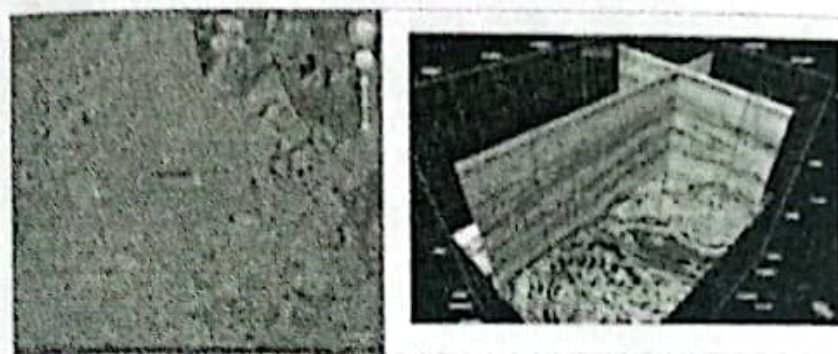


Figure 3 Location satellite image of the FJ Block seismic survey (left) and location of the seven correlation wells in the 3D seismic survey

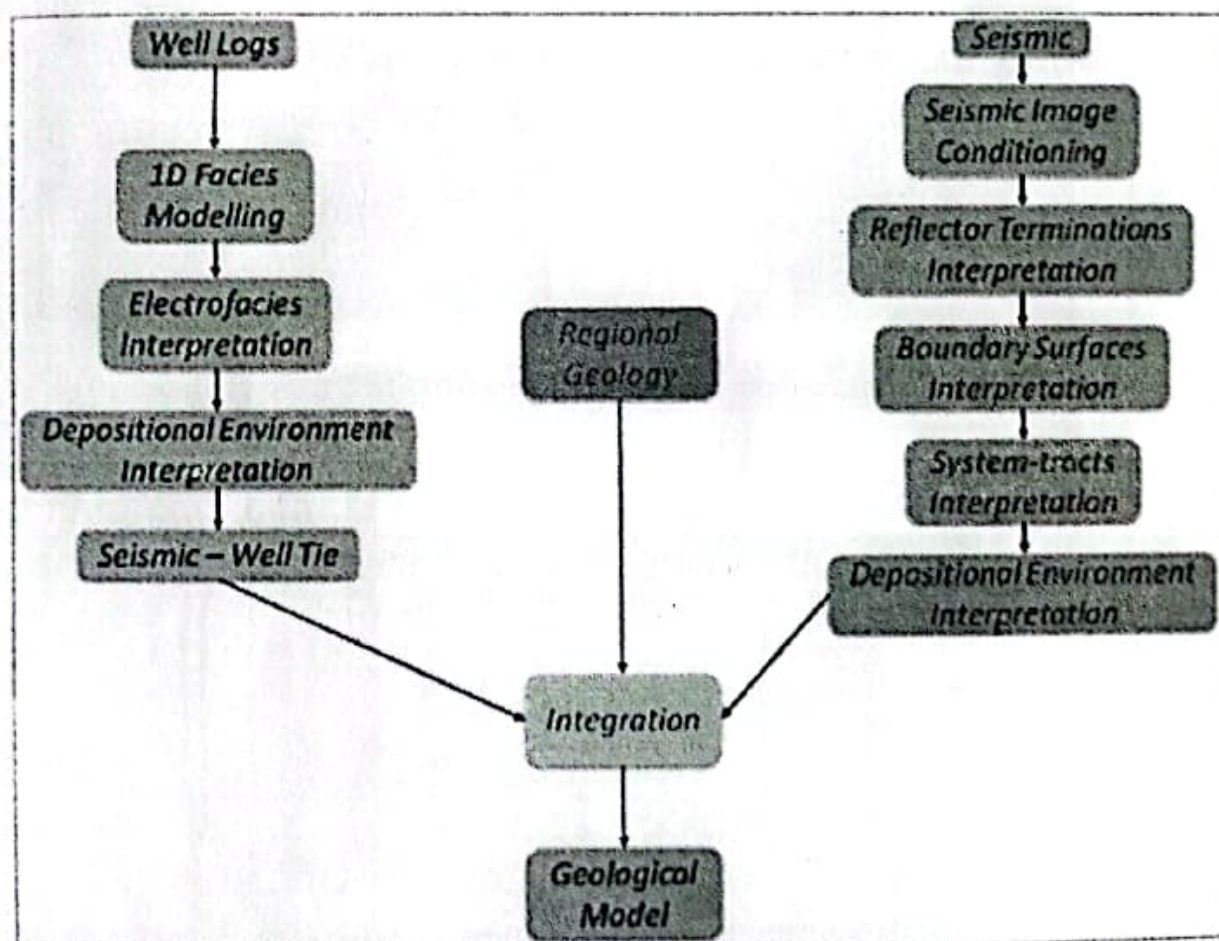


Figure 4. Workflow applied to transform petrophysical and geophysical information into a 3D geological model.

