Sedimentology and the Oil and Gas Industry

by

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with 59 Figures

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Kurzfassung

In den letzten hundert Jahren haben Sedimentologen aus Wissenschaft und Industrie in enger Zusammenarbeit die Sedimentgesteine und deren Porenraum beschrieben und klassifiziert, die physikalischen und chemischen Prozesse während der Ablagerung und der Diagenese untersucht sowie die Ablagerungsräume in Raum und Zeit erfasst. Die Ergebnisse dieser sehr fruchtbaren Zusammenarbeit reichen von sehr genauen und schnellen Labormethoden bis zu Beckenanalysen und sind damit wichtigste Voraussetzungen für die Vorhersage der Kohlenwasserstoffgeneration aus Muttergesteinen und ihren Weg in die Speichergesteine in Raum und Zeit.
Im Bereich der angewandten Sedimentologie wird heute verstärkt multidisziplinär gearbeitet. Sedimentologen, Paläontologen, Petrophysiker, Geophysiker und Ingenieure arbeiten dabei in der heutigen Öl- und Gasindustrie eng zusammen, um von den seismischen Eigenschaften der Sedimente (z. B. Geschwindigkeiten der p- und s-Wellen, Dichte, Amplitude, Frequenz und Phasen) die Gesteinseigenschaften (z. B. Mineralogie, Lithologie, Ablagerungsraum, Porosität, Porenraumfüllung, Permeabilität und Druck- und Temperaturbedingungen) abzuleiten. Daraus wird dann in weiterer Folge im Zuge von Iterationsprozessen (Modellierung) wiederum auf die seismischen Eigenschaften rückgeschlossen. Diese Vorgehensweise hat sich bezahlt gemacht, denn heute wird mehr Öl und Gas gefördert als je zuvor und das in steigendem Maße umweltverträglich und kostengünstig.
Auf diesem Wege kann heute der tiefe Untergrund in einer Weise durchleuchtet werden, wie es noch vor wenigen Jahren undenkbar gewesen ist. Das ist möglich durch eine Kombination verschiedener Methoden, z. B. 3-D Seismik, dreidimensionale seismische Spektralanalyse, Multikomponentenseismik sowie Sequenzstratigraphie und Graphic Correlation. Diese Methoden sind die Vertrauensbasis dafür, daß die Industrie extrem teure Bohrungen (z. T. >50 Mio. $) mit großer Zielgenauigkeit abteuft, z. B. in mehr als 1500 m Wassertiefe einen gashöffigen Turbidit unter einem Salzüberhang in 7000 m Bohrtiefe. Dabei können die Sedimentologen auf ihren Beitrag zu diesen Möglichkeiten stolz sein.

Öl, Gas und Kohle sind Massengüter auf dem Weltmarkt. Um konkurrenzfähig zu bleiben, muß die Energieindustrie die Explorationskosten, die Erschließungskosten und die Produktionskosten so niedrig wie möglich halten, selbst wenn die Erschließung von Öl und Gas immer mehr in technisch schwierigere Bereiche, z. B. in Tiefwasser-Gebiete vorstößt.
Zukünftig wird deshalb die Energieindustrie eine noch genauere Vorhersage der Lithofazies im Untergrund benötigen: die Reife des Gesteins, den Porenraum und den fluid flow in drei und vier Dimensionen mit einer Genauigkeit von weniger als 10 m in einer Tiefe von 10 km voherzusagen, wird angestrebt. Altersdatierungen mit einer Genauigkeit von 10.000 Jahren bei 500 Mio. Jahre alten Sedimenten werden benötigt. Aber diese Genauigkeit wird vergebens sein, wenn es nicht gelingt, Daten dreidimensional darzustellen. Heute steckt die Entwicklung dieser hochauflösenden Darstellung noch in den Kinderschuhen. Bald werden aber Teams von Wissenschaftlern und Ingenieuren diese dreidimensionale Welt von Sedimentkörpern und ihrem Porenraum in jedem Detail virtuell darstellen können.

Die Zukunft der Öl-, Gas- und Kohleindustrie hängt stark davon ab, welche Kosten in der Form von Treibhauseffekt und Klimaveränderungen die Menschheit bereit ist zu zahlen im Tausch für Energie, Licht und Mobilität. Der Sedimentologie kommt dabei eine tragende Rolle zu in der Erforschung von Paläoklimaänderungen und den daraus resultierenden Vorhersagen, was uns in Zukunft erwarten kann.

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Abstract

During the **past hundred years,** sedimentologists in academia and industry have collaborated in describing and classifying sedimentary rocks and their pore content, in deducing the physical and chemical processes that govern deposition and diagenesis of sediments, and in characterising and predicting sedimentary environments and their spacial settings. The results of this collaboration are truly fascinating and stretch from highly accurate and fast laboratory methods to basin analysis as tools to predict hydrocarbon generation in source rocks, migration through carrier beds, and entrapment in reservoir rocks in space and time.

Today, progress in applied sedimentology comes increasingly from multidisciplinary integrated teams that bring together sedimentologists, palaeontologists, petrophysicists, seismologists, and engineers. The daily relentless effort by the oil and gas industry to link and integrate seismic properties of sediments (such as p- and s- wave velocity, density, amplitude, frequency, and phase) to the rock properties of sediments (such as mineralogy, lithology, environment of deposition, porosity, pore fill, pressure, and permeability) and back to the seismic properties in thousands of iterations (inverse and forward modelling) is paying off: more oil and gas is being produced today than ever before, and it is done in an increasingly environmentally friendly and cost effective way.

We are now able to illuminate the subsurface in ways unthinkable only a few years ago. New tools include 3-dimensional seismic coherency, 3-dimensional seismic spectral decomposition, multicomponent seismic as well as sequence stratigraphy and graphic correlation using a composite standard. Methods like these give industry the confidence to drill extremely expensive wells (costing $ 50 million plus each) in more than 1500 m of water aiming, for instance, for a gas bearing turbidite channel which is located underneath a salt overhang more than 7000 m below the seabed. Sedimentologists can be proud of their part in making this possible.

Oil, gas, and coal have become commodities in the world markets. To stay vital, the energy industry will need to keep finding costs, development costs, and lifting costs as low as possible, while oil and gas operations expand into high cost areas such as deep water.

In the future, the energy industry will need to accurately predict subsurface lithofacies variations, thermal maturity, pore content, and fluid flow in 3 and 4 dimensions with resolution of less than 10 metres at a depth of more than 10 kilometres. Age dating with an accuracy of better than 10,000 years in sediments more than 400 million years old are needed. High resolution and high accuracy would be wasted in sedimentology and elsewhere, if we would not also enhance our capabilities in 3-D visualisation. Today's immersive visualisation systems are just a beginning. Soon multidisciplinary teams of scientists and engineers will be jointly diving and climbing through the 3-dimensional virtual reality of sediment bodies and their pore spaces, seeing every minute detail.

The future of the oil, gas, and coal industry ultimately depends on the price humankind is willing to pay for power, light, and mobility in terms of greenhouse gas emissions and climate change. Sedimentology will have a major role to play in understanding past climate changes and predicting what is in store for us all in the future.

1. Introduction and Context

Almost 65 percent of the primary energy supply to the economies of the world comes from oil (39 %), and gas (26 %) (Fig. 1). The exploration for, and the production of, oil and gas requires an accurate understanding of sediments. After all, the organic matter that is the source of oil and gas has been deposited in sediments and it matures in sedimentary rocks, oil and gas migrate through sedimentary rocks, are trapped in sedimentary rocks, and are extracted by man from sedimentary rocks. Knowledge of the 3-dimensional distribution of lithology, mineralogy, fossils, porosity, permeability, thermal maturity, and pore fill of sediments and the comprehension of how these distributions change in space over geologic time is of essence to the oil and gas industry.

It is not surprising then, that the oil and gas industry plays

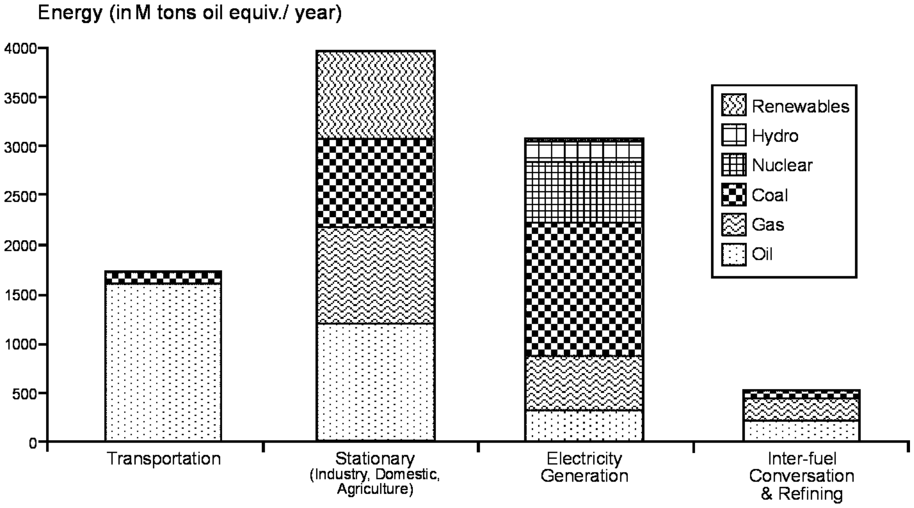


Fig. 1: Energy supply to the world's economies (energy traded in markets, from International Energy Agency 1996, data for the year 1995). Oil is the dominant energy source for transportation and a very important source for stationery process heat, heating and cooling. Natural gas is important for stationery process heat, heating and cooling; its share in electricity generation is rapidly growing. Liquid fuels derived from gas will play a larger role in transportation in the future.

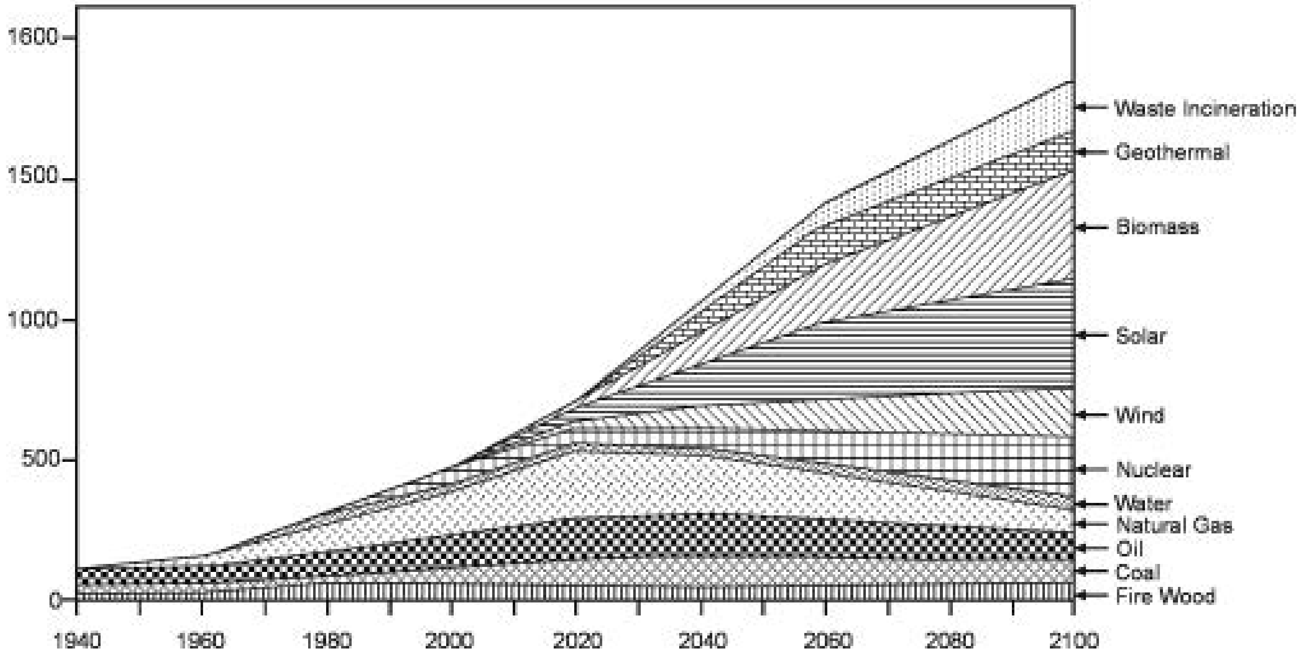


Fig. 2: Energy supplies to the world's economies in the past, present, and future: in an "energy mix" scenario, oil and gas will be needed for many decades to come (modified from Shell 1996 and SCHOLLNBERGER 1998a).

an important role in the development and the progress of sedimentology. Industry assembled an enormous data base on sedimentary rocks from field studies, millions of wells, and millions of kilometres of seismic lines and has the computer capabilities to handle, process, and display large data sets in three dimensions.

Academia and industry jointly developed truly remarkable methods to analyse and describe sediments and sedimentary rocks, in order to interpret their origin and to predict changes in sediment properties in space and time. The oil and gas industry provides wide ranging opportunities for many thousands of sedimentologists to develop, test, and apply sedimentological methods, models, and knowledge. Many leading sedimentologists at universities around the world have worked for some time of their careers in industry and vice versa. In the context of this paper, it is irrelevant whether a researcher in industry or a scientist in academia first developed a method or a useful model. However, it is significant that sedimentology would not be in the place where it is today without mutually beneficial collaboration between industry and academia. This paper presents a small selection of truly remarkable examples of how the efforts of both, academia and the oil and gas industry, have created capabilities to illuminate sedimentary features in the deep subsurface to a clarity which was unthinkable only a few years ago.

The future of the oil and gas industry ultimately depends on the price humankind is willing to pay for power, light, mobility, and comfort in terms of greenhouse gas emissions and climate change. If carbon dioxide emissions are 100 units/ BTU for coal, they are about 50 units for oil and 25 units for natural gas. For a few years now, those who want to improve the quality of their environment, and can afford

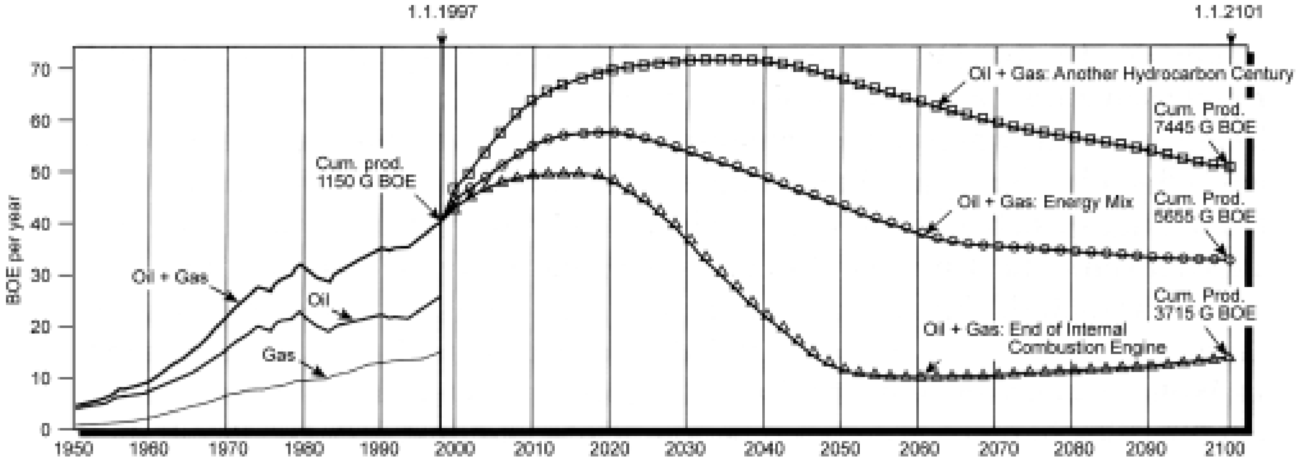


Fig. 3: Forecast of annual world wide hydrocarbon extraction through 2101 (in G barrels of oil equivalent); actual data through 1.1.1997, beyond that projections for three scenarios (SCHOLLNBERGER 1998a, b).

to do so, demand cleaner energy sources. Since the beginning of the 20th century, there is a trend away from relatively carbon-rich coal to more hydrogen-rich oil and natural gas as the energy sources of choice. Solar energy, wind derived energy, and geothermal energy will become increasingly more important during the next decades (Fig. 2). Even a future clean world economy entirely based on hydrogen is a theoretical option now. It will become reality as soon as a cheap and environmentally friendly source of hydrogen (e.g. a highly efficient photocatalyst to split water, or nuclear fusion driven electrolysis) has been found and made ready for mass deployment. This may take 20 years or longer, or it may never happen. But oil and gas will be needed in all scenarios, at least as a convenient raw material for a wide range of useful chemicals (Fig. 3; see also SCHOLLNBERGER 1998a, b). Thus, **the petroleum industry will continue to apply sedimentology and provide challenging jobs for many sedimentologists for a long time to come**.

2. Historic Perspectives

2.1. General Remarks

Looking back over the last one hundred years, we can recognise three trends in sedimentology, which were significantly influenced by the needs of the oil and gas industry:

- a trend from vagueness to precision
- a trend from description to prediction (in space and time)
- a trend from (attention to) small scale phenomena (point observations) to the inclusion of basin wide and world wide aspects (while small scale phenomena never lost their importance).

Scientists are generally not deliberately **vague** or inaccurate. They make choices as to what accuracy is needed to answer a particular question or solve a problem. Searching and drilling for oil and gas costs a lot of money. Up to 50 years ago, oil and gas production was land based, now exploration and production activities are taking place increasingly in deep water environments, where a single well may cost $ 50 million or more. Industry cannot afford to gamble away money by drilling expensive wells in search of ill defined targets. Wherever open market conditions prevail in the economic world, companies which fail to fullfill their stakeholder's expectations are eventually driven out of business. Seen this way, the industry's push towards the greatest possible **precision** in sedimentology and the clearest possible illumination of the subsurface is not surprising.

While the end points of the trend from vagueness to precision are mutually exclusive, the end points of the other two trends are not. Sedimentologists in the oil and gas industry are deeply involved in both **description and prediction**, because description alone does not lead to oil or gas discoveries. Predictions, however, of the porosity/permeability distribution in a basin, or the thermal maturity of a source rock, can lead to the discovery of hydrocarbon accumulations. Good predictions are almost always based on careful and detailed descriptions.

The third trend in sedimentology, the occupation with **progressively larger scale** sedimentological aspects (sedimentary bodies and environments, sequence stratigraphy, and basin analysis) while paying continued attention to small scale phenomena (such as particle mineralogy, grain size and shape, and pore space geometry) also reflects the changing needs of the oil and gas industry over the last one hundred years (Fig. 4).

In the following - without laying claim to any completeness at all - we shall touch on a few stations along sedimentology's path from small to large scale. We shall also demonstrate how accuracy and predictive capabilities in sedimen-

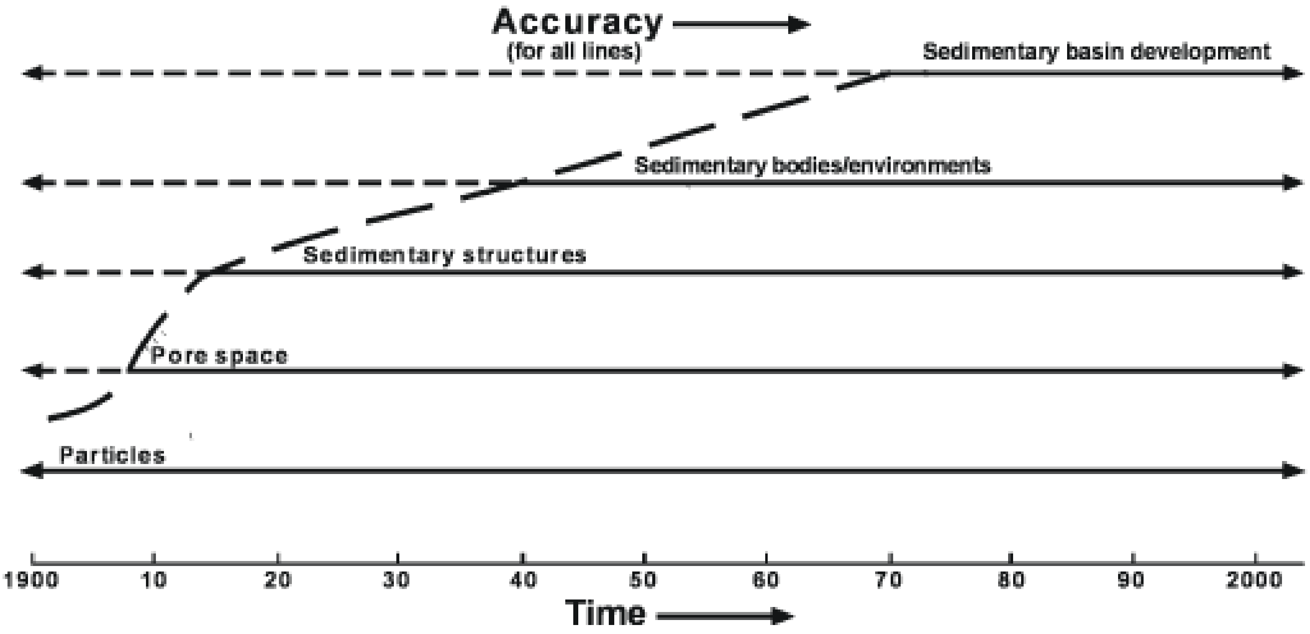


Fig. 4: Intensive research in sedimentology (full lines) progressed generally from small scale (grains) to large phenomena (basins), partly in response to the needs of the oil and gas industry.

tology increased with time.