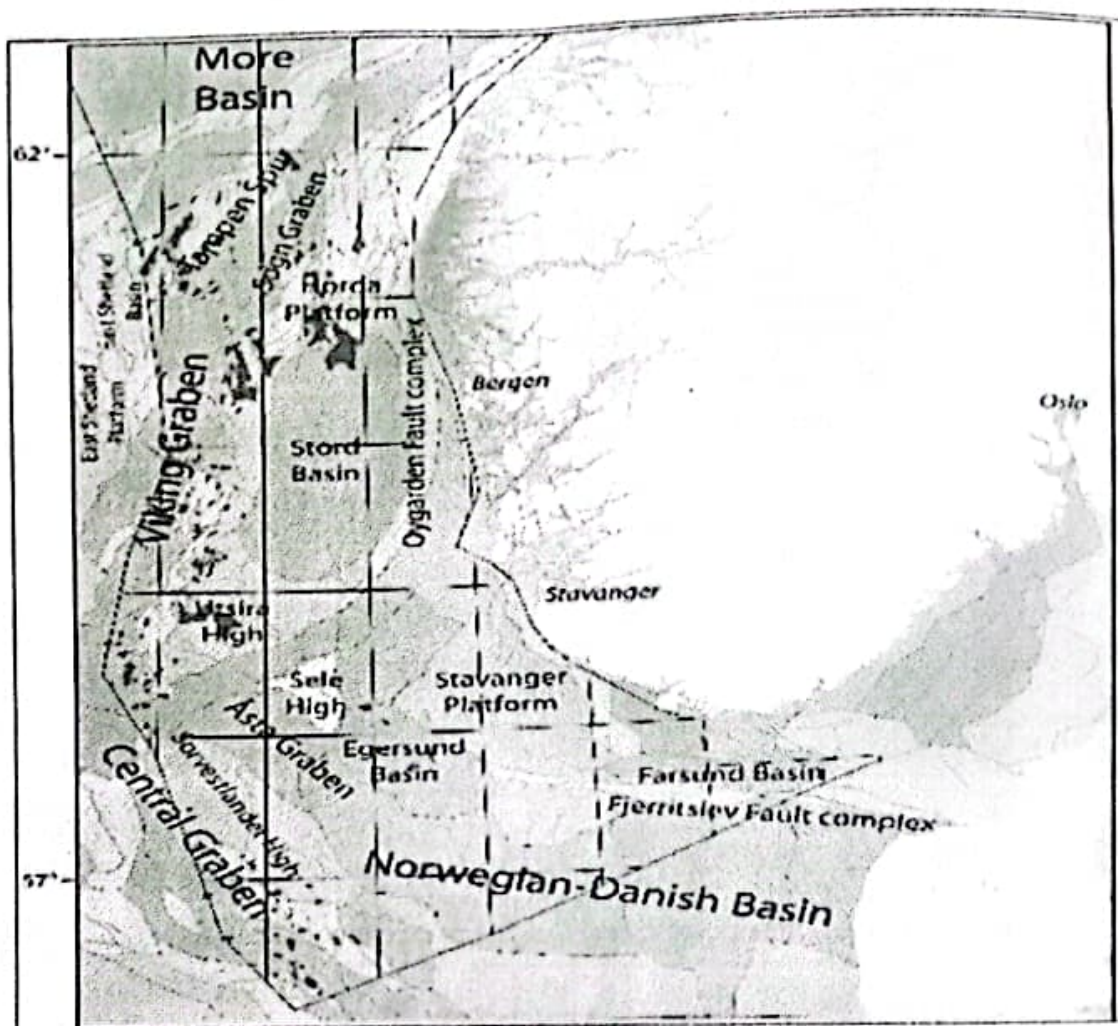


Figure 5. Regional context of the study area. Modified from Halland, 2014.