2.2. Particles, Pore Space, and Diagenesis

The interest of the petroleum industry in sedimentology stems from the fact that nearly all oil and gas originates from sediments and that it migrates through and accumulates in the pore space of sedimentary rocks. Tight rocks with low porosity/permeability block hydrocarbon migration. Would oil and gas be trapped in the holes of Emmental cheese, the petroleum industry would be interested in Emmental cheese instead of sediments. While sedimentologists distinguish between siliciclastic and carbonate sediments, evaporites, silicious sedimentary rocks (incl. radiolarites and cherts), iron rich sedimentary rocks, phosphorites and carbonaceous sedimentary rocks (incl. coal, oil shales and bitumen), and others, the petroleum industry looks at sediments in the first place as **source rocks**, **reservoir rocks,** and **seals**. This is a simplification, but it has not prevented the industry from developing the highly efficient methods, which it needs to describe, classify, and interprete sediments. The industry developed several useful classifications of clastics based on mineral content, grain size (clay, silt, sand, etc.), grain shape (angular, rounded etc.), grain orientations, grain packing, etc. Industry needs also triggered the two most widely used modern carbonate classification systems. The one by Folk (1959) is based on the relative abundance of (1) carbonate grains, (2) microcrystaline carbonate mud (micrite), and (3) sparry calcite cement. The classification by Dunham (1962) is based on (1) the distinction between grain and mud (matrix) supported carbonates and (2) the depositional binding of grains. Dunham's classification is now the most favoured in industry, because it can be easily applied using a handlens in the field as well as under the microscope in the laboratory (Fig. 5).

Füchtbauer (1988) gives a good overview of methods how to describe minerals, grains and particles of siliciclastics and carbonates, as well as how to measure grain size, grain size distribution, grain shape, grain orientation and packing, porosity, and permeability. The very important role of fossils in characterising and genetically interpreting the (micro) facies of sediments has been demonstrated by Flügel (e.g. 1977). Microfacies analysis is widely used in the industry.

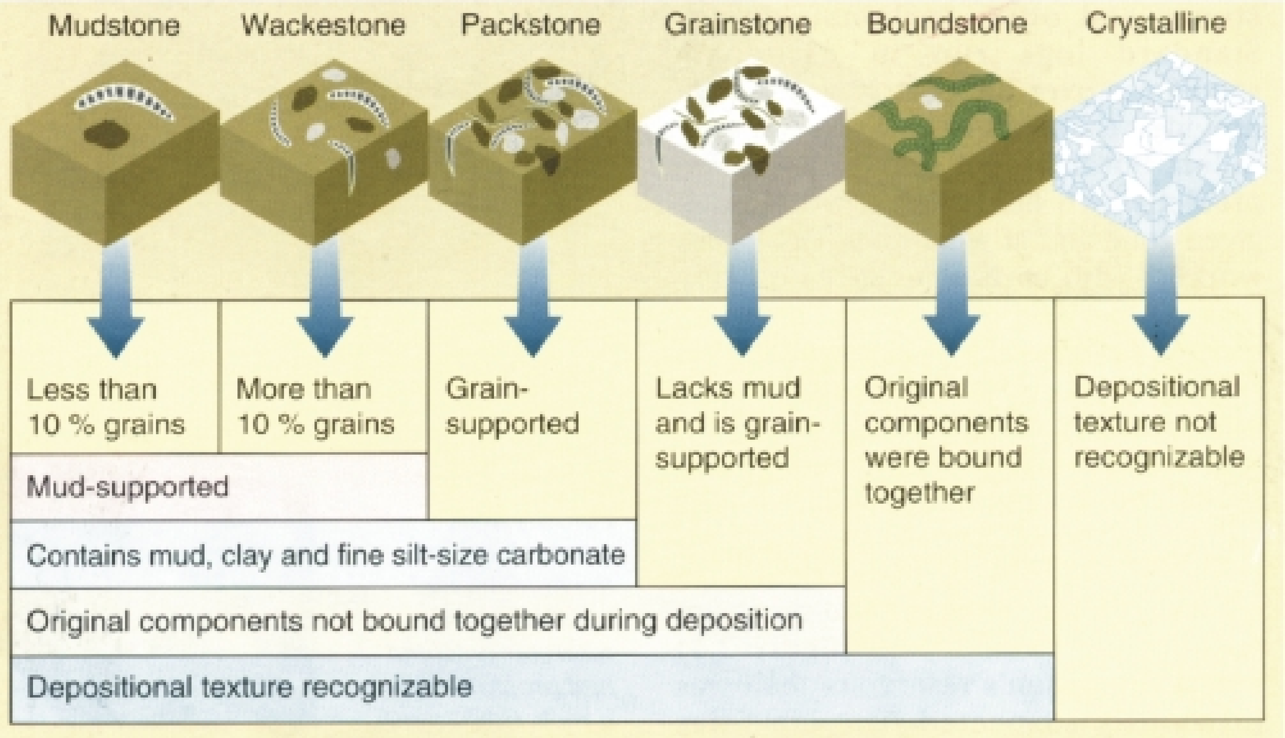


Fig. 5: The classification of carbonates devised by Dunham (1962) (reproduced with permission of Schlumberger).

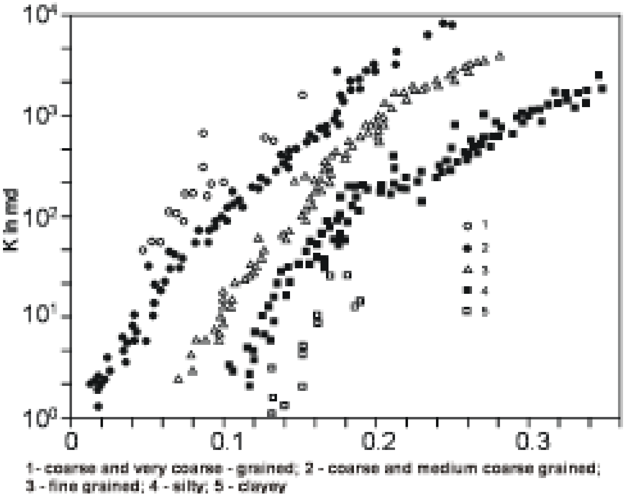


Fig. 6: The permeability (k) versus porosity relationship in sediments is influenced by grain size and grain shape (Schön 1996; modified from Serra 1984).

Understanding and correctly predicting the flow of oil, gas, and water through sediments in space and time is of enormous economic importance to the petroleum industry. **Fluid flow in porous sediments** is governed by DARCY's law which he published in 1856. Fluid properties such as density are, of course, important for calculating Darcy flow, but also important are sediment characteristics such as size and shape of sediment grains/particles (including primary grains/particles and diagenetically created and transformed ones), together with porosity and pore space geometry (Fig. 6). SCHÖN (1996) deals with Darcy flow and other petrophysical aspects of sediments in an excellent way.

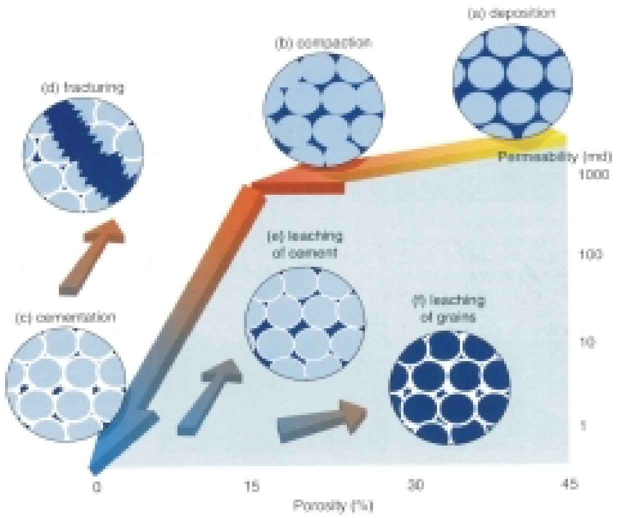


Fig.7: Diagenetic changes of inter-particle pore space. Compaction (b) and cementation (c) decrease porosity, whereas fracturing (d) and leaching of cement (e) and grains (f) increase porosity (NURMI & STANDEN 1984, reproduced with permission of Schlumberger).

Diagenesis is of interest to the petroleum industry because it can create or destruct porosity (Fig. 7). Many of the classic diagenesis studies in the petroleum industry dealt with the influence of temperature, pressure, and pore fluid chemistry on the alteration of the original minerals in a sedimentary rock and on the growth of new minerals around the original grains and into the primary pore space. Today, the prediction of porosity/permeability and hydrocarbon flow volume in very porous, poorly consolidated siliciclastic sands (mostly of Tertiary age) is of great economic importance and the focus of diagenetic studies. This is so, because the reservoirs in many recently discovered giant hydrocarbon fields are rapidly deposited and poorly consolidated sandstones (e.g. offshore Trinidad, along the Apsheron Ridge in the Caspian, and in the deep water areas of the Gulf of Mexico, Brazil, and central West Africa). Core information is hard to obtain from such sediments, and log interpretation is very difficult. Nevertheless, the industry needs to predict (e.g. through modelling) porosity and permeability in these sediments, and the conditions under which stabilizing early rim cement may form around quartz grains. Hence, industry focuses current research in diagenesis on poorly consolidated sediments.

2.3. Sedimentary Structures

Primary sedimentary structures have been observed since

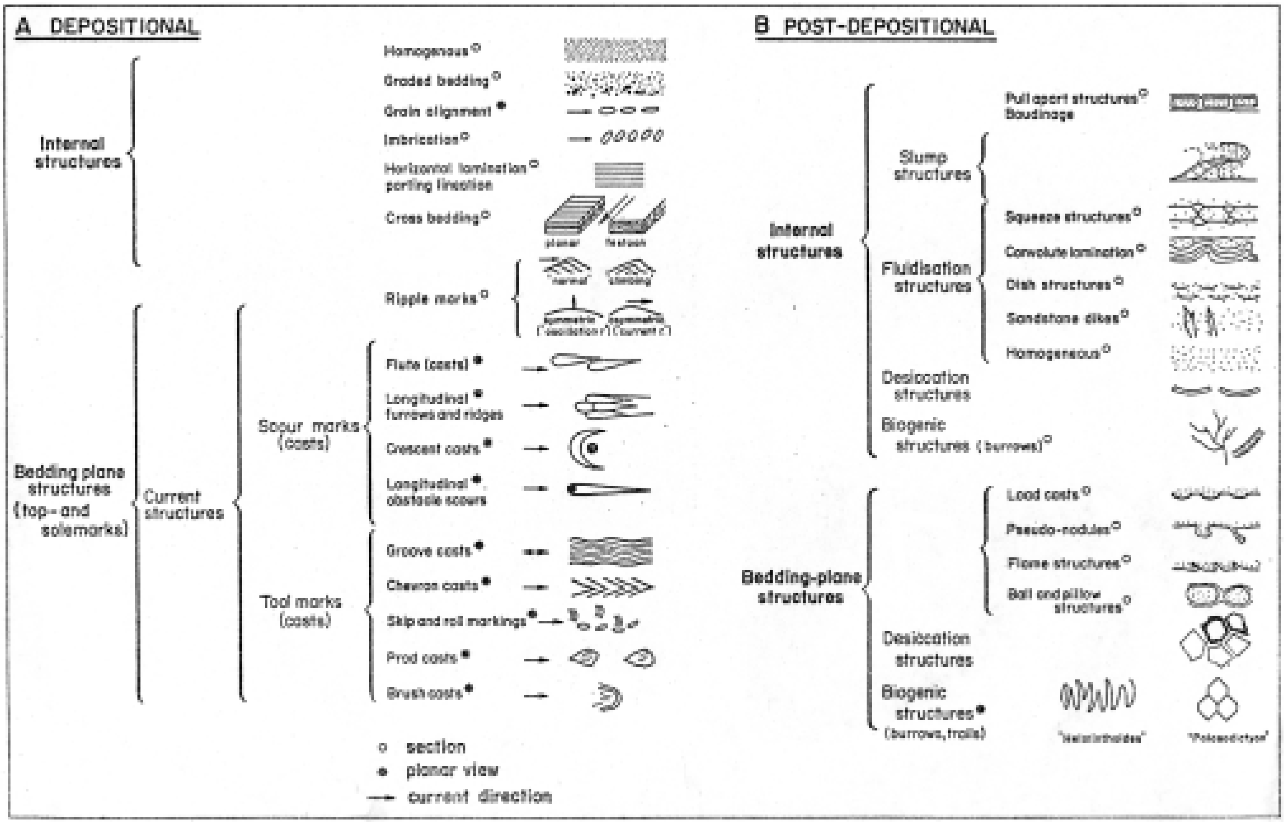


Fig. 8: Common primary sedimentary structures in clastics.

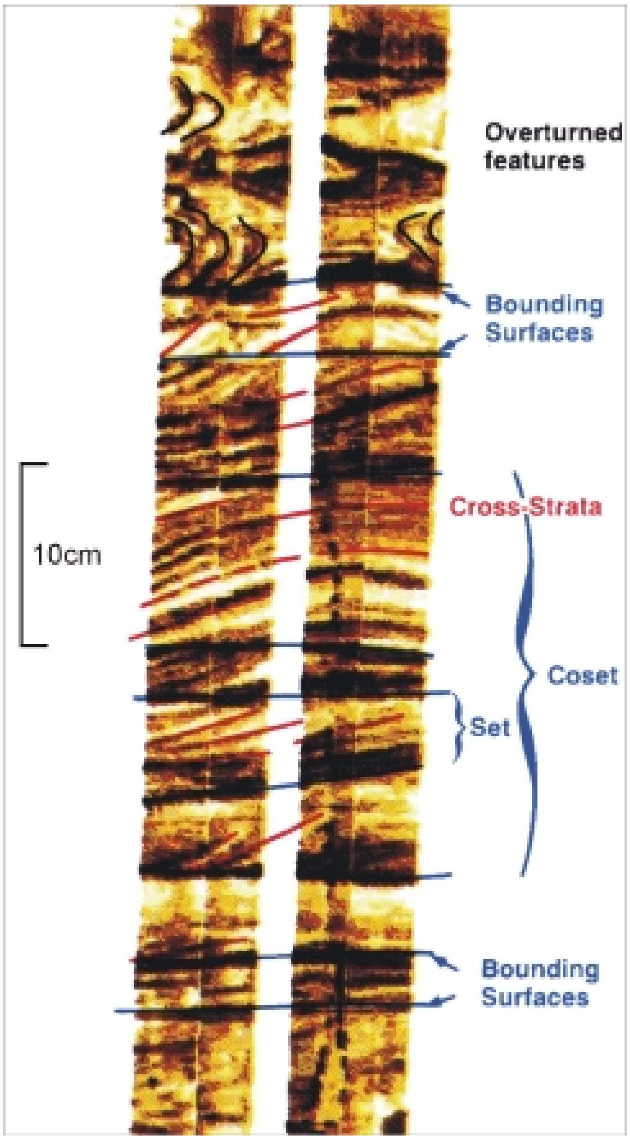


Fig. 9: High-resolution logging tools such as the Formation Micro Scanner produce detailed images of sedimentary features (reproduced with permission of Schlumberger).

the scientific study of sediments by pioneers such as Nicholaus Steno and William "Strata" Smith began in the 17th and 18th century. Primary structures and their diagenetic overprint influence the vertical and horizontal permeability in sedimentary rocks. Good modern compilations of primary and diagenetic sedimentary structures and their genetic interpretations can be found in Füchtbauer (1988) and Boggs (1995). Useful earlier discussions of clastic sedimentary structures are presented by Middleton (1965) and Blatt et al. (1972). Carbonate fabrics are classically described by Folk (1962) and Dunham (1962). Seilacher (1964) comprehensively presents trace fossils and other biogenic sedimentary structures. Frequently occurring primary sedimentary structures in clastics are pictured in Fig. 8.

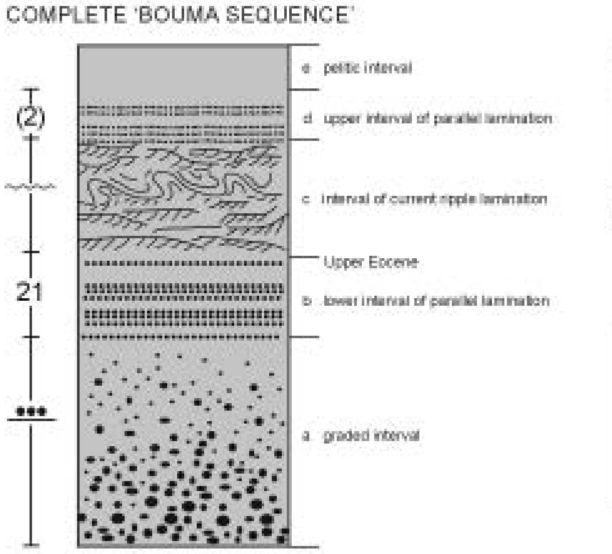
Sedimentary structures are an essential element in explaining the mechanical and chemical processes that lead to the formation of sediments. The interpretation of depositional sedimentary environments requires the knowledge of the origin of sedimentary structures (see also chapter 2.4). It is interesting to note that not only does the recognition of sedimentary structures help explain the origin of sediments, sometimes the understanding of the origin of sediments leads to the recognition of previously neglected sedimentary structures. As an example: after certain clastic beds were recognised as turbidites, i.e. deposits from turbidity currents by Kuenen & Migliorini (1950), many 'new' sedimentary structures were found in turbidites (Fig. 10; see also Djulinsky et al. 1959, Bouma 1963). For sedimentary structures it is certainly true that 'we see what we know', 'we know what we understand', therefore 'we see what we understand'.

2.4. Sediment Bodies and Depositional Environments

The knowledge of the shape, volume, and spatial relationships of porous and non-porous sedimentary bodies in three dimensions is of paramount importance for the oil and gas industry. Until about 1955, the porosity distribution in the subsurface was mainly deduced from well cuttings, cores, wireline logs, and occasionally from low resolution seismic. In order to make more sense of widely spaced log and core data and of (then) inaccurate seismic information, industry and academia joined forces beginning in the 1950's to collect information on size, shapes, and distribution of porous and tight sedimentary bodies in present day depositional environments (e.g. Glennie, 1970 for deserts, Houbolt & Jonkers 1968, Sturm & Matter 1978 for lakes, Williams & Rust 1969 for braided rivers, Bernard et al. 1962 for meandering rivers, Kruit 1955 and Oomkens 1967, 1974 for deltas, Purdy 1963, Wilson 1970, 1975, Purser 1973, Enos & Perkins 1977 for carbonate platforms, Houbolt 1968 for clastic continental shelf areas, Mutti & Ricci Lucchi 1972 for deep water fans). These efforts and the contributions of many others resulted in a set of well characterised present-day depositional environments which now serve industry and academia as analogues for the interpretation of past depositional settings.