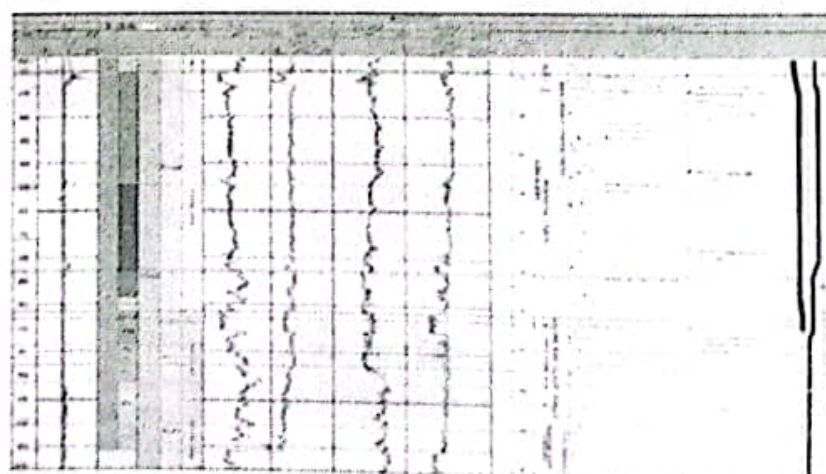


Figure 6. Well log and stratigraphic analysis from core and cuttings samples for one of the correlation wells

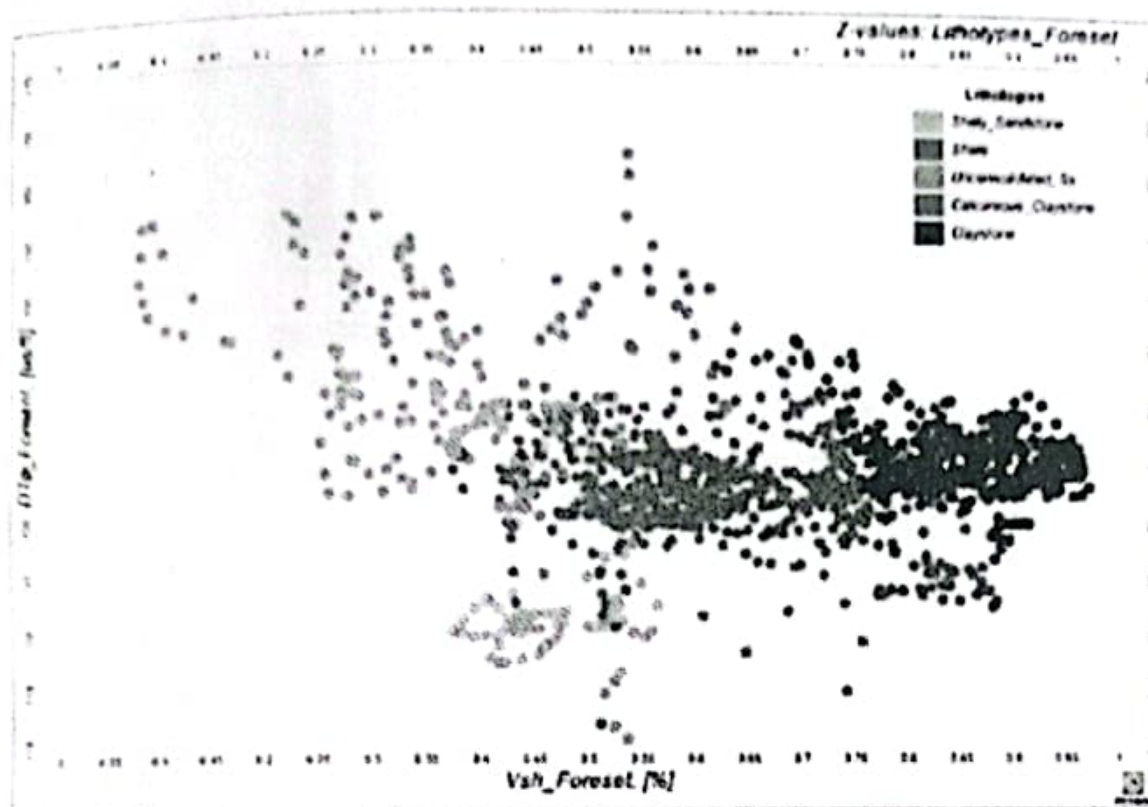


Figure 7. Final crossplot for the facies modeling, applying neural networks and Vshale.