Right from the beginning of these studies of modern environments, the industry emphasised the documentation of vertical and lateral variations in lithology (including rock density and clay content), grain size, and porosity. These are the important rock properties which influence wireline log shapes in wells (e.g. gamma ray, sonic, density and resistivity logs) as well as amplitude, frequency, and phase in reflection seismic. Already in the 1950's and 60's vertical successions of lithologies were translated to wireline log shapes and vice versa (Figs. 11 and 12). Enlightened sedimentologists built on this and successfully applied J. Walther´s "law of succession of facies" to predict lateral facies variations from vertical boreholes. Walther (1894) states that only those facies can be superimposed in vertical sections which can be observed beside each other at the present time. The application of this law was of enormous importance to the oil and gas industry, which before 1970 relied mainly on vertical wells for subsurface information.

From about 1970 on, industry learned to convert reflections



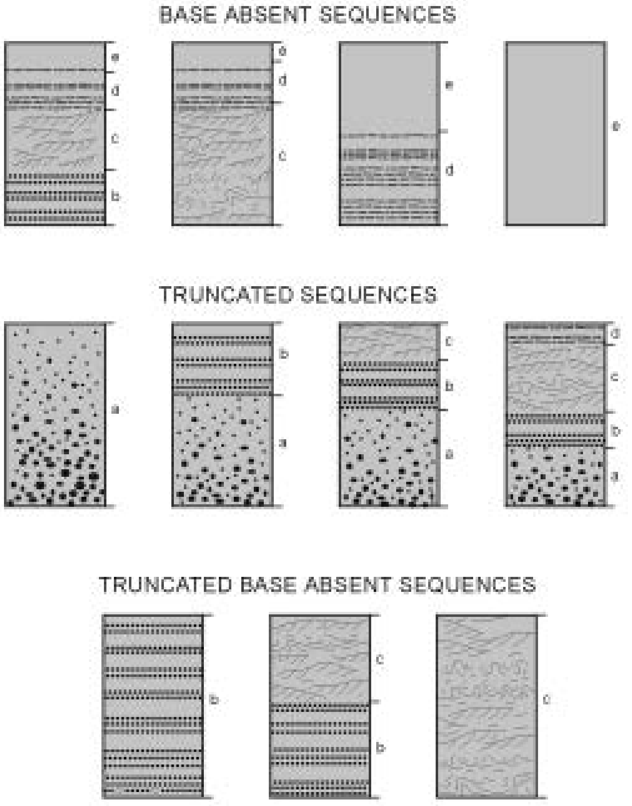


Fig. 10: Complete and incomplete BOUMA sequences in turbidite beds.

in seismic profiles to detailed lithological successions (see Brown 1991; more about this in chapter 3.3) . Using wireline logs and seismic data, depositional environments with their

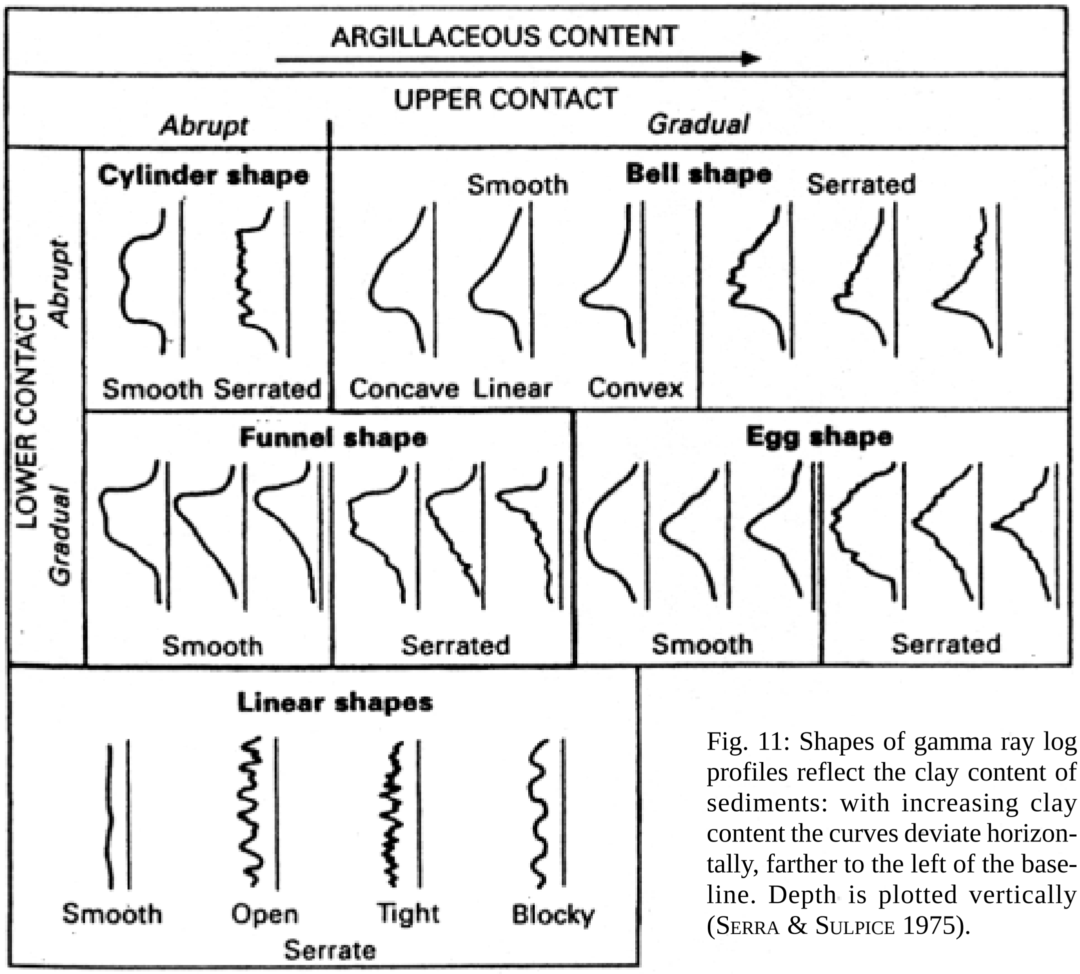


Fig. 11: Shapes of gamma ray log profiles reflect the clay content of sediments: with increasing clay content the curves deviate horizontally, farther to the left of the baseline. Depth is plotted vertically (Serra & Sulpice 1975).

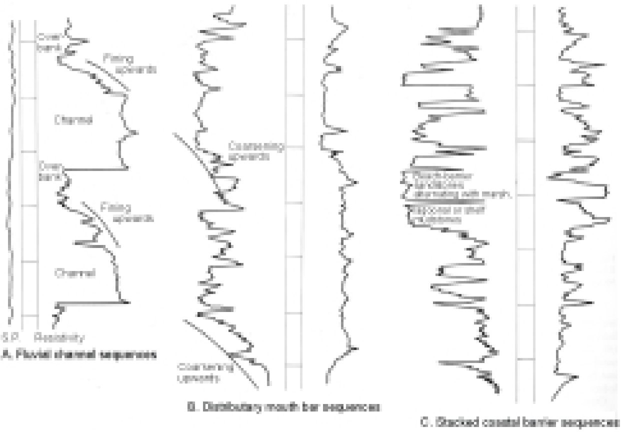


Fig. 12: Shapes of gamma ray or spontaneous potential log profiles (left curves) and resistivity log profiles (right curves) for a delta complex in the Tertiary Upper Wilcox Group, Gulf of Mexico (after Fisher & McGowen 1969).

porous and non-porous sedimentary bodies could be defined and mapped in the subsurface, even remote from outcrops and in between wells (Figs. 13 and 14).

It can not be emphasised enough, how important fossils are in interpreting past depositional environments. **Sedimentary features** (such as the mineralogy of particles, grain size, sedimentary structures, etc.) **by themselves are hardly ever indicative of a particular depositional environment**. The interplay of physical and chemical processes that creates such features is normally not limited to just one depositional environment only. For instance, the water turbulence caused by a ripple on the floor of a channel may be of the same kind and may have the same degree of intensity whether the environment is a river or a deep marine channel. Even the fact that the resulting sediments in one case have been deposited by a waning traction current in fresh water and in the other case by a waning turbidity current in salt water may not be distinguishable based on the resulting sedimentary structures. There are for instance, near Yesa in the Spanish Pyrenees, graded beds of Oligocene age, which display A, B, and C members of the Bouma sequence as it is often found in deep water turbidites, but with the footprints of water birds as sole marks. The birds certainly did not have 200 m long legs. The micro fauna in the claystones immediately underlying and overlying the beds with the bird tracks indicates a continental environment of deposition and places the sediments in a lacustrine setting. This example makes it clear that the **interpretation of depositional environments has to be based in the first place on characteristic autochthonous faunas** rather than on mechanical and chemical sedimentary features. The occurrence of benthonic foraminifera, molluscs, and other fossil groups is well known in modern environments. Benthonic foraminifera are especially good indicators of water depth (such as inner, middle, and outer neritic, bathyal, abyssal). Going back in time, we can recognise past depositional water depth by taking into account phylogenetic relationships between present day organisms and their fossil relatives and by assuming that species lived in the past in the same environment as where they live now. Some petroleum companies (e.g. BP, ExxonMobil, Shell) and academic institutions have assembled large data bases on the quantitative occurrence of benthonic foraminifera in various modern and past

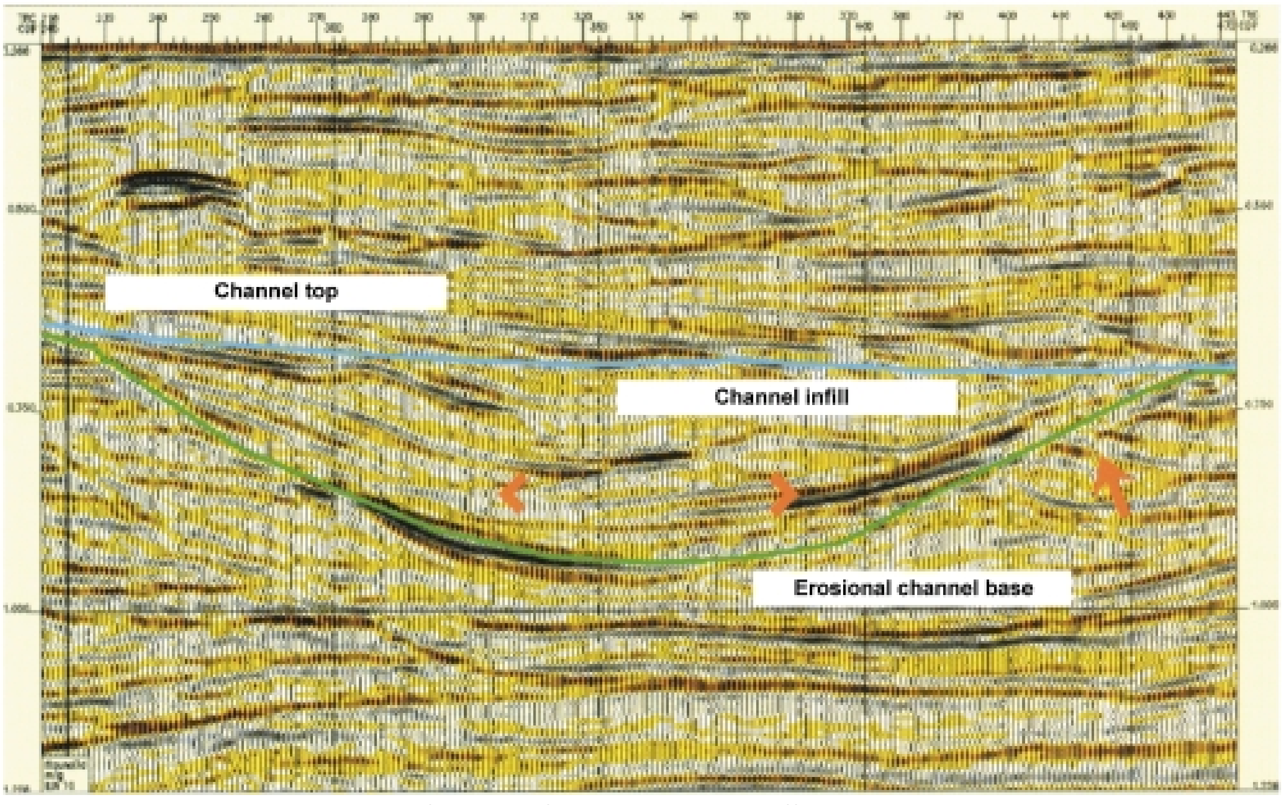


Fig. 13: High resolution seismic image of a channel fill (Gippsland basin, offshore Australia). Amplitude changes (between the chevrons) indicate the presence of stratigraphically trapped oil and gas (reproduced with permission of Schlumberger).

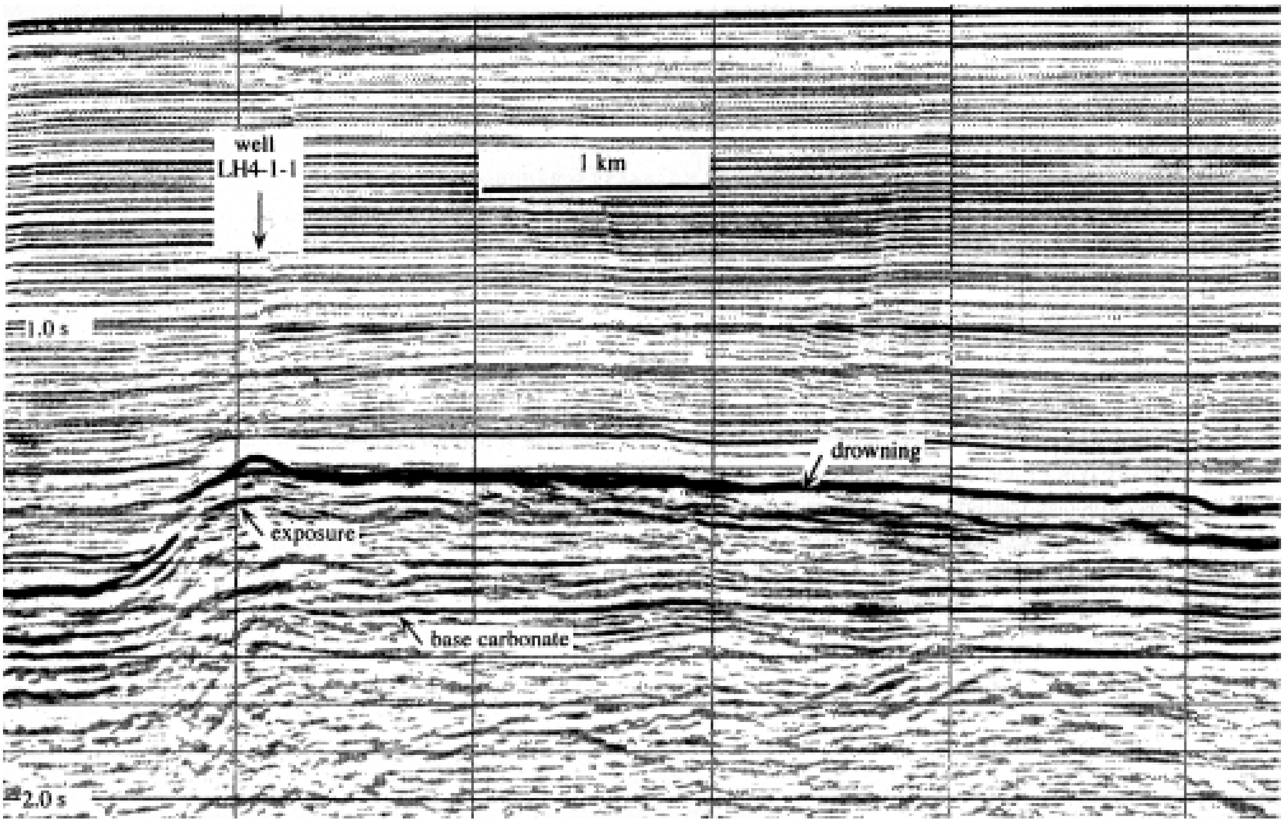


Fig. 14: High resolution seismic image of the Liuhua carbonate platform (Miocene, South China Sea). The platform repeatedly backstepped before finally drowning, after a period of condensed sedimentation it was covered by claystone (Schlager 1999 after Erlich et al. 1990, reproduced with permission of BP).

sedimentary environments (e.g. Kruit et al. 1975). This approach based on faunas works very well back to the beginning of the Tertiary, in some cases to the beginning of the Late Cretaceous; beyond that, benthonic foraminifera assemblages become too different from present day ones and we have to use analogues and comparisons with modern depositional environments based on biogenic and non-biogenic sedimentary features. In this way we are able to interpret e.g. Carboniferous Kulm greywackes as deep marine turbidites, or Precambrian stromatolites as intertidal sediments, and we may be right. **One just has to be very**

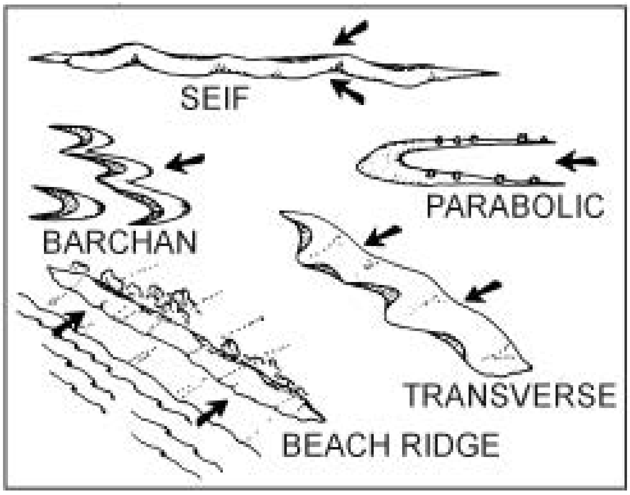


Fig. 15: Various types of sand dunes (arrows indicate wind directions, from Spiering 1971).

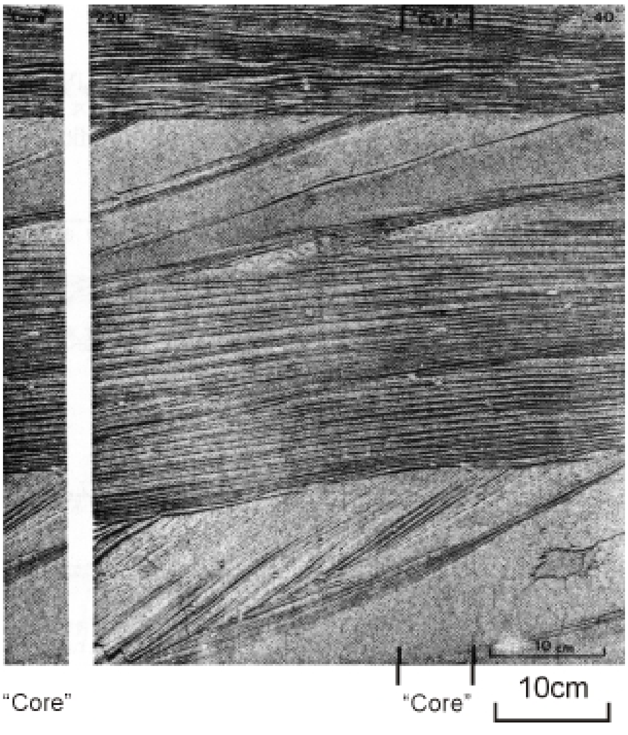


Fig. 16: Lacquer peel from a recent seif dune in Dubai. Column on the left shows what a "core" of these sands would look like (original position of "core" is indicated) (from Glennie 1970).

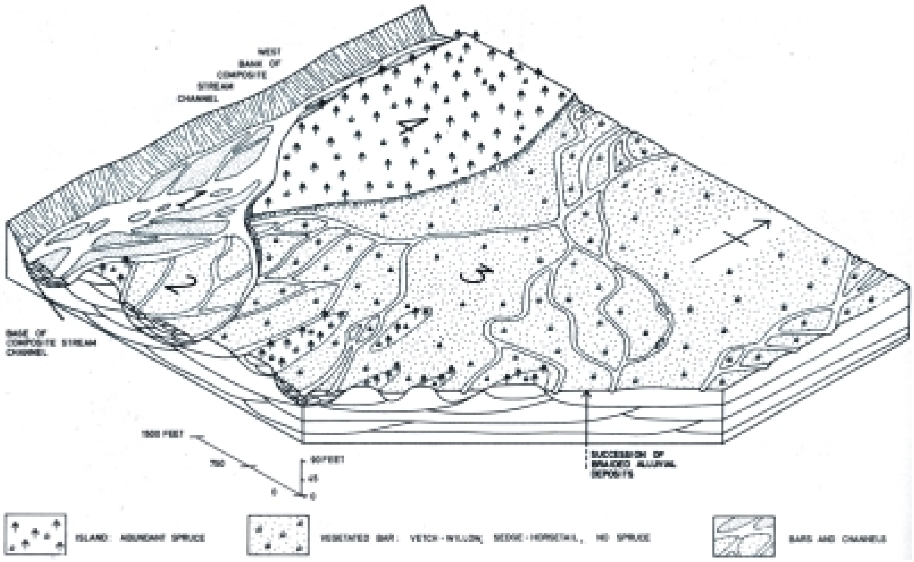


Fig. 17: Facies model of the floodplain of a braided river. The floodplain is dissected into four levels, numbers in order of increasing elevation. The lowest levels are the most active, the higher are least active and stabilised by vegetation (from WILLIAMS & RUST 1969).

careful with the interpretation of pre-Tertiary depositional environments and it is wise to keep an open mind.

As a result of many years of fruitful collaboration between industry and academia a collection of ‘icons’, which illustrate the occurrence of porous and non-porous sedimentary bodies in major depositional environments, is available. Here we present only a small number of them. The selection is a personal one: it contains those ‘icons’ (illustrations of monumental importance), which helped me finding oil and gas during the last thirty years (Figs. 15 through 27).

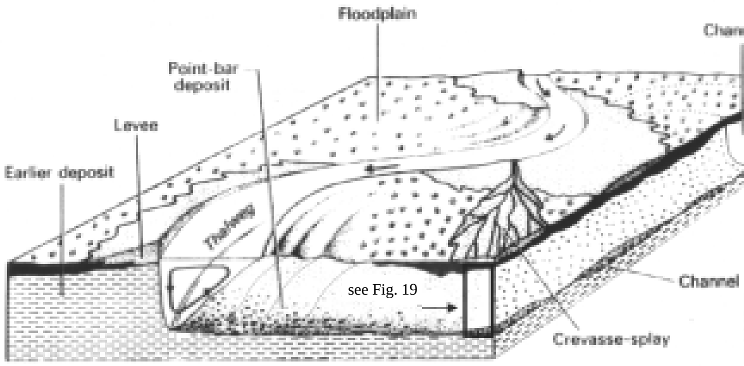


Fig. 18: Facies model of the floodplain of a meandering river (from ALLEN 1964). The sedimentary structures within a point bar are shown in Figure 19.

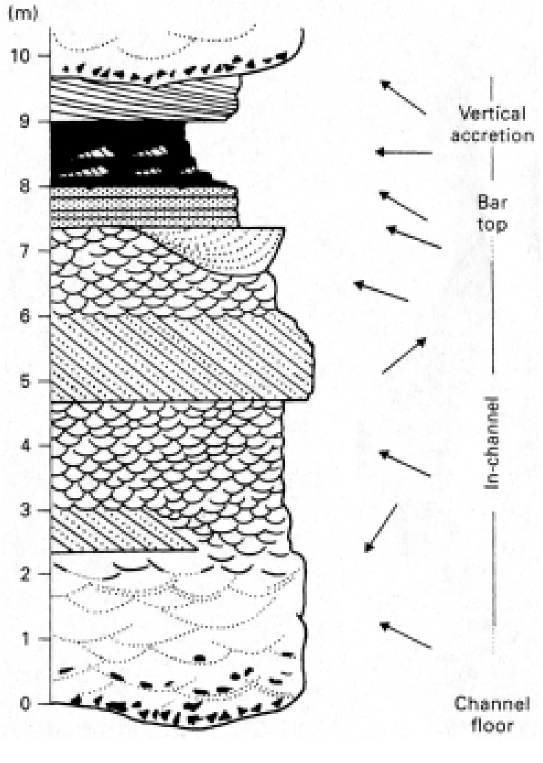


Fig. 19: Blow-up from Figure 18. The vertical succession of internal structures in a point bar (arrows indicate current directions) (from ALLEN 1964).

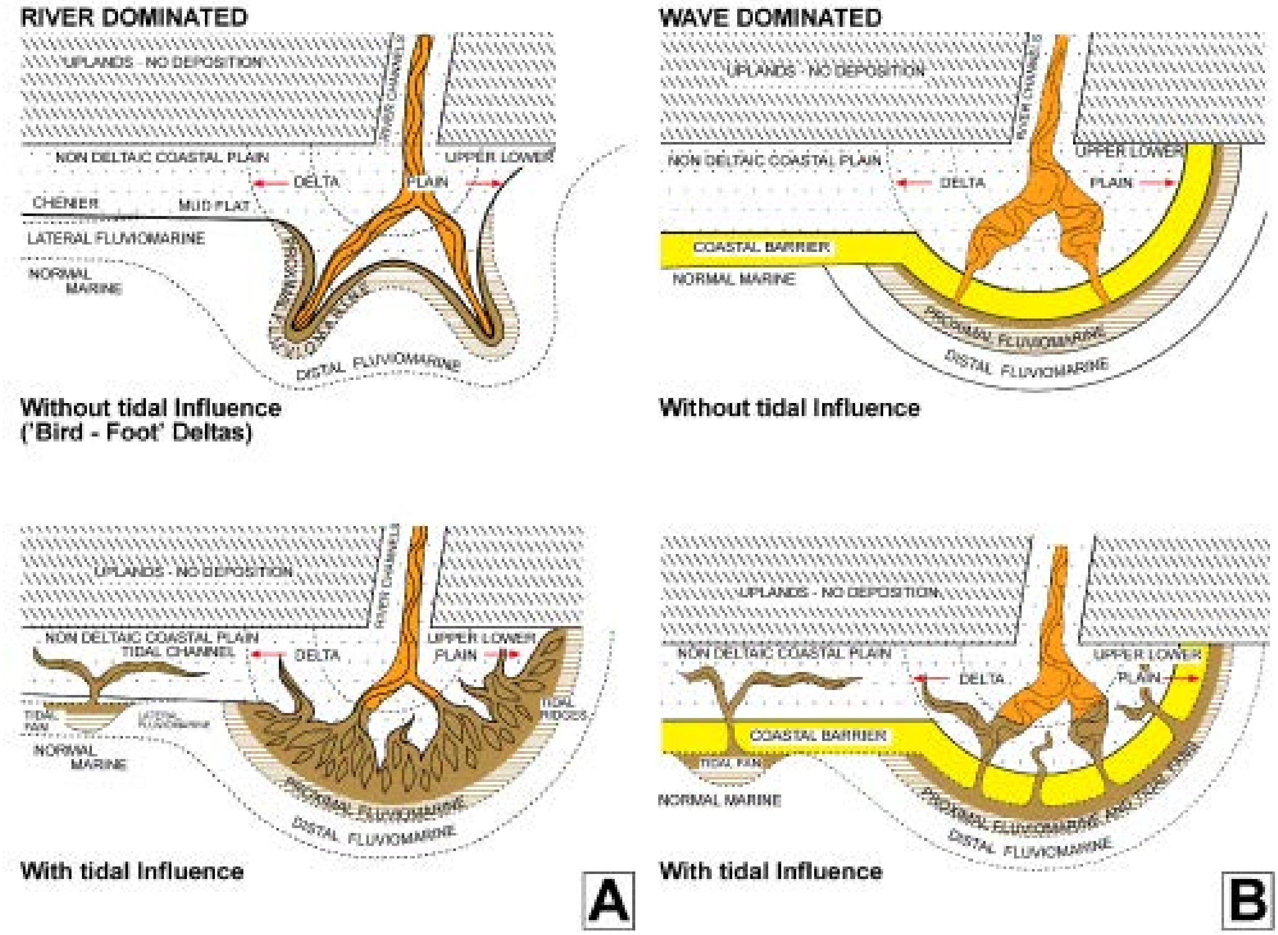


Fig. 20: An immensely practical classification of deltaic and non-deltaic coastal clastics (modified from Kruit 1955 and Oomkens 1967, 1974). Deltas are composed of various facies such as fine grained distal fluviomarine claystones and siltstones, sandy coastal barriers/bars and dunes, sandy tidal channels and fans, fine grained lagoonal deposits, sandy fluvial channels, fine grained interchannel deposits, etc. Wave dominated deltas without tidal influence contain well developed, porous, well interconnected sand bodies, whereas river dominated deltas without tidal influence contain relatively few, with lower porosity, isolated sand bodies.

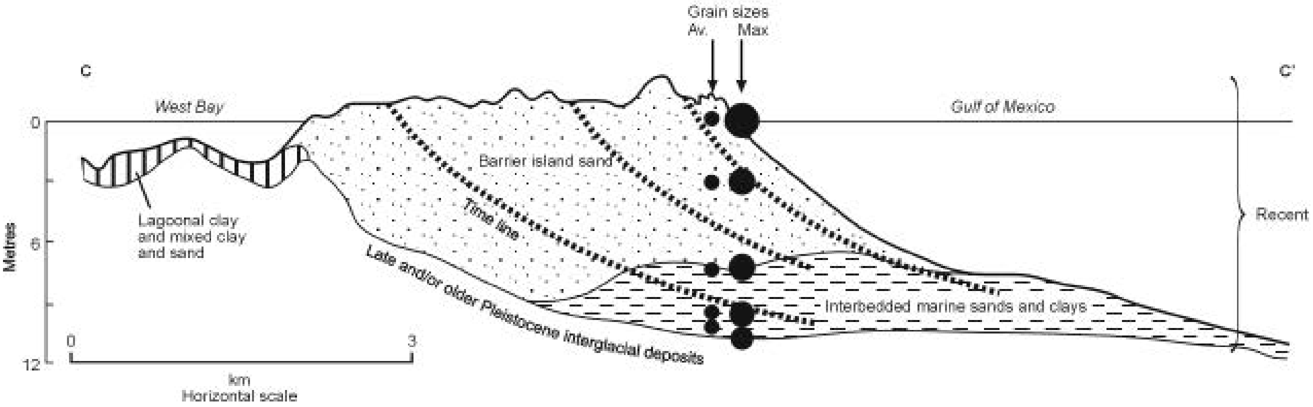


Fig. 21: The prograding coastal barrier of Galveston Island, Texas is a coarsening upward sandbody (after Bernard, Leblanc & Major 1962).

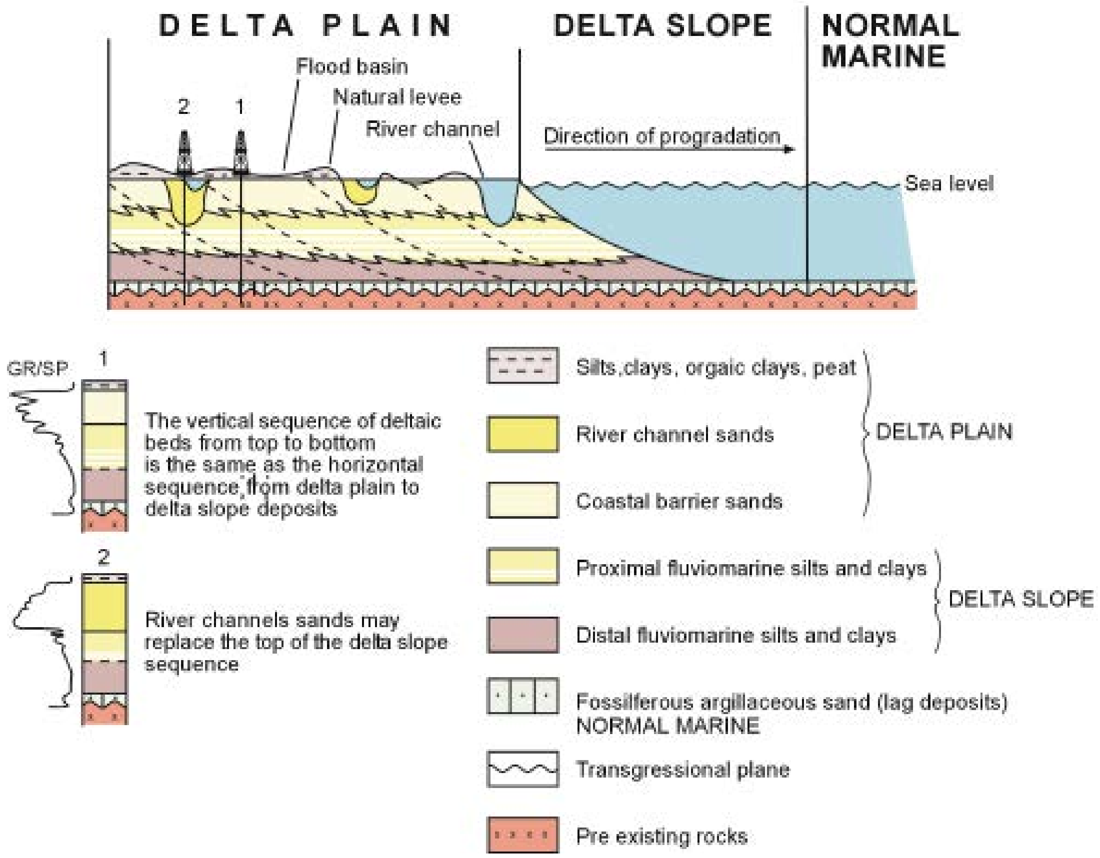


Fig. 22: A schematic cross-section through a prograding, coarsening, and thickening upwards coastal barrier with characteristic gamma ray/spontaneous potential log profiles.

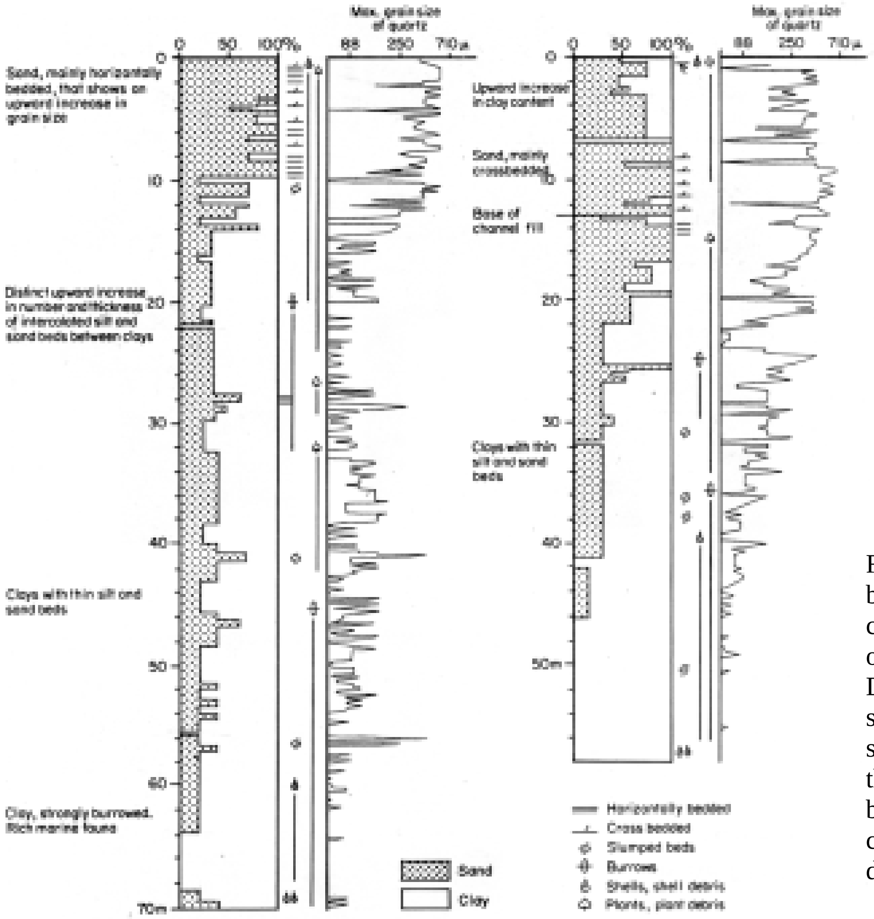


Fig. 23: Lithologies and grain size distribution from 2 cores through prograding, coarsening upwards coastal barrier sands of the recent Rhone Delta (KRUIT 1955). Deeper water sediments are overlain by sediments deposited in progressively shallower water. The highest member of the sequence may consist of horizontally bedded coastal barrier sands (left) or of cross bedded fining upward channel fill deposits (see also Figs. 12 and 22).

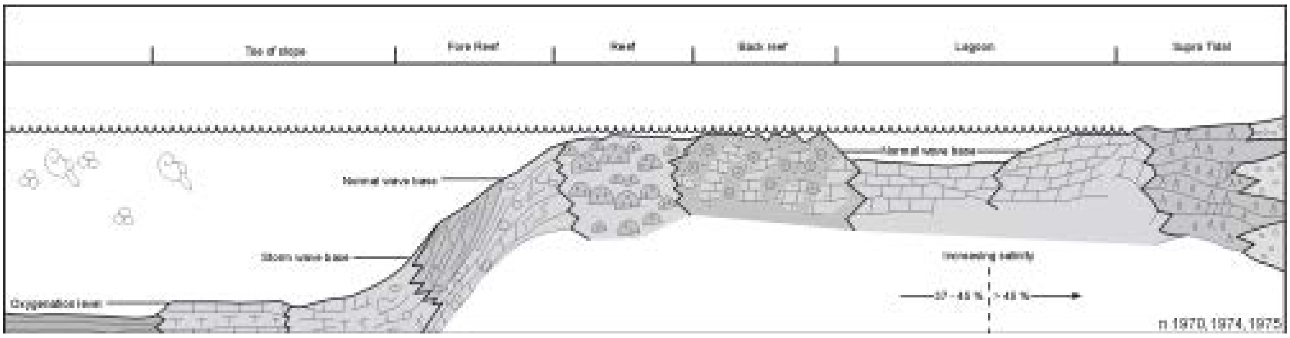


Fig. 24: Facies belts in carbonate platforms, after WILSON (1970, 1975).

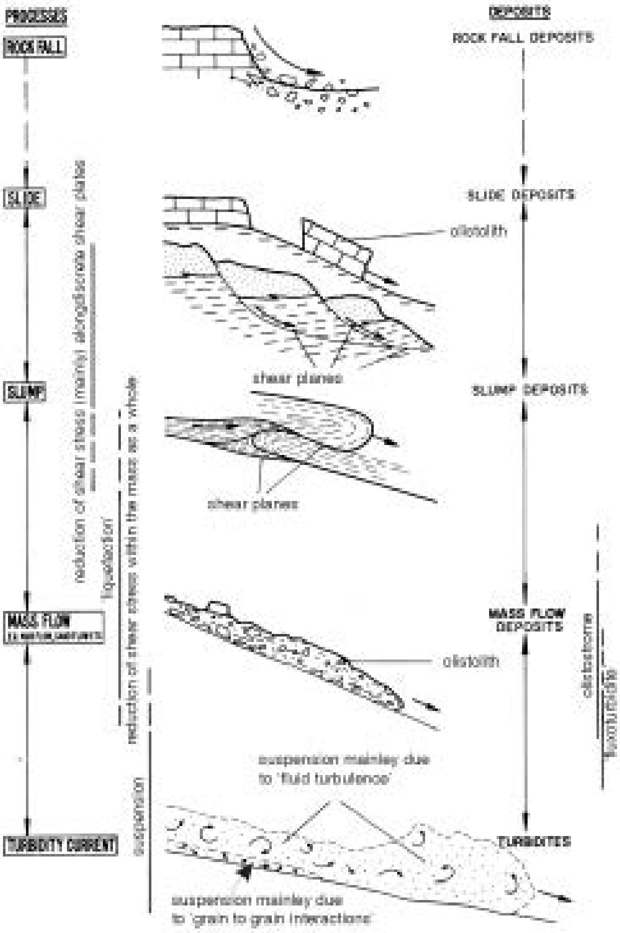


Fig. 25: Gravity induced transport of coarse clastics from shallow into deep water (KRUIT, BROUWER, KNOX, SCHOLLNBERGER & VAN VLIET 1975).