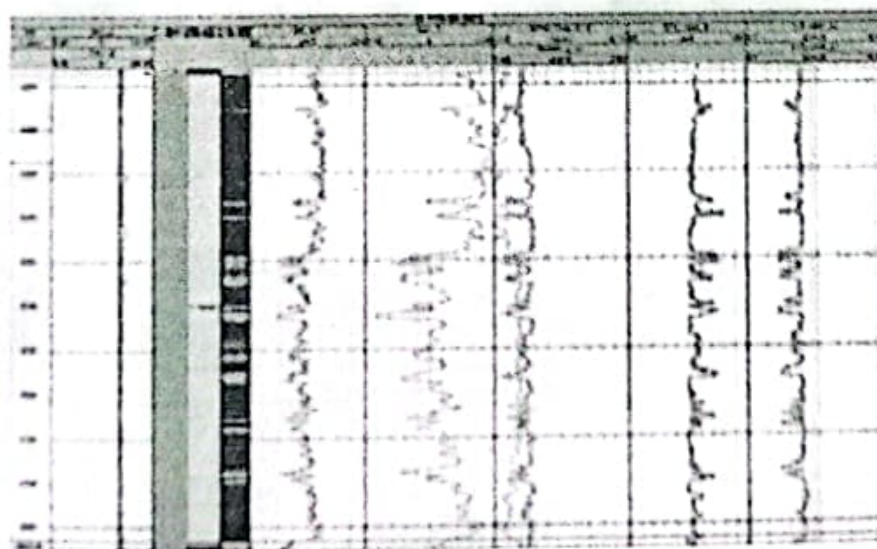


Figure 8. 1D Facies model for one of the correlation wells obtained applying neural networks and Vshale.

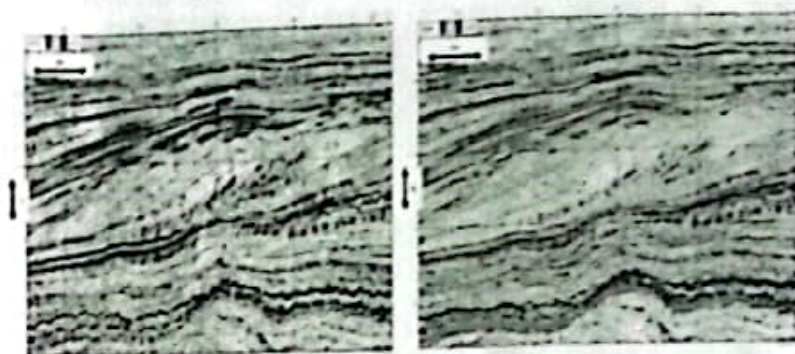


Figure 9 (a) Conditioned seismic image, and (b) its corresponding horizons framework defined from the Dip-Steering attribute