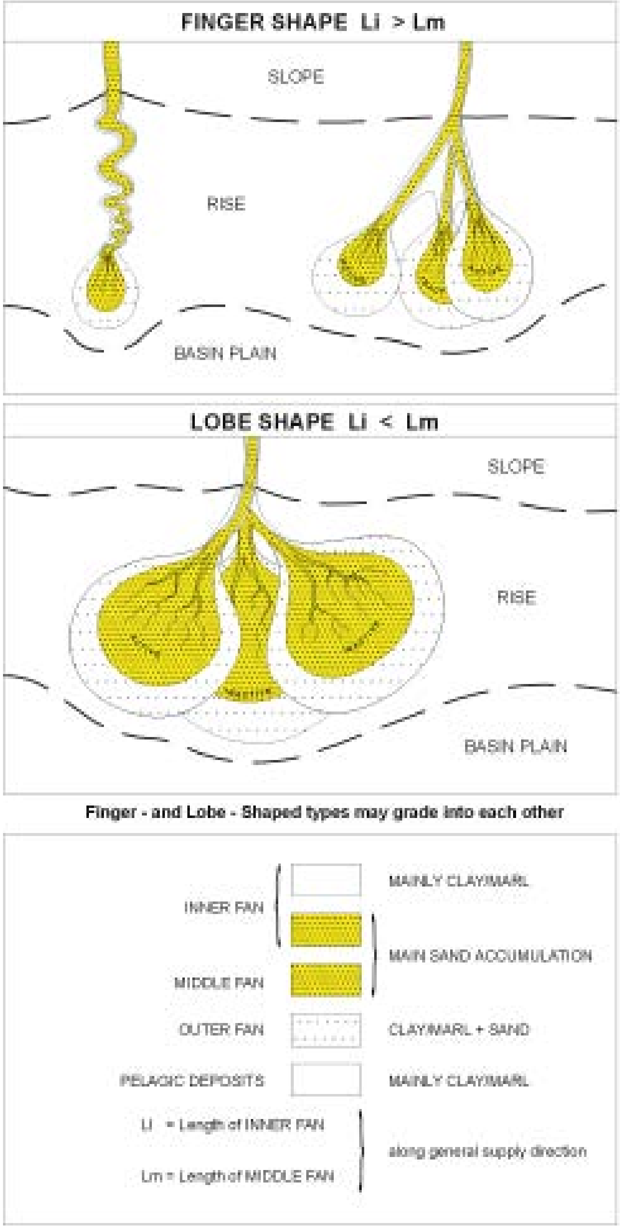


Fig. 26: Shapes of deep water fans: single finger fan, multiple finger fan, and lobe shape fan (modified from KRUIT, BROUWER, KNOX, SCHOLLNBERGER & VAN VLIET 1975). The shape of a deep water fan depends on the frequency and hydrodynamics of turbidity currents, the synsedimentary basin floor topography (e.g. salt swells), the shifting of depositional systems at the fan surface, and the patterns of other depositional systems in the basin (e.g. direction and strength of contour currents). Compare to Figures 49, 57, and 58.

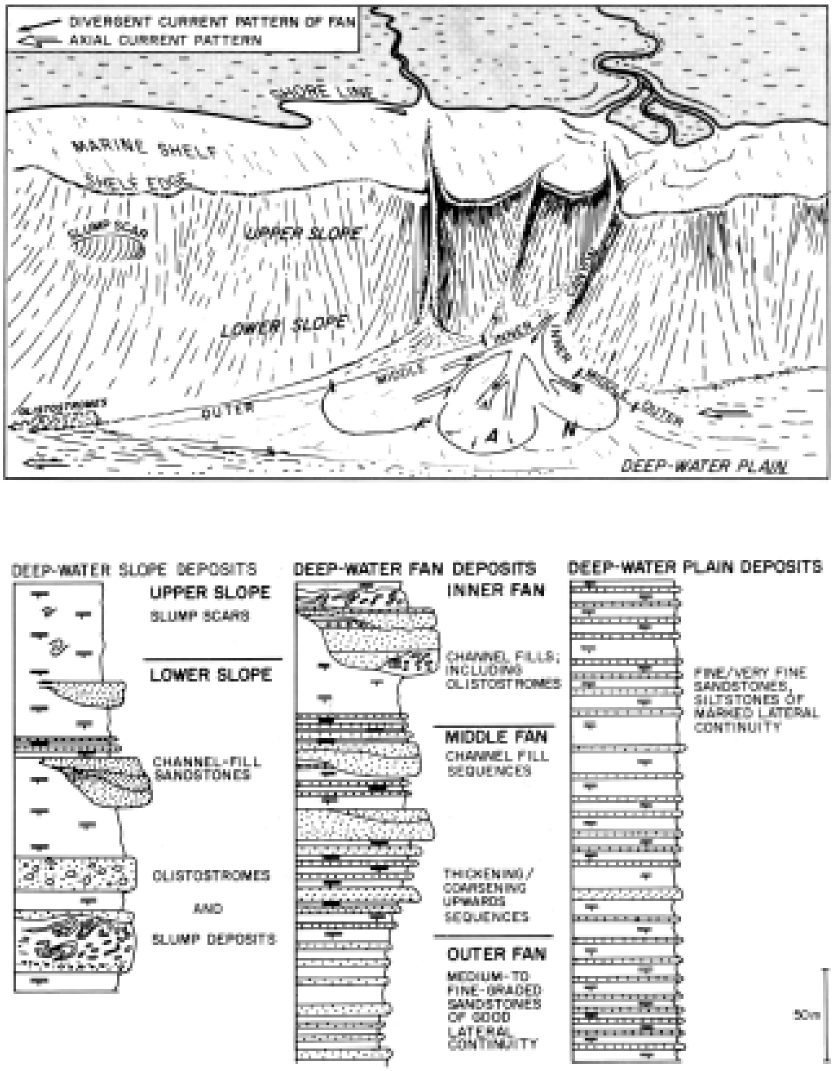


Fig. 27: Facies model of a deep water slope, fan, and basin plain system. The progradation of a deep water fan (during fall of relative sea level) results in a vertical succession with claystones and thin bedded turbidites of the basin plain and outer fan at the base, overlain by coarsening and thickening upwards turbidite lobes of the middle fan, which are in turn overlain by sandy to conglomeratic channel fill deposits of the inner fan (KRUIT, BROUWER, KNOX, SCHOLLNBERGER & VAN VLIET 1975 after WALKER & MUTTI 1973).

2.5. Basin Analysis

Exploration for hydrocarbons is expensive and risky. Successful exploration activities need to be focused on the most promising basins, and within these basins on the most promising areas (SCHOLLNBERGER 1996). This requires a good understanding of the geological development of an entire basin in space and time. Through basin analysis, the oil and gas industry discovers the hydrocarbon systems within a sedimentary basin. Hydrocarbon systems are characterised by such elements as the distribution of lithology, porosity, and permeability, the preservation of organic matter and its alteration during burial, and the generation, migration, and entrapment of hydrocarbons. Of special importance is the **timing** of hydrocarbon generation and migration relative to the timing of trap formation. Only when a stratigraphic or structural trap existed in a hydrocarbon system **before** hydrocarbon migration, are the conditions favourable for oil or gas accumulations to form.

Many scientists from industry and academia have built the elements of modern basin analysis, for which wells and seismic provides the bulk of data. HUNT (1961), LOPATIN (1971), TISSOT & ESPITALIE (1975), and TISSOT & WELTE (1978) have shown the way how to treat the thermal maturation of organic matter within sedimentary rocks in a quantitative way, and how to calculate the conversion of kerogene to oil and gas (Figs. 28 and 29).

The application of hydreous pyrolysis, in order to mature organic matter under laboratory conditions, led to a better understanding of the kinetics of the chemical reactions during the conversion (‘cooking’) of kerogene to oil and gas within a source rock (WELTE 1965). Pyrolysis also allows the extraction of oil from a source rock so that the chemical characteristics of the extract can be compared to the chemical characteristics of oil in known reservoirs (e.g. as defined by gas chromatography and infrared analysis). Thus, from the late 1960’s on there were good answers available to the old question how to link an oil found in a reservoir with its source rock.

Also in the late 1960´s, the industry learned how to accurately derive present day formation temperatures from downhole temperature measurements during logging runs (see ALLEN & ALLEN 1990). A further important step was the calibration of paleo-temperature with vitrinite reflectivity, sporomorph translucency, and conodont coloration as well as with mineralogy changes and fluid inclusions

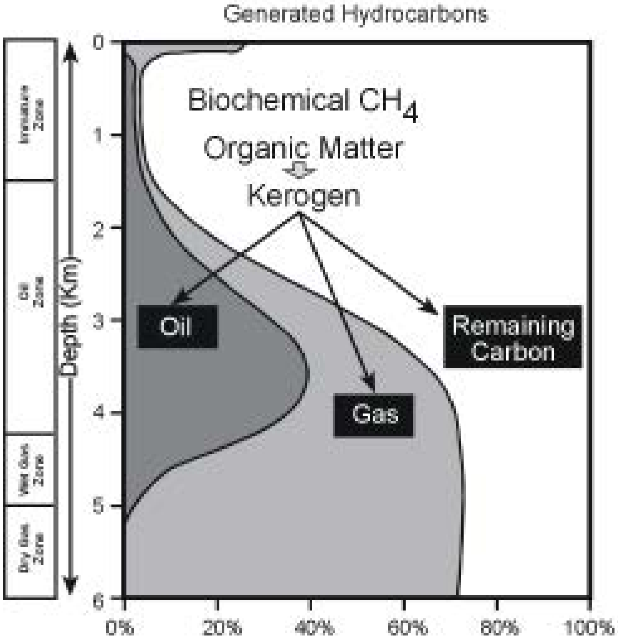


Fig. 28: Conversion of organic matter to hydrocarbons as a function of burial of source rocks. Actual depths may vary with type of kerogene, burial history, and variation in geothermal gradient (modified after Tissot & Welte 1978). See also Figs. 29 and 30.

during the 1960's and early 70's. Vitrinite - a coal maceral - is especially useful because it occurs frequently in sedimentary rocks (Teichmüller 1971). Changes in conodont coloration are now used in academic research in Austria, to unravel the complex tectonic history of the Northern Calcareous Alps (Gawlick, Krystyn & Lein 1994).

The contribution of Lopatin (1969) was of great importance in launching predictive modelling of the thermal maturity of organic matter and of its alteration to oil and gas during burial. After the very important relationship between the burial history of a source rock, its vitrinite reflectancy, and the maturity of its kerogene was recognised, basin analysis and predictive basin modelling became widely used in the petroleum industry throughout the 1970's and 80's (Tissot & Welte 1978, Waples 1980, Yalcin 1991). Important aspects of hydrocarbon expulsion from source rocks and subsequent migration were clarified by Mackenzie & Quigley (1988) and Lehner (1991). Aigner et al. (1991) built practical computer programs based on sequence stratigraphic principles and showed how to simulate the sedimentation history in a basin in two dimensions.

Today it is possible to relate the subsidence history of a basin, the depositional and diagenetic history of its sedimentary fill, and its tectonic deformation to paleo-temperature information and source rock characteristics. This allows the prediction of migration and entrapment of hydrocarbons (Fig. 30). **The best modern basin analysis methods use extensive modelling packages, which combine sophisticated sedimentological, tectonic, geochemical, and geophysical computer programs** (Tissot & Welte 1978, Allen & Allen 1990, Welte 1997).

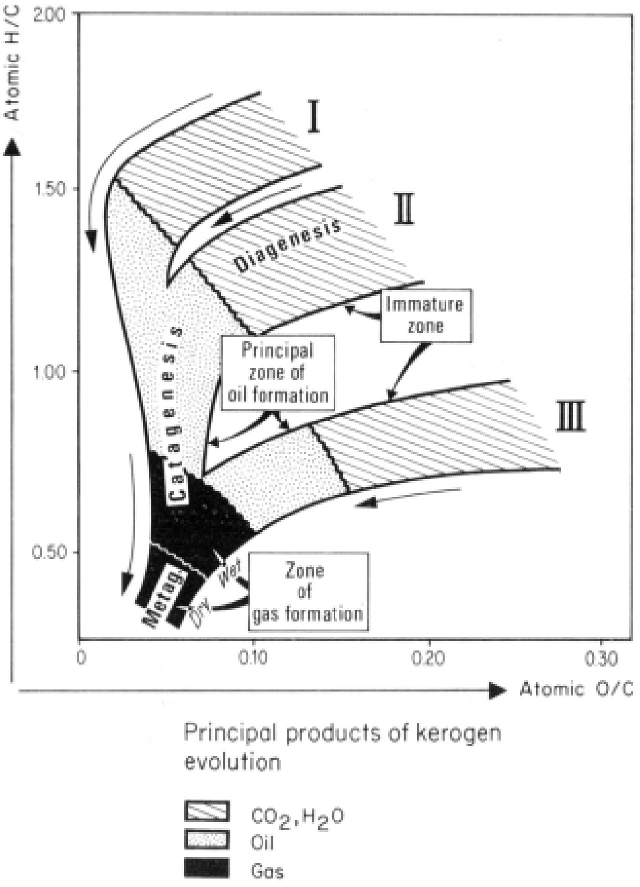


Fig. 29: Kerogene conversion with increasing temperatures. The successive conversion stages and their principal products are presented on a van Krevelen diagram (from Tissot & Welte 1978).

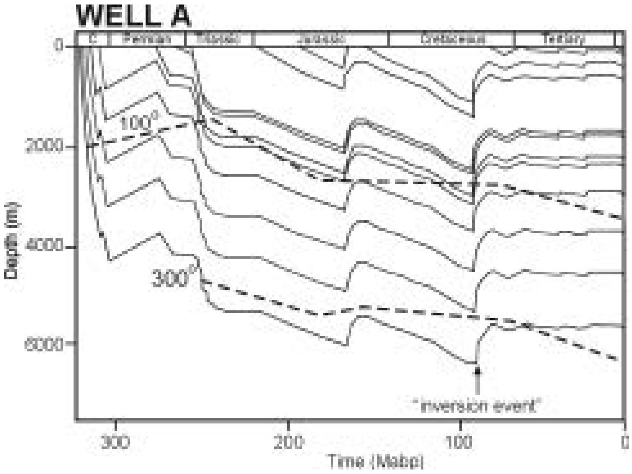


Fig. 30: Schematic sediment accumulation diagram ("burial graph") with temperature curves for formations penetrated in a fictitious well. The diagram illustrates the paleotemperature history for each formation top (modified from Welte et al. 1997).

Since the late 1990's, integrated basin modelling programs increasingly utilise 3-dimensional Darcy flow calculations to better predict hydrocarbon and water migration in basins (Fig. 31). These calculations take into consideration the 3-

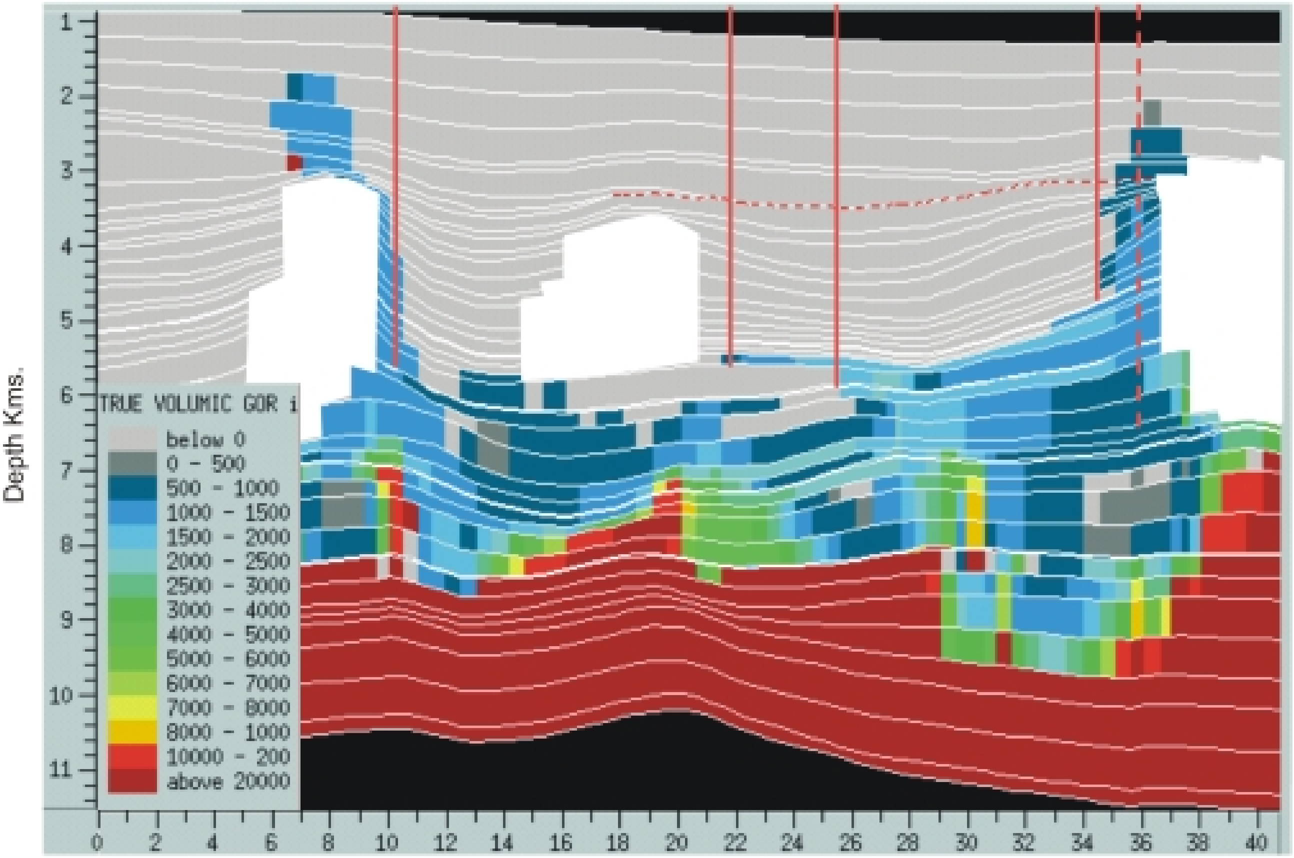


Fig. 31: Present day Gas/Oil Ratio (GOR in scf/barrel) predicted from hydrocarbon migration modelling, Gulf of Mexico. Migration path is determined by Darcy flow calculations, which take into account the permeability of the sediments involved (reproduced with permission from BP).

dimensional nature of changes in sediment porosity and permeability, temperature, and pressure over geologic time (WELTE personal communication).

3. Current Industrial Methods in Sedimentology

3.1. Continua and Discontinua

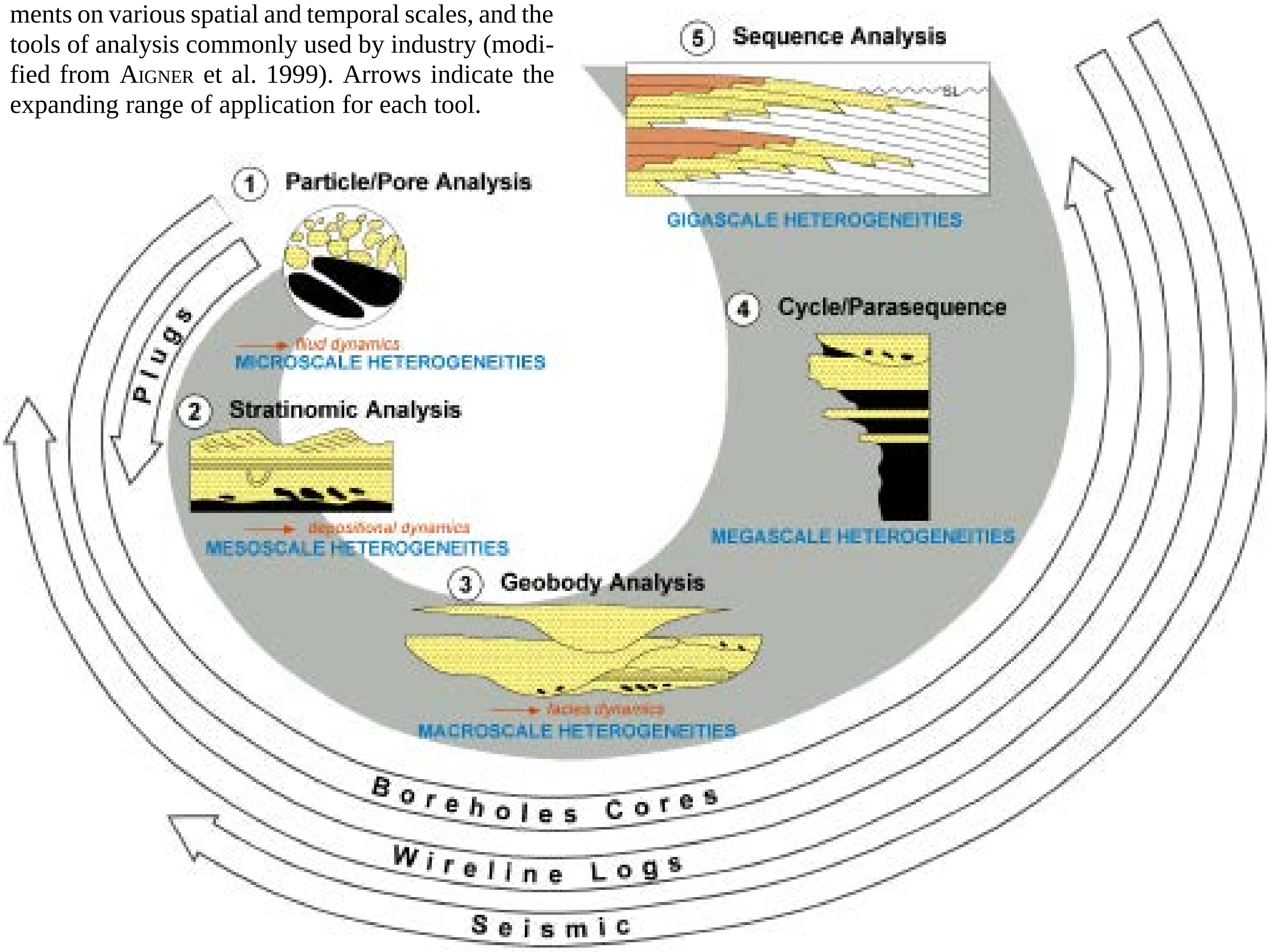
On any scale - from subatomic to astronomic - **the universe is a discontinuum**. In daily life and in science, we choose scales and at each scale certain discontinua then appear as continua and can be treated as such. We may choose to see the forest and ignore the individual trees and the ‘empty’ space between trees. We may choose to see the tree, and ignore that it consists of a trunk, branches and leaves, and ‘empty’ space between them, and so on. The question that we need to answer, and the resources, and the time that we have available will drive us to choose an appropriate scale. Critical assessment of the result of our approach will confirm the appropriateness of the selected scale, or will make us change the scale upward or downward for the next attempt.