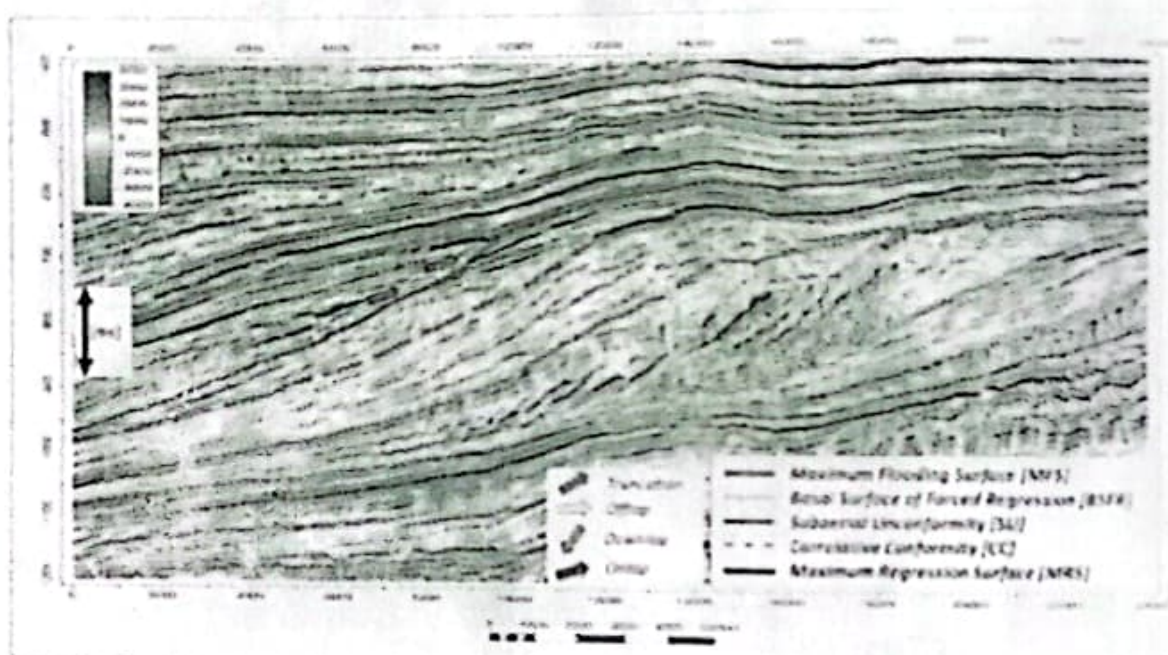


Figure 10. Stratigraphic surfaces associated to reflectors terminations

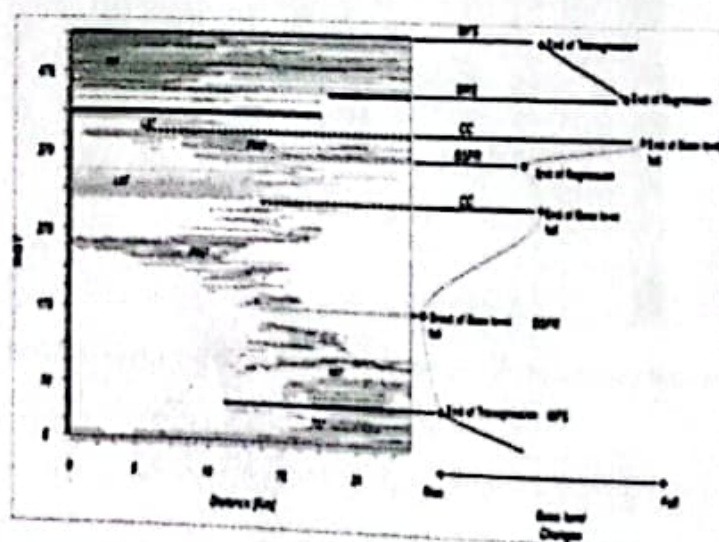


Figure 11. Wheeler domain along with the system tract interpretation and the base level change curve. RGT means "Relative Geological Time"

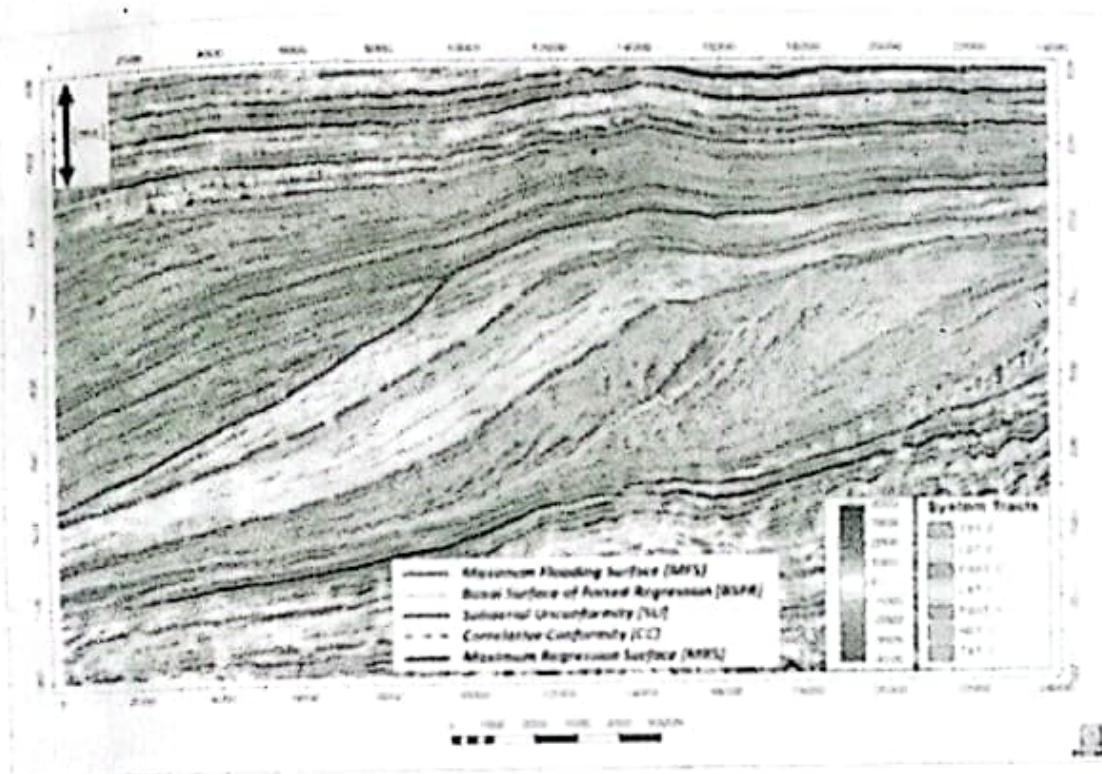


Figure 12. Systems tracts interpreted for the interval of interest.

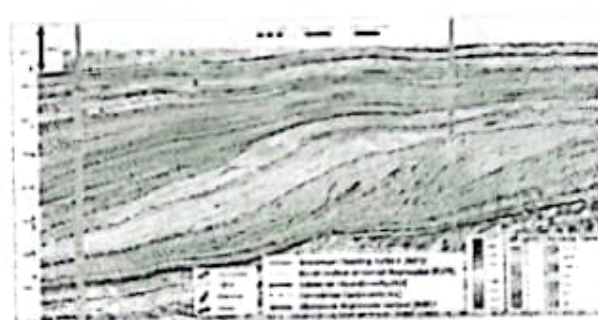


Figure 13. Turbidite geobody (transparent horizons) interpreted at the end of the prograding offlapping lobes inside the F3ST defined for the study area.

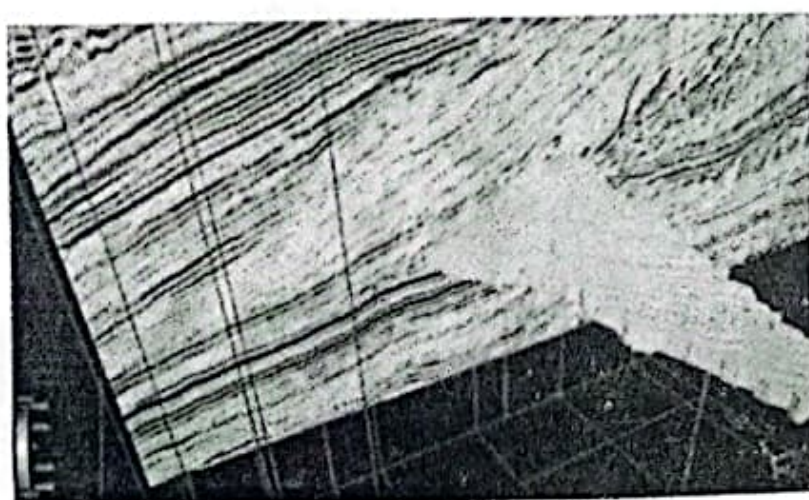
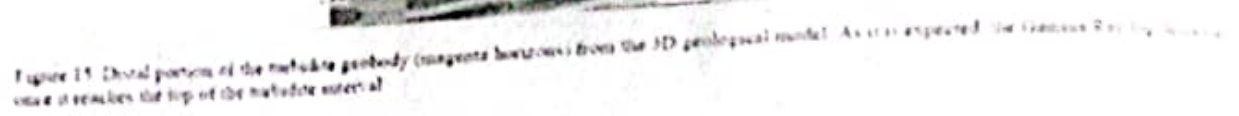


Figure 14. 3D model of one of the turbidites interpreted in the seismic volume.



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GLOSSARY OF TERMS

accommodation space: the space made available for potential sediment accumulation ... which ... is a function of both sea level fluctuation and subsidence (Jervey, 1988). Accommodation space can be positive, implying deposition, or negative, implying erosion and the formation of a sequence boundary. Variations in shelfal accommodation space control the sequence development geometry, i.e., whether prograding, aggrading, or retrograding.

aggradation: accumulation of a facies or group of facies within a depositional system, with no significant lateral migration of the facies or facies belts towards either the land or basin. Occurs when the increase in accommodation space is equal to the sediment supply rate. Causes parasequences to stack vertically. Requires a perfect balance between sediment supply rate and rise in relative sea level (Van Wagoner et al, 1990).

apparent truncation: describes the termination of relatively flat-lying seismic reflectors beneath a dipping seismic surface, where that surface represents a marine condensed section. May look like erosional truncation, but represents a facies change from appreciable sedimentation to condensed section. Frequently characterizes the top surface of the transgressive systems tract.

base level: a) the theoretical limit or lowest level toward which erosion of Earth's surface constantly progresses but seldom, if ever, reaches; esp. the level below which a stream cannot erode its bed. The general or ultimate base level for the land surface is sea level; b) a curved or planar surface extending inland from sea level, inclined gently upwards from the sea and representing the theoretical limit of stream erosion; c) the surface toward which external forces strive and at which neither erosion nor deposition takes place (Barrel, 1917); a surface of equilibrium (American Geological Institute, 1984). In sequence stratigraphy, a change in base level associated with falling sea level leads to erosion and progradation, while rising sea level leads to accumulation and retrograde deposition. Sediments are eroded above a base level and aggrade below it.

biostratigraphy: the study of the paleontological aspects of rocks, and the

differentiation of rock units through the study of the fossils they contain (American Geological Institute, 1984). High-resolution biostratigraphy is performed on wells at small sampling intervals (e.g., 30 to 60 feet).

bright spot: seismic reflection amplitude anomaly caused by the high reflection coefficients (sometimes) associated with the presence of gas.