On an outcrop or map scale, sedimentologists generally emphasise lateral continua more than lateral discontinua; For instance, a lithofacies is given a formation name, which in turn is identified with a certain age; in the next outcrop a reasonably similar lithofacies is, sometimes without detailed checking, given the same formation name and assumed to be of the same age as in the first outcrop. Conversely, geologists are used to read a formation name on a map or in a paper and to associate it, without critical reflection, with a certain lithofacies and age. In this way, geologists fail to recognise lateral lithofacies changes and construct a sedimentary ‘layer cake’, sometimes correctly, but more often incorrectly. The habit of overemphasising lateral continua at the expense of lateral discontinua in sedimentology goes back to Nicholaus Steno (1638-1687) and Abraham Gottlob Werner (1749-1812). James Hutton (1726-1797), however, clearly recognised the importance of lateral discontinua in sediments.

Modern methods in geoscience make increasingly use of discontinua, specifically of boundary surfaces, which limit an apparent continuum in three dimensions. A seismic reflector, for instance, occurs in a certain position (in two way travel time) within the seismic image of a succession of sedimentary rocks, because a change in acoustic impedance (rock density x rock acoustic velocity) exists at that very position within the succession of sedimentary rocks. A formation density log and a sonic log in a well that penetrates this seismic reflector, will indicate at what depth the acoustic impedance contrast occurs in the well.

Geoscientists can now choose from a box of handy tools to describe and understand the internal architecture of

Fig. 32: Lithologic heterogeneities in clastic sediments on various spatial and temporal scales, and the tools of analysis commonly used by industry (modified from Aigner et al. 1999). Arrows indicate the expanding range of application for each tool.



sedimentary bodies and sequences (Fig. 32; Aigner et al. 1999). These tools are increasingly based on the quantification of 3-dimensional discontinuity surfaces within sediments.

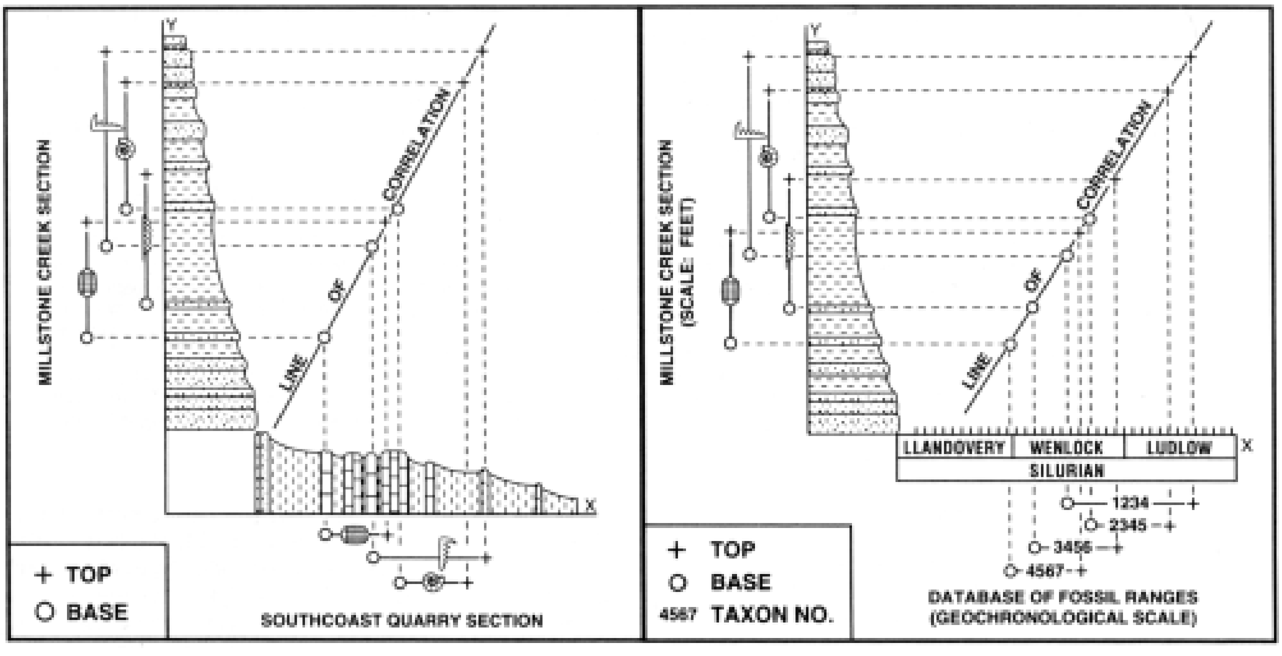


Fig. 33: Graphic correlation can be used to compare two stratigraphic sections (left), and to compare one stratigraphic section against a composite standard database (right) (Carney & Pierce 1995).

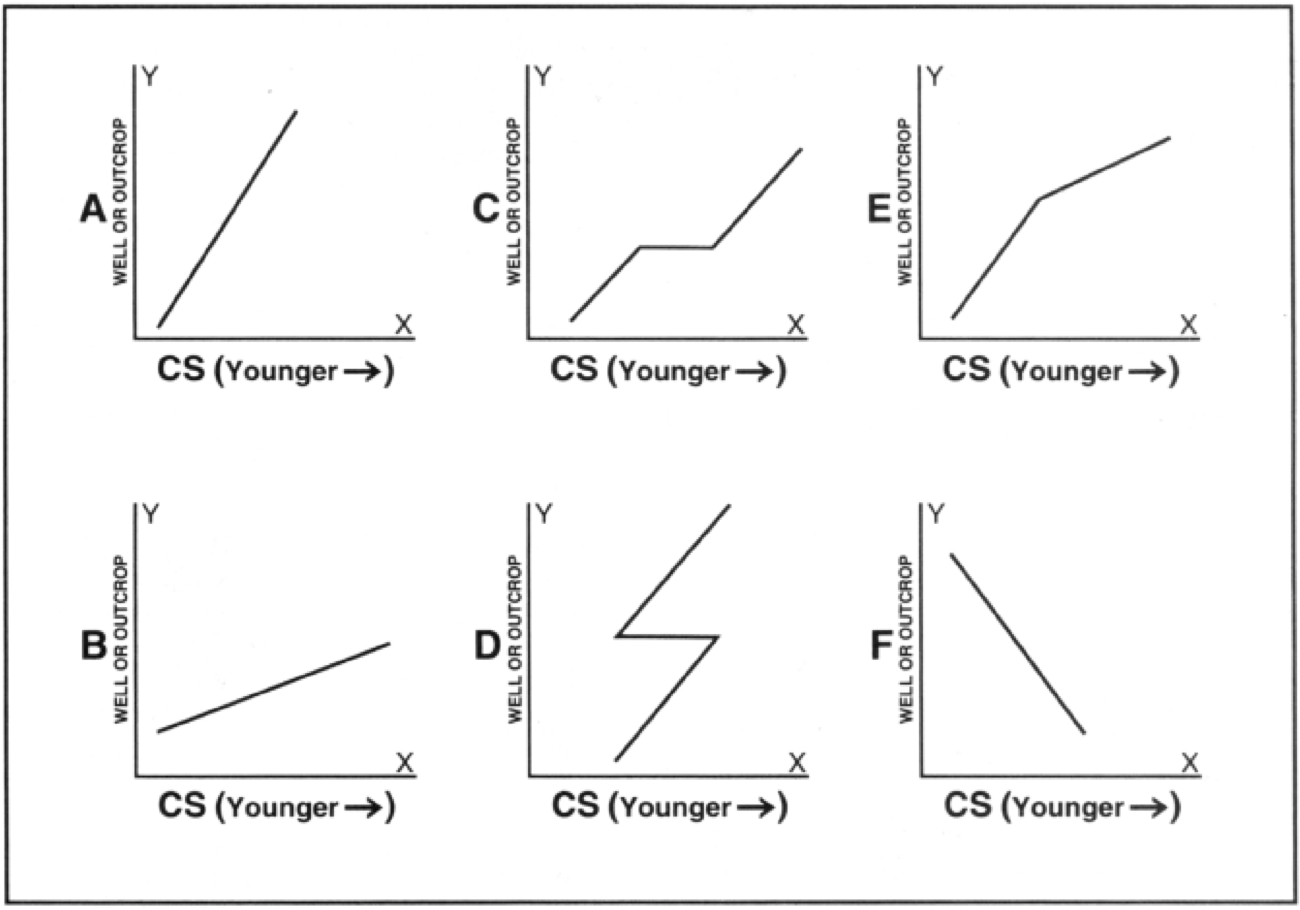


Fig. 34: Line of Correlation (LOC) patterns produced by Graphic Correlation: (A) LOC representing continuous rapid sedimentation, (B) continuous slow sedimentation, (C) two LOC segments separated by a horizontal terrace indicate a stratigraphic discontinuity (ie a fault, an unconformity, or an extremely condensed section), (D) two LOC segments separated by a horizontal terrace in a pattern typical for reverse faulting, (E) "dog leg" LOC typical of downthrown blocks in an expansion fault setting, (F) a LOC with reversed slope is seen when an overturned stratigraphic section is present (CARNEY & PIERCE 1995).

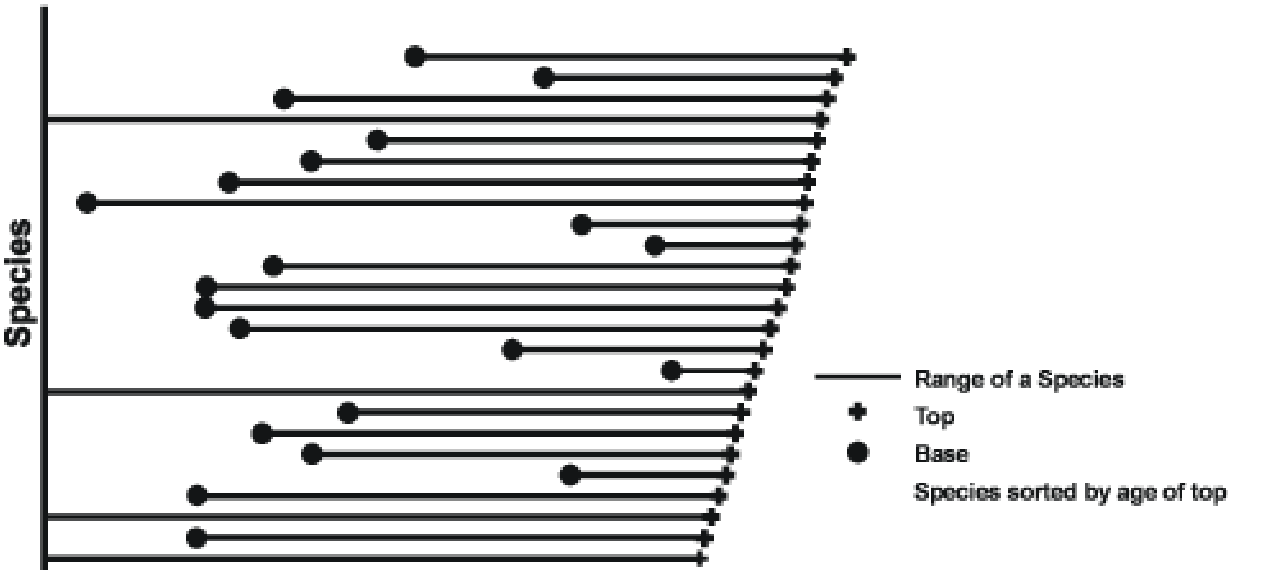


Fig. 35: Ranges of species in a Composite Standard, sorted by the age of extinction (= top of occurrence) of each species. BP has currently about 55,000 fossil ranges in its Composite Standard.

3.2. High Resolution Biostratigraphy

Graphic correlation was designed by Shaw (1964) as a method to obtain precise and consistent biostratigraphic age dating (see also Mann & Lane 1995). The process of graphic correlation involves crossplotting the observed ranges of fossils in a single stratigraphic section (in an outcrop or in a wellbore), against a data base of composited ranges scaled in chronostratigraphic units, e.g. years. This data base is referred to as a composite standard. A composite standard is initiated by crossplotting two stratigraphic sections/wells of similar age, one on the y-axis and the other one on the x-axis, and projecting the observed fossil ranges of both sections to a line of correlation (LOC; Fig. 33). A third section/well (on the y-axis) is then crossplotted against a composite standard (on the x-axis) consisting of the first two sections, a fourth section is crossplotted against a composite of the first three wells, etc. Various LOC configurations and what they mean are shown in Fig. 34. Strata and geologic events, which can be absolutely dated (e.g. sediment layers with Ar/Ar dates, volcanic layers, magnetic reversals, etc.) are included in the standard. In between absolutely dated layers, absolute ages may be interpolated by applying cyclostratigraphy (Schwarzacher 1993).

As more and more sections and fossil groups are added, the composite standard becomes more robust, and accurate (Fig. 35). Ultimately, a world-wide composite standard for the entire Phanerozoic emerges by using fossil ranges from many different and widely spaced sedimentary basins, or a provincial standard can be constructed for individual basins, where some fossil ranges may be endemic, or restricted because of local environmental conditions. In any case, a composite standard is always a dynamic data base in which fossil ranges can be extended and new ranges can be added, should data from new sections require this.

BP acquired a composite standard containing 55,000 fossil ranges through the mergers with Amoco and Arco. Amoco had built a composite standard of 45,000 fossil ranges over a span of 30 years. The BP composite standard has now been made available to the industrial members of the Earth and Geoscience Institute (EGI) at the University of Utah and to academia. Contact the e-mail address rlevey@egi.utah.edu for information how academia can access the composite standard at EGI.

Graphic correlation has greatly enhanced the accuracy and practicality of biostratigraphic age dating. With the enhanced accuracy, the **episodic nature of sedimentary processes** becomes now very apparent: sedimentation actually happens in events of relatively short duration, and much more time is not represented in the sedimentary record than there is. This is very powerfully demonstrated in Fig. 36. Plotted along the y-axis is a sediment succession as it was penetrated in a real well (scale in meters). On the x-axis the same sediment succession is plotted in time (scaled in Composite Standard Units, a proxy for time). The various inclinations of the line of correlation give an indication of net sediment accumulation rates - as steeper as higher - with the flat portions indicating time of non-deposition/erosion. Note how much time is **not** represented by sediment! This example also illustrates the reason why sedimentation rates, which are calculated for short time intervals, are generally higher than sedimentation rates calculated over longer time

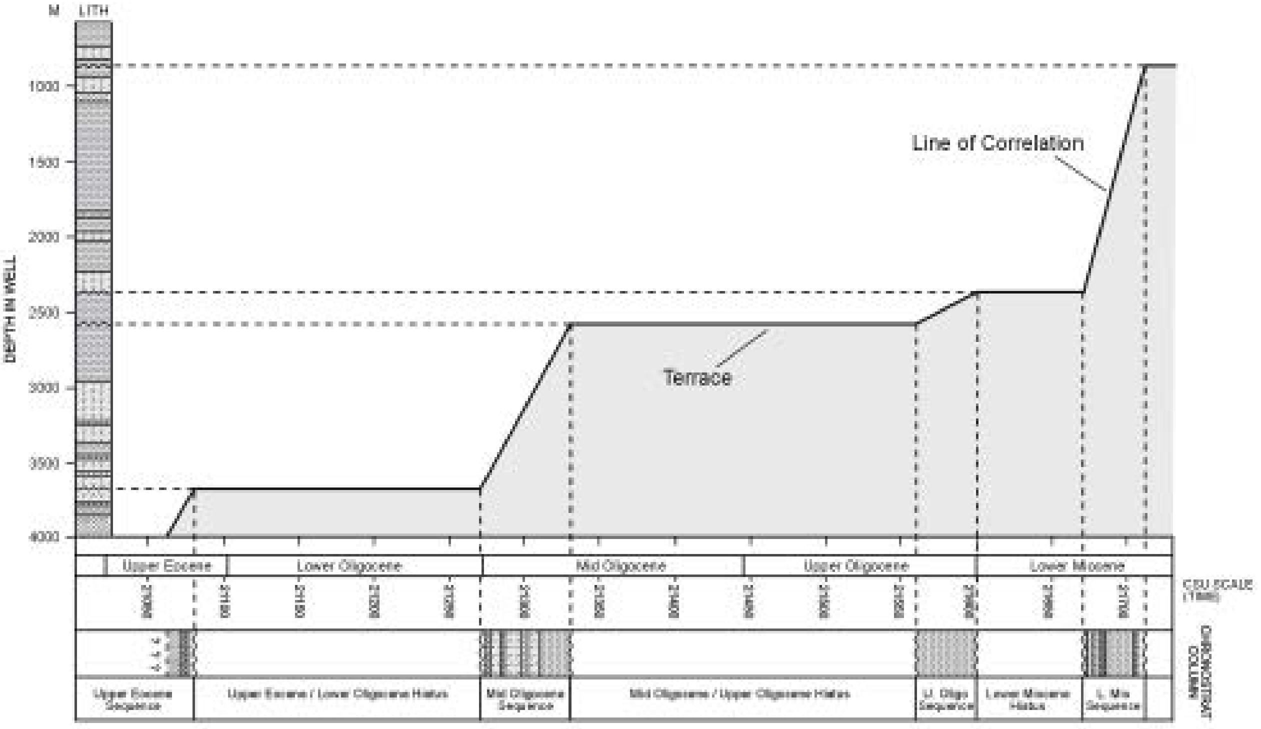


Fig. 36: Plotting the lithology of an actual well against Composite Standard Time Units (CSU, a proxy for absolute time) demonstrates how episodic sedimentation really is: much more time is not represented in the lithologic record than there is (reproduced with permission of BP).

intervals: the rates for longer time intervals include more non-depositional/erosional events (see also REINECK 1960, SCHLAGER 1999a). This also makes it abundantly clear that all stratigraphic tables showing lithologic successions as temporal continua are wrong (compare Fig. 37 to Fig. 38). Moreover, because paleogeographic reconstructions are supposed to show lateral facies relations at a given moment in time, inaccurate age dating leads to erroneous paleogeographic reconstructions.