clinoform: a sloping depositional surface, commonly associated with strata prograding into deep water (Mitchum, 1977). Categorized according to shape: sigmoidal, oblique, tangential, parallel, complex and shingled, and containing bottomsets, foresets and topsets. Clinoforms record the migration of a sloping sediment surface. In a basin margin setting, clinoforms generally record the progradation of a shelf-slope system into deeper water.

coastal onlap: onlap is a base-discordant relation in which horizontally inclined strata terminate progressively updip against a surface of greater initial dip. Coastal onlap is the progressive landward onlap of the coastal (littoral or coastal non-marine) deposits in a given stratigraphic unit. The vertical and horizontal components of coastal onlap are coastal aggradation and coastal encroachment. Coastal onlap is generally inferred from seismic data as the landward onlap of topset reflectors. Does not necessarily occur at the coastline (recent usage by Exxon extends this concept landward), nor need it involve coastline facies, i.e., coastal onlap could represent lagoonal facies.

composite sequence: a succession of genetically related sequences in which the individual sequences stack into lowstand, transgressive and highstand sequence sets. (Van Wagoner et al., 1990). Involves the stacking of higher order sequences (i.e., third order) within lower order sequences (i.e., second order).

condensed section: a thin, marine stratigraphic unit characterized by very low sedimentation rates and consisting of pelagic to hemipelagic sediments. Condensed sections reach their maximum aerial extension at the time of maximum regional transgression of the shoreline, and are diachronous across a basin. (Loutit et al., 1990). As the product of very low rates of sedimentation, a condensed section may be associated with hardgrounds, glauconitic bands, bio-erosion, submarine winnowing,

and faunal abundance peaks. Have a characteristic signature on well logs- a thin unit of anomalously high gamma, high or low sonic velocity, and/or high density. Biostratigraphic analysis is a powerful tool for identifying condensed section intervals.

continental shelf: the part of the continental margin between the shoreline and the continental slope; or, when there is no noticeable slope, a depth of 200 m. Characterized by a very gentle slope of 0.1 degrees. (American Geological Institute, 1984).

continental slope: the part of the continental margin between the continental shelf and the continental rise or oceanic trench. Characterized by a relatively steep slope of 3 to 6 degrees. (American Geological Institute, 1984).

correlative conformity: the correlative conformity to a sequence boundary is the depositional surface at the base of the lowstand systems tract (or shelf margin systems tract).

cyclothems: repetitive strata resulting from repeated marine transgressions and regressions (Wanless and Weller, 1932).

depositional sequence analysis: an integrated method for conducting a seismic sequence stratigraphic interpretation. Involves a number of tools, including seismic reflection profiles, synthetic seismograms, vertical seismic profiles, well logs and biostratigraphy.

depositional system: a three-dimensional assemblage of lithofacies, genetically linked by active (modern) or inferred (ancient) processes and environments (Fisher & McGowan, 1967; Brown & Fisher, 1977). Grouping of lithofacies into common workable groups, such as submarine fan systems, barrier island systems, and alluvial systems. Recognized on logs, cores, and seismic profiles as an interval of related facies assemblages. For example, depositional systems associated with the highstand systems tract would consist of alluvial, coastal plain, shallow marine and slope to deepwater environments.

diachronous: literally, "across time." Applied to lithological units (e.g., a sandstone bed, a limestone reef) which appear to be continuous beds but which in fact represent the development of the same facies at different places at different times. Said of a rock unit that is of varying age in different areas or that cuts across time planes or biozones; e. g. , a marine sand that was formed during an advance of a shore line (transgression) and becomes younger in the direction in which the sea was moving. (AGI Dictionary of Geological Terms, 1984).

downlap: a base-discordant relation in which initially inclined strata terminate downdip against an initially horizontal or inclined surface (Mitchum, 1977).

equilibrium point: the point along a continental shelf profile where the rate of eustatic change equals the rate of subsidence. Seaward of this point, the rate of subsidence is greater than the rate of eustatic fall, resulting in the addition of new space; landward of this point, the opposite occurs. Alternatively, the equilibrium point defines two zones: 1) a zone of relative sea-level rise seaward of the equilibrium point and, 2) a zone of relative sea-level fall landward of the equilibrium point (Posamentier and Vail, 1988).

eustasy: a change in elevation in sea level on a worldwide basis relative to a stationary datum such as the center of Earth (Christopher et al., 1988). Eustatic sea level is a component of relative sea level and is independent of uplift or subsidence of the land surface. Eustasy is recognized from global correlations of relative sea level change. Eustasy occurs on a wide variety of scales, termed "orders" in sequence stratigraphy.

genetic sequence or unit: a package of sediments recording a significant episode of basin margin outbuilding and basin filling, bounded by periods of widespread basin-margin flooding (Galloway, 1989a). Now accommodated with the clastic sequence model of Vail (Xue and Galloway, 1993).

hiatus: a) a break or interruption in the continuity of the geological record, such as the absence in a stratigraphic section of rocks that would normally be present but are missing either because they were never deposited or because they were eroded before the deposition of the beds immediately overlying the break; b) a lapse in time, such as the time interval not recorded by rocks at an unconformity. The term has been

used for the time value of an episode of nondeposition and for the time value of nondeposition and erosion together (American Geological Institute, 1984).

highstand: interval of time during a cycle or cycles of relative change of sea level when sea level is above the shelf edge in a given local area (Mitchum, 1977).

highstand systems tract: the upper systems tract in either a Type 1 or a Type 2 sequence (Van Wagoner et al., 1988). A unit of rock bounded below by a maximum flooding surface and above by a Type 1 sequence boundary. The highstand systems tract is commonly widespread on the shelf and may be characterized by one or more aggradational parasequence sets succeeded by one or more progradational parasequence sets with prograding clinoform geometries. Parasequences within the highstand systems tract onlap onto the top of the transgressive or lowstand systems tracts in a landward direction and downlap onto the top of the transgressive or lowstand systems tracts in a basinward direction.

HCI: hydrocarbon indicator, usually by means of remote sensing, such as geophysical reflection profiles.

incised valley: entrenched fluvial systems extending their channels basinward and eroding into the underlying strata in response to a relative fall in sea level. On the shelf, the incised valleys are bounded below by the sequence boundary and above by the first major marine flooding surface, called the transgressive surface. Can be part of either transgressive or regressive relative sea level phases.

inflection point: the points on a relative sea level curve of greatest rate of rise and fall of relative sea level. The sea level curve is usually depicted as a sine wave, where inflection points are apparent. The curve may, however, be depicted as a saw tooth, with inflection points taken when and where sea level changes occur, so the change from falling to rising phases may be sudden.

insolation curve: curve depicting the variation of incoming solar radiation to Earth, usually for a fixed latitude. Originally derived by Milankovitch (1920) based upon variations in Earth's orbit and inclination relative to the sun.

lowstand: interval of time during a cycle or cycles of relative change of sea level when sea level is below the shelf edge. A comparative lowstand occurs where sea level is at

its lowest point on the shelf during the deposition of a series of sequences (Mitchum, 1977). Eustatic lowstands are times of generally low relative sea level. The EPR model predicts that a distinctively evolving set of facies, the lowstand systems tract, will be associated with sea level lowstands.

lowstand systems tract: the lowermost systems tract in a depositional sequence, if it lies directly on a Type 1 sequence boundary (Van Wagoner et al., 1990). The lowstand systems tract, if deposited in a basin with a shelf break, can generally be subdivided into three separate units — a basin floor fan, a slope fan, and a lowstand wedge (prograding complex).

marine flooding surface: surface separating younger from older strata across which there is evidence of an abrupt increase in water depth. This deepening is commonly accompanied by minor submarine erosion or non-deposition (but not by subaerial erosion due to stream rejuvenation or a basinward shift in facies), with a minor hiatus indicated. The marine flooding surface has a correlative surface in the coastal plain and on the shelf (Van Wagoner et al., 1990).

marine onlap: the onlap of marine strata (Mitchum, 1977). Recognized on seismic data by the termination of low-angle reflectors. Marine onlap should not be confused with coastal onlap, which occurs beyond and below the offlap break (shelf edge), is unaffected by, and cannot be used to determine, relative sea level.

maximum flooding surface: the surface corresponding to the time of maximum flooding; also called the downlap surface (Posamentier et al, 1988). The most landward flooding surface within a transgressive/regressive cycle. Commonly associated with a condensed section seaward, and forms the boundary between the transgressive and highstand systems tracts. Represents the downlap surface of the highstand systems tract on seismic profiles. Also represents the bounding hiatal surfaces that defined the genetic stratigraphic units of Galloway (Xue and Galloway, 1993).

maximum progradation surface: the conceptual surface forming the boundary between a progradational unit and the overlying retrogradational unit (Milton, 1990).

ABOUT THE BOOK

This book deals with the evolution and concept of sequence stratigraphy. The relationship and applications of this concept is presented in a concise, user friendly format. Sequence stratigraphy has become an indispensable tool for studying rock relationships, particularly in coal, oil and gas exploration. This book affords the reader the basic understanding of sequence stratigraphic analysis for the identification, classification and description of depositional geometries and stratigraphic sequences. It is recommended as a handy tool to geologists and non-geologists alike as a reference material in the study of sequence stratigraphy.



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