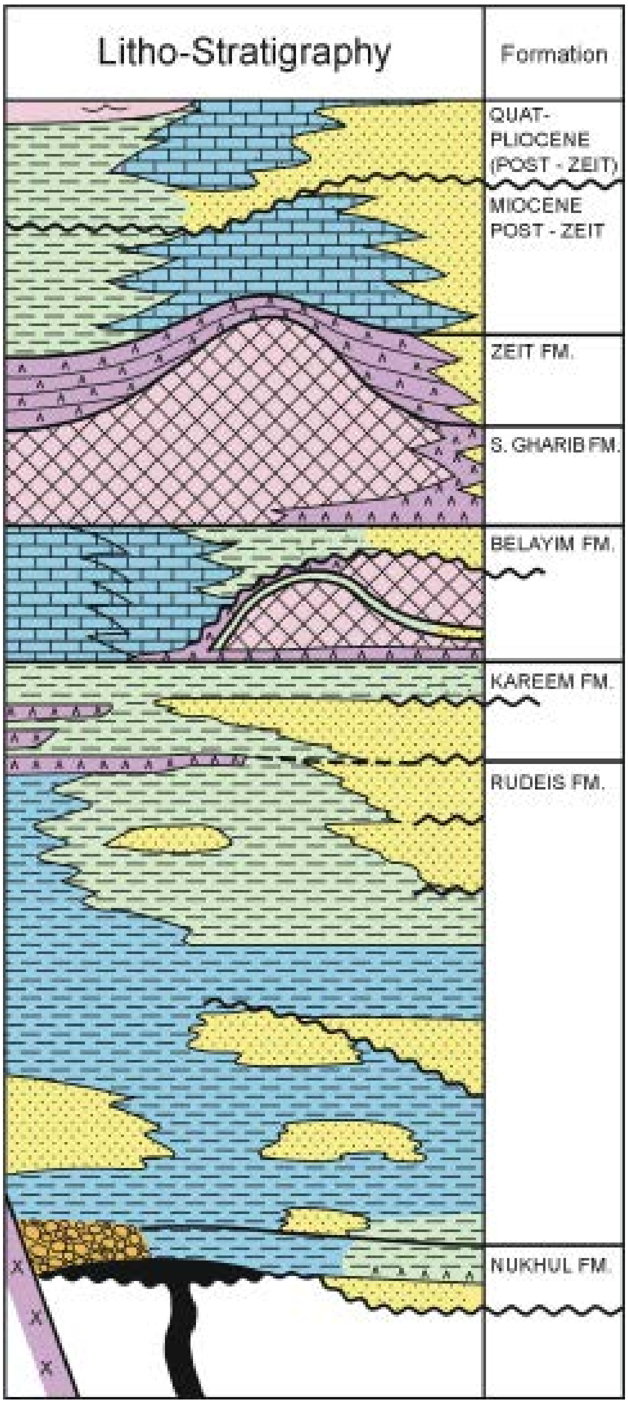


Fig. 37: “Old fashioned” lithostratigraphic chart of the Neogene from the Gulf of Suez, Egypt (SCHOLLNBERGER 1984 unpubl.). Such a display does reflect the relative but not the absolute ages of lithofacies; compare to Figure 38.

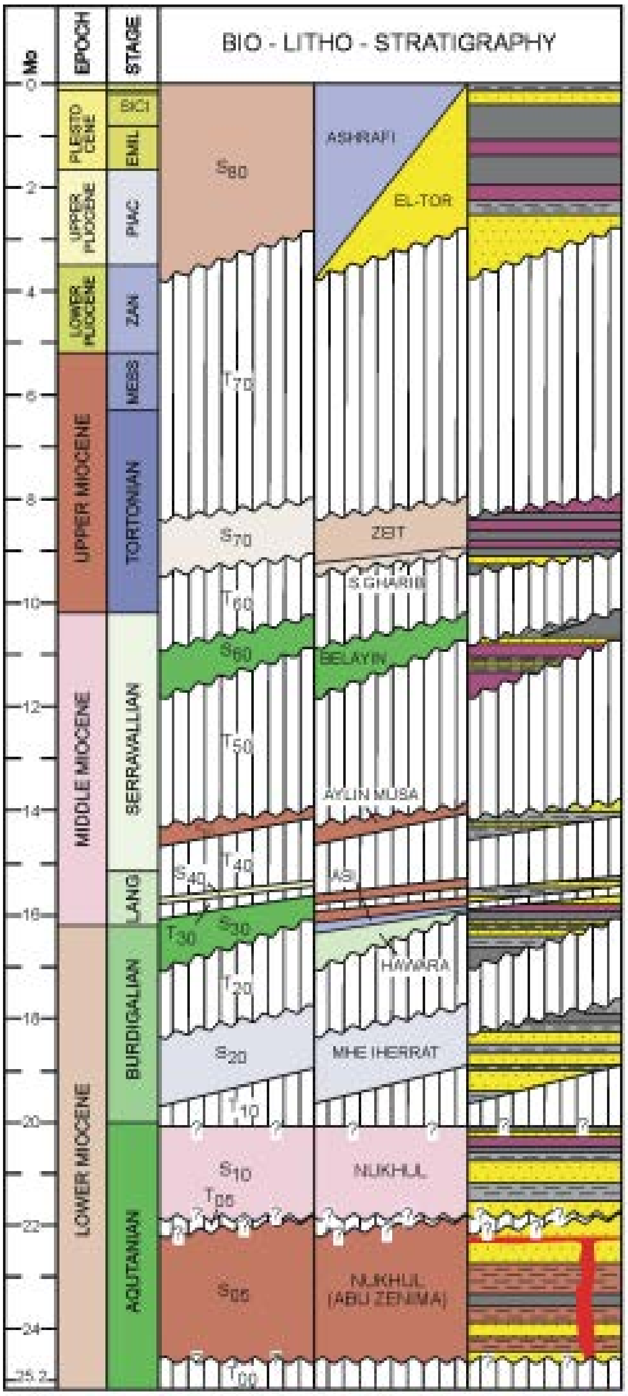


Fig. 38: Chronostratigraphic chart of the Neogene from the Gulf of Suez. The solid coloured areas represent periods of sediment accumulation in absolute time (S = biostratigraphic sequences); the areas marked by vertical lines represent lacunae or gaps in the sediment record (T = graphic correlation terrace) (modified from WESCOTT et al. 1998).

3.3. High Resolution Seismic

Reflection seismic and well logs (density and sonic) are two independent sources of information about the rho (density) and v (acoustic velocity) of sediments in the subsurface. Methods have been developed, which use properties of the

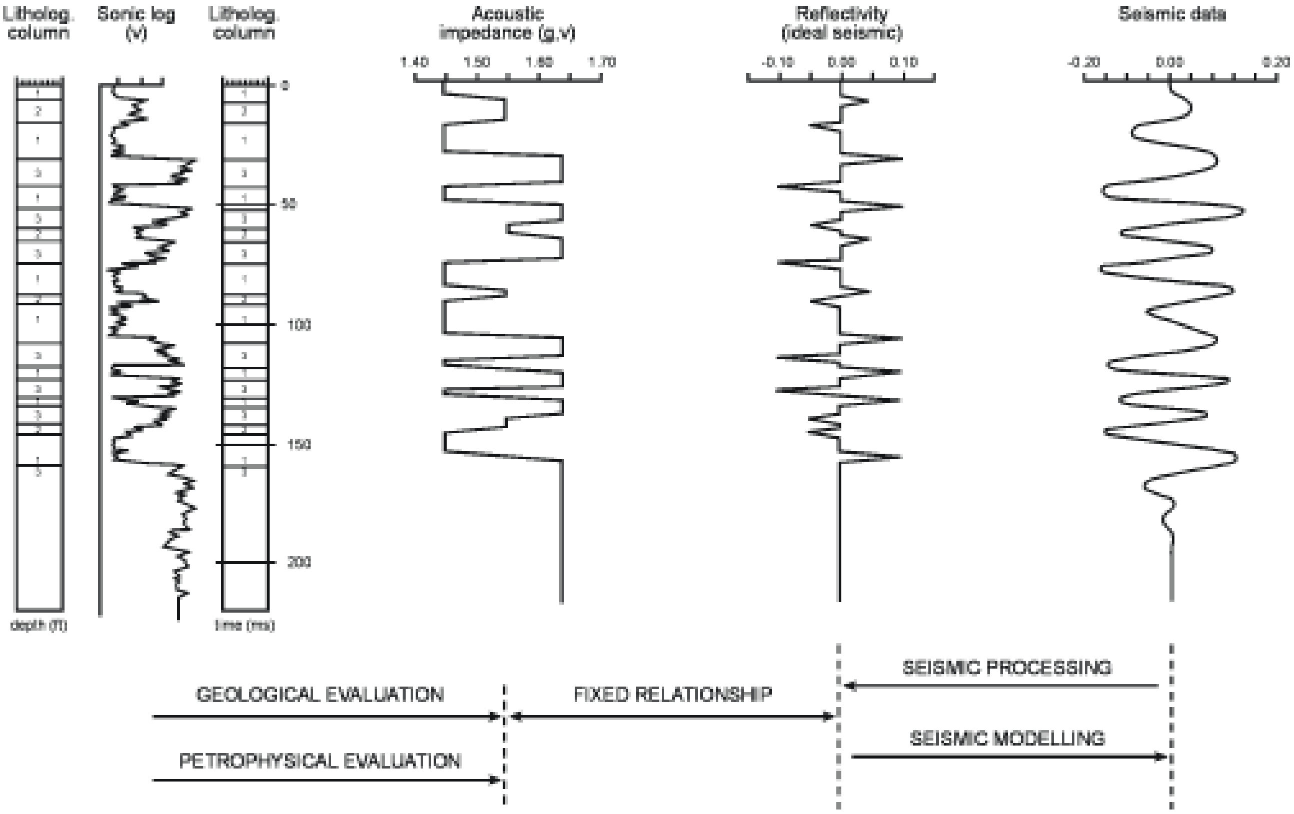


Fig. 39: The relationship between the lithologic column penetrated in a well (left) and seismic (right). Note: an acoustic impedance log is constructed by multiplying the sonic log response (shown) with the formation density log response (not shown) at the same depth; reflectivity is proportional to the acoustic impedance contrast across a lithologic boundary and can be positive or negative.

reflected seismic wavelet (frequency, amplitude, and phase) to determine the lithology shaping that wavelet (inverse modelling). Conversely, methods also have been developed to model the seismic response of an actual succession of lithologies (in a well or an outcrop). This is called forward modelling (Fig. 39). Modern computing techniques allow us to quickly go repeatedly through the loop from seismic to rock and back to seismic (or from rock to seismic and back to rock) and obtain a clear picture of the lithofacies and pore fluid (oil, gas, or water) distribution in the subsurface. This way, oil and gas fields can actually be discovered **before** the first well has been drilled.

A big breakthrough in seismic, with positive consequences for sedimentology came in the early 1970's, when computing power had sufficiently increased to allow 3-dimensional processing of large data volumes (instead of 2-dimensional seismic lines), Fig. 40. Since then, numerous algorithms and methods were developed by industry and academia for the accurate and detailed 3-dimensional illumination of sedimentary bodies in the deep subsurface (Brown 1991).

For illustration, we demonstrate here two very successful methods patented originally by Amoco and now used by BP: 3-dimensional seismic coherency, and 3-dimensional spectral decomposition. Coherence is commercially available through CTC (Coherency Technology Corporation), a Corelab company licensed by BP.

Three-dimensional **seismic coherence** is obtained by correlating waveform similarity of adjacent traces within a time slice in both directions, in-line and cross-line. Waveforms on one side of a lateral lithological boundary will have a different character than the waveforms on the other side. This results in a **discontinuity** in trace to trace coherence at the **lithological boundary**. Calculating coherence for each grit point along a reflection time slice results in linaments of low coherence along lateral

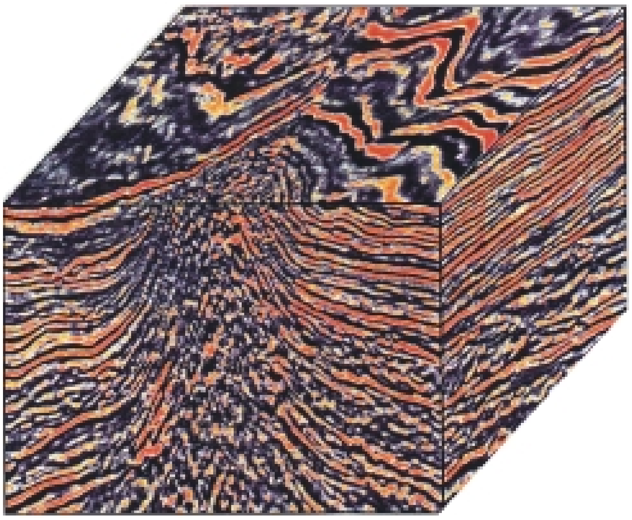


Fig. 40: Cube display of a 3-dimensional seismic data volume (reproduced with permission from Halliburton).

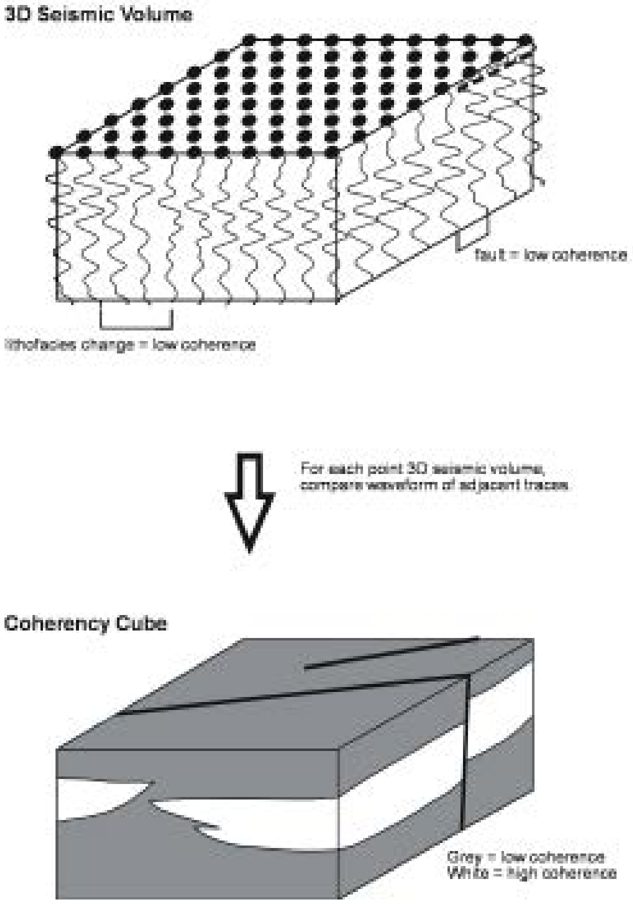


Fig. 41: Three-dimensional seismic coherency illuminates lateral lithological discontinuities such as lithofacies changes and faults; also see Figs. 43 and 44.

lithological boundaries (Fig. 41) (BAHORICH & FARMER 1995). Map views of coherence data are particularly useful to illuminate the lateral boundaries and inner architecture of sediment bodies such as river channels, point bars, crevasse splay fans, coastal barriers, reefs, slumps, deep water channels and fans (for examples see Figs. 42 through 45).

The **spectral decomposition** method uses a discrete Fourier transform to convert seismic data from the time domain to the frequency domain. For certain frequencies, amplitude and phase are then investigated as to their resolution of stratigraphic or structural complexities (Fig. 46). **Amplitude spectra better delineate bed thickness variability, whole phase spectra more clearly indicate lateral geologic discontinuities** such as pinch-outs or faults. The frequency (with the corresponding amplitude and phase) which best delineates a certain sedimentary setting (e.g. a meandering deep marine channel) is then chosen for processing (Fig. 47). Sometimes mixing of certain frequencies enhances the picture. The resulting images are very spectacular and have contributed greatly to the improvement of drilling success (Fig. 48).

Top companies now find economic quantities of oil and gas in more than 60 % of their exploration wells (industry average used to be 10 % before 1985) and in more than 90 % of their production wells. Seismic interpretators look more and more at map pictures (time slices or depth slices) rather than at vertical profiles (in time or depth), which were for many years the standard for displaying seismic data.

Other current developments also bode well for ever finer resolution of sedimentary features through reflection seismic: e.g. the refining of seismic sources and receivers to preserve the full frequency and amplitude spectrum in

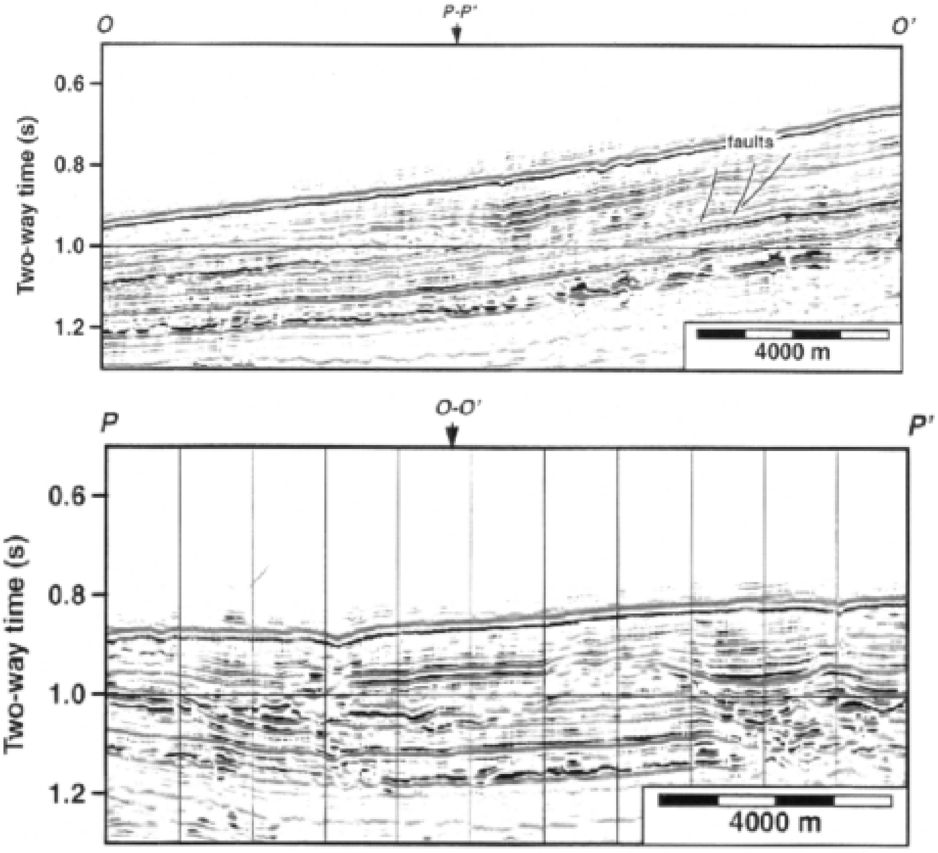


Fig. 42: Two crossing seismic sections through a slump (for location see Fig. 43), offshore West Africa. The chaotic reflection character at 1 second (two way time) in the centre of the sections indicates the presence of a body of slumped sediments (reproduced with permission of BP).

Fig. 43: A coherency slice (map view) at 144 milliseconds below the seafloor illuminates the slump in much greater detail than the vertical sections in Figure 42 (reproduced with permission of BP).

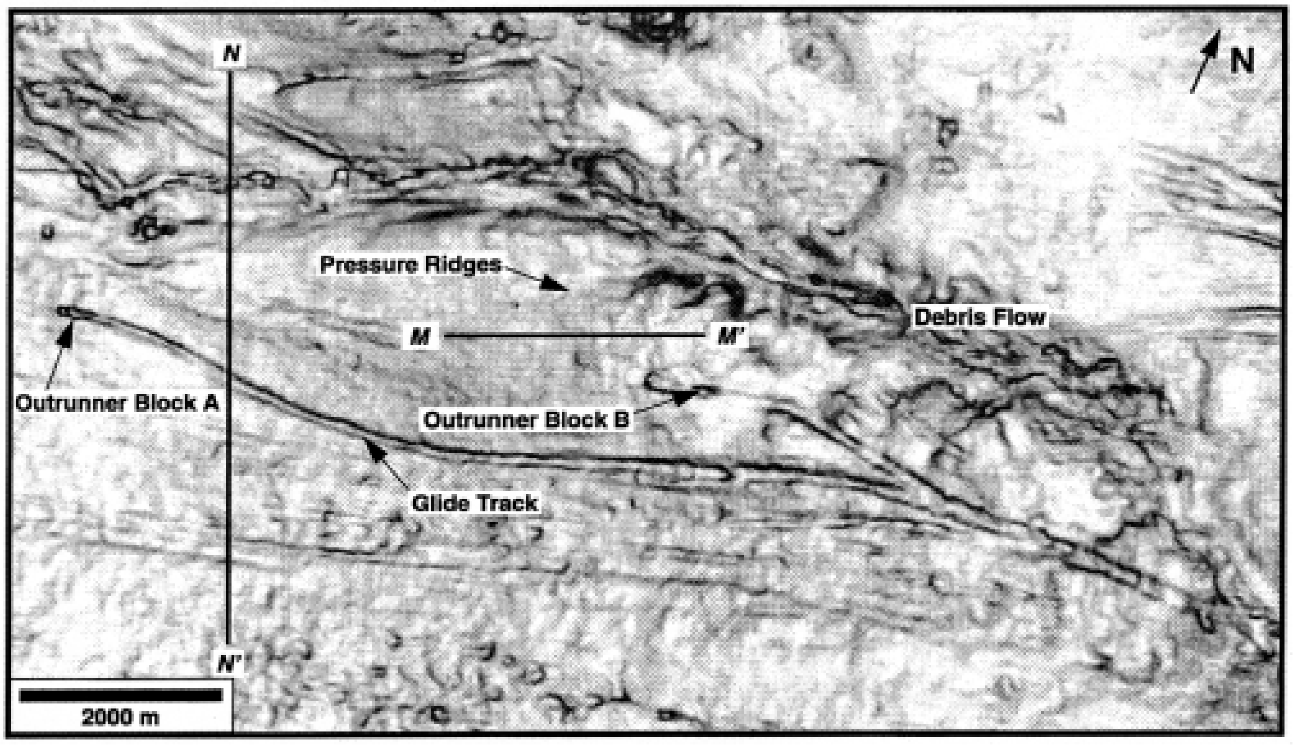


Fig. 44: A coherency slice (map view) at 144 milliseconds below the seafloor from 3-dimensional seismic data, offshore West Africa. Note a branching 12 km long glide track and associated blocks A and B, which “outrun” the slump mass from right to left (reproduced with permission of BP).

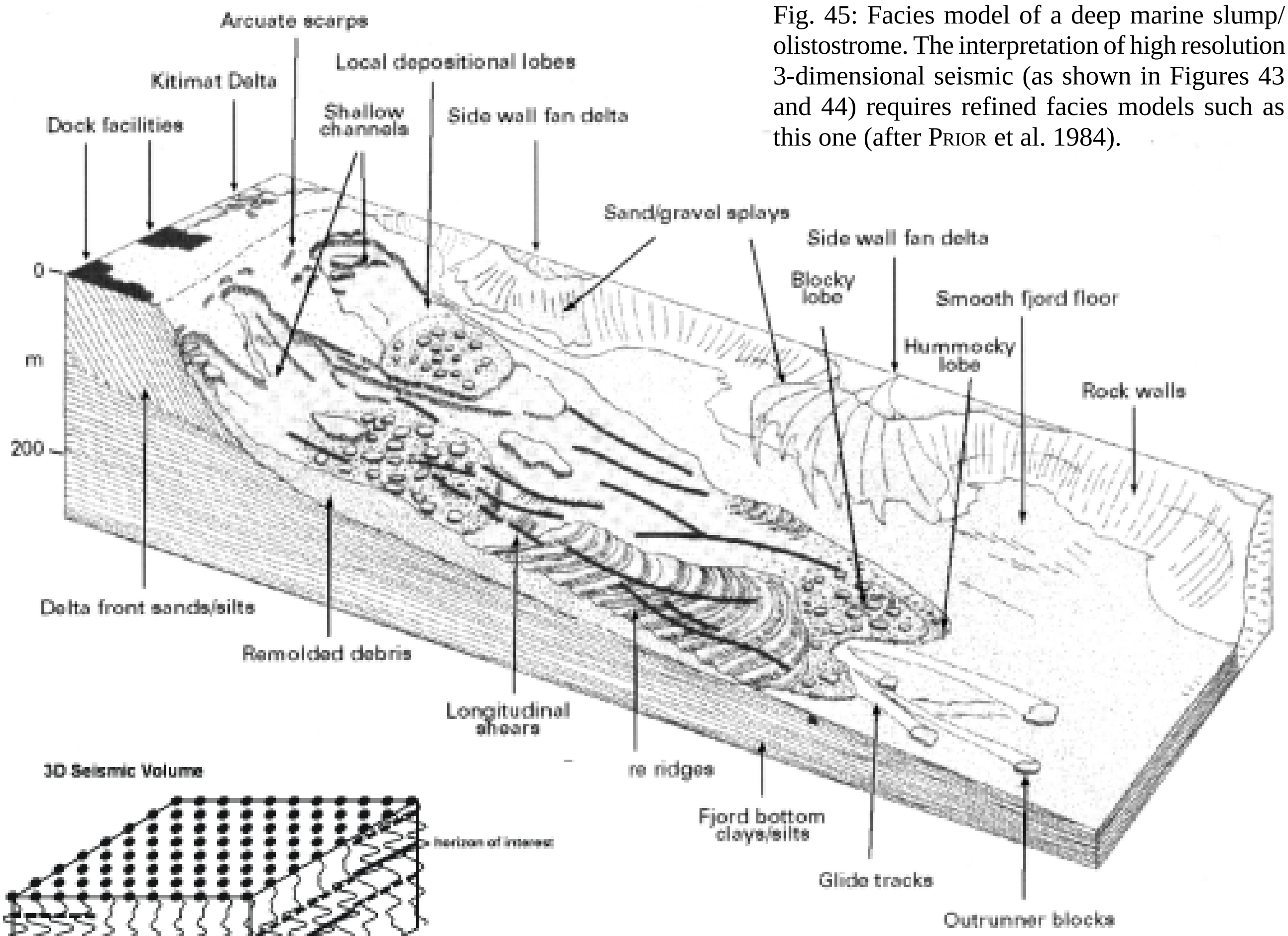


Fig. 45: Facies model of a deep marine slump/olistostrome. The interpretation of high resolution 3-dimensional seismic (as shown in Figures 43 and 44) requires refined facies models such as this one (after Prior et al. 1984).

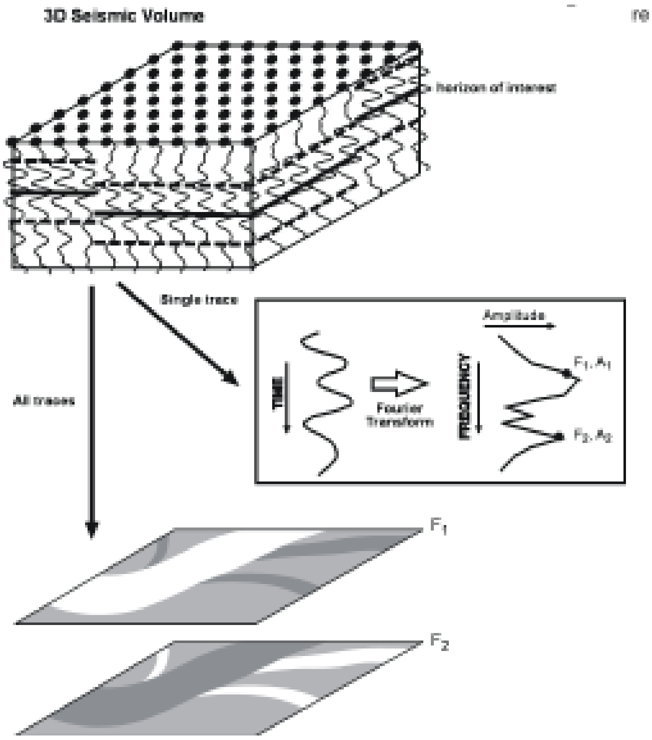
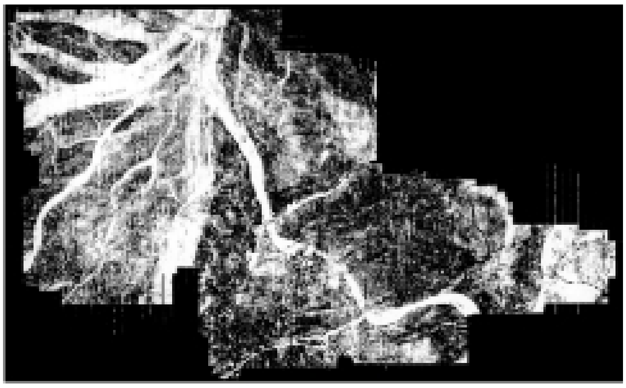
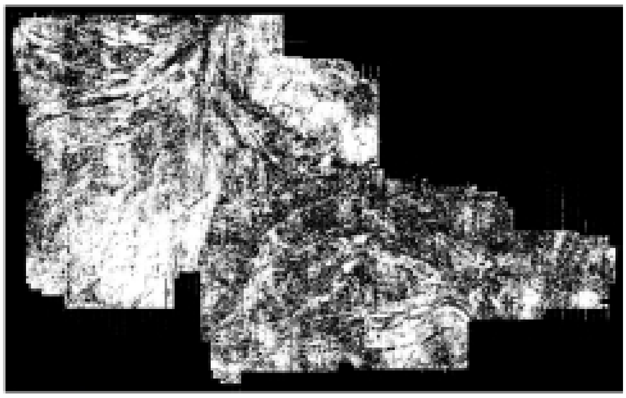


Fig. 46: Spectral decomposition illuminates the thickness of sedimentary bodies and their lateral boundaries (reproduced with permission of BP).



A : 16hz amplitude component



B : 46hz amplitude component

Fig. 47: Spectral decomposition displays (map views). In this Gulf of Mexico example the 16hz frequency (with corresponding amplitude and phase) delineates the channels of a Pliocene deep water fan much better than the 46hz frequency. The fan is buried under several thousand feet of sediments. Compare also with lobe shape fan in Figure 26.

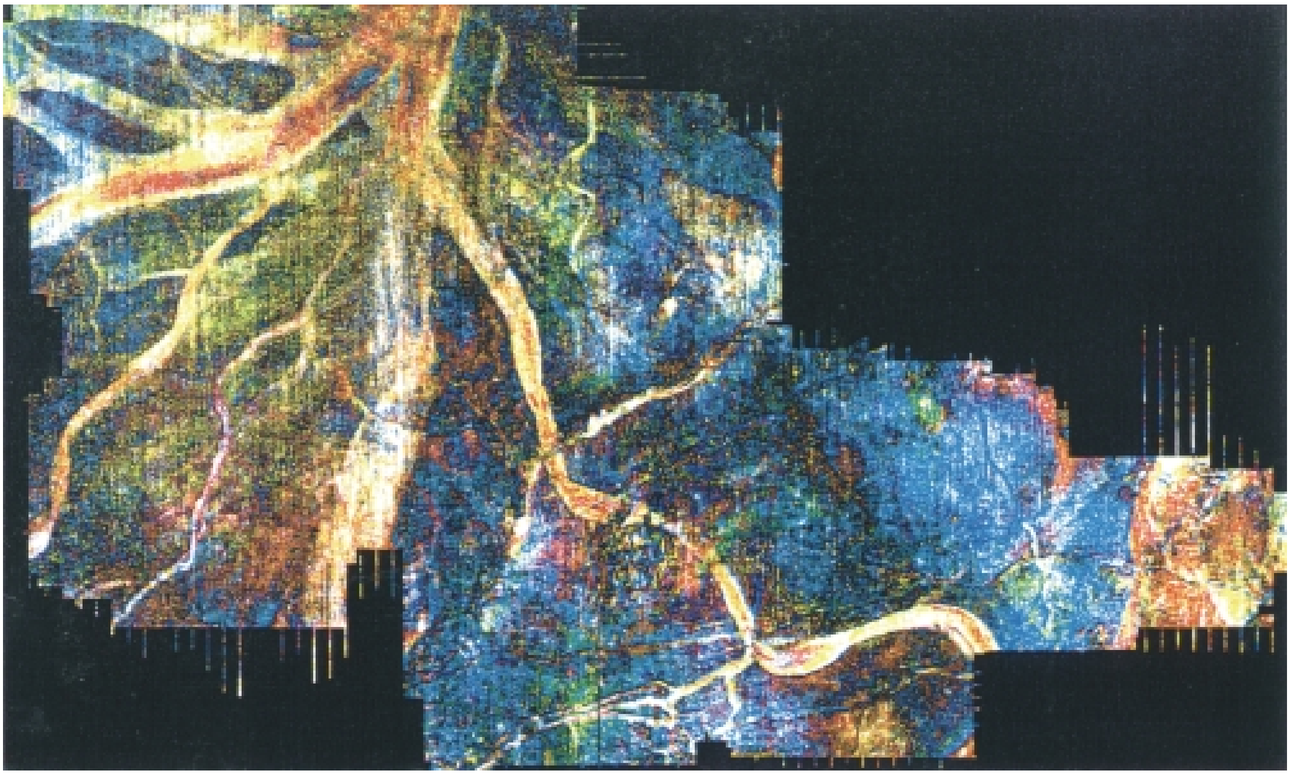


Fig. 48: Same deep water fan as Fig. 47; spectral decomposition 18 hz, 24 hz and 32 hz displayed as red, green, and blue, respectively. Thicker sections of the channel sands appear as pinks and magenta (reproduced with permission of BP).

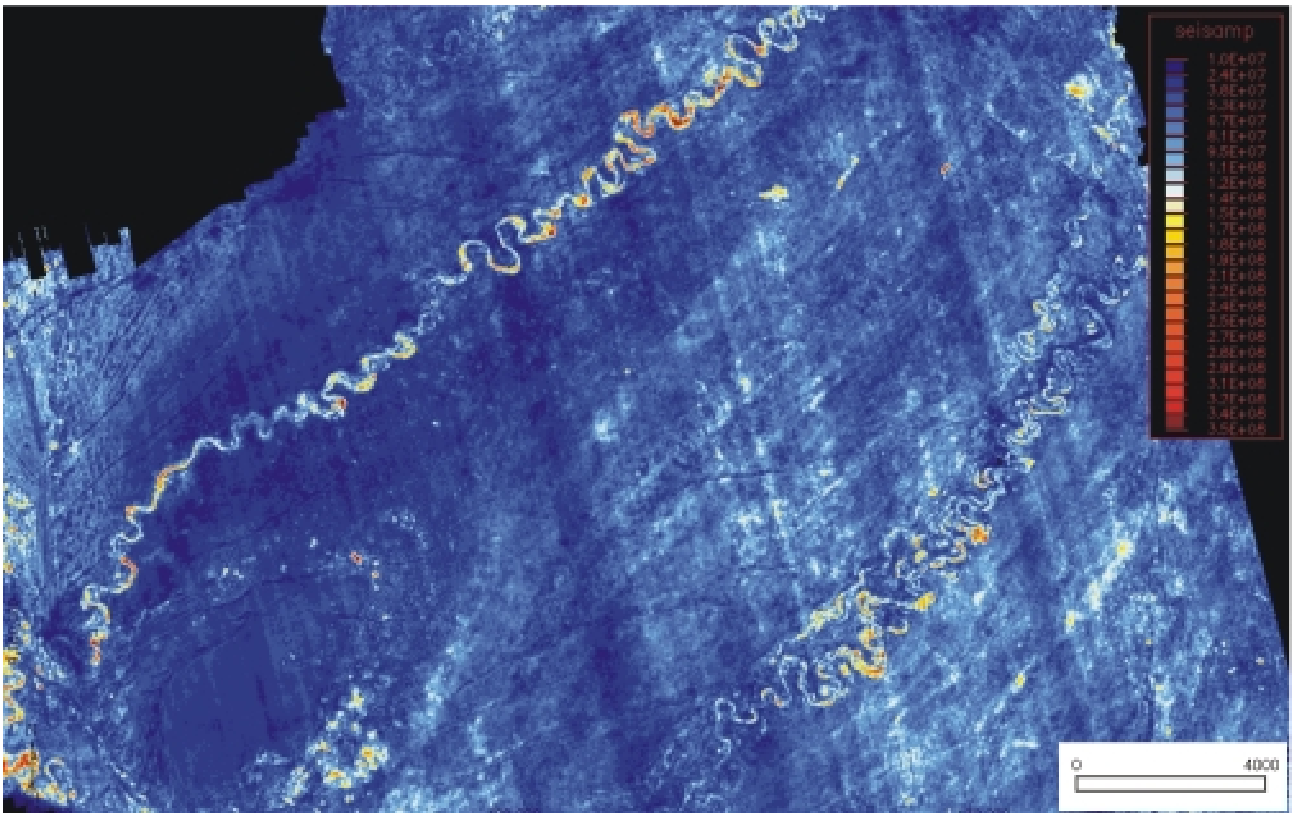


Fig. 49: Amplitudes displayed on a time slice (map view) from a 3-dimensional seismic data set. Visualisation of two deep marine turbidite channels, which are located several thousand feet below the seafloor, offshore West Africa. (reproduced with permission of BP). Compare with deepwater single finger fan in Fig. 26 and with meandering river in Fig. 18.

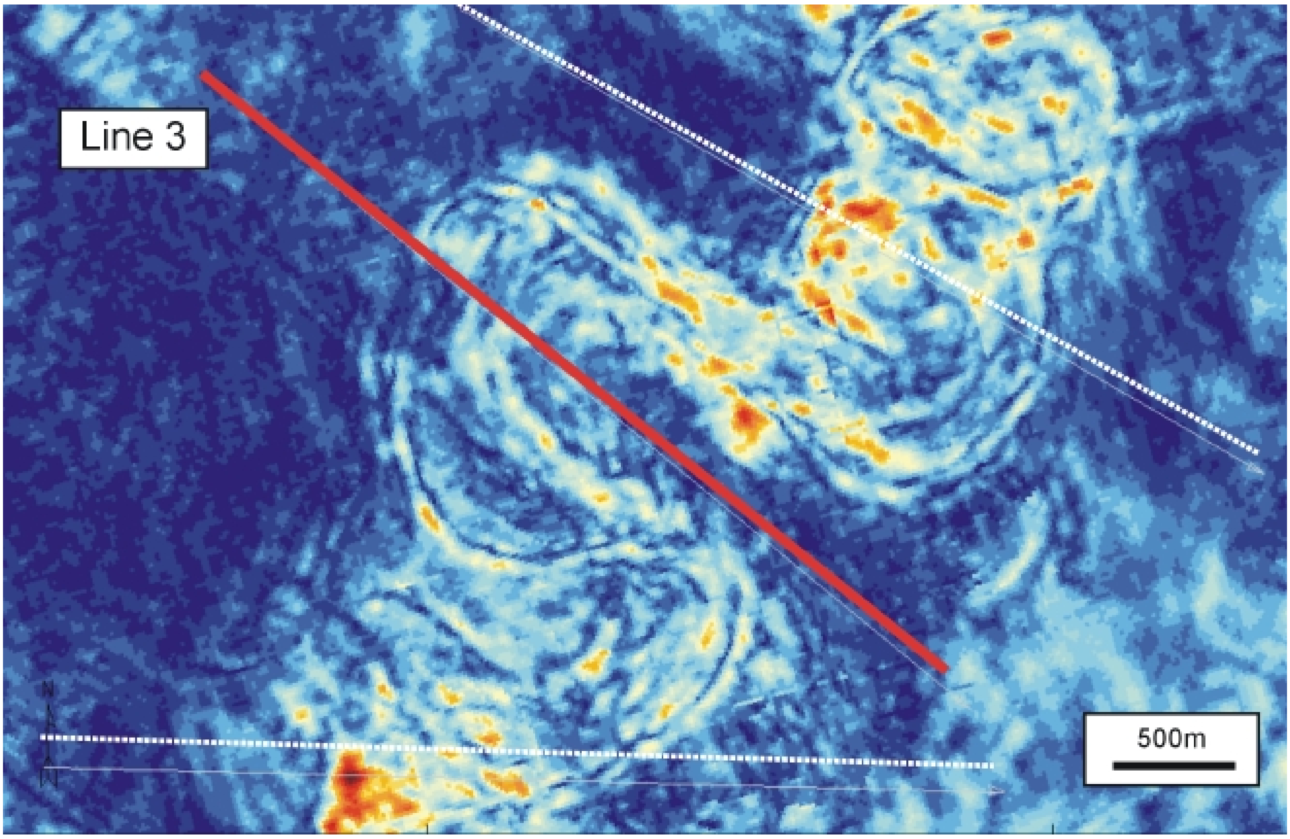


Fig. 50: A meandering deep marine turbidite channel with point bars (reproduced with permission of BP). See Figure 51.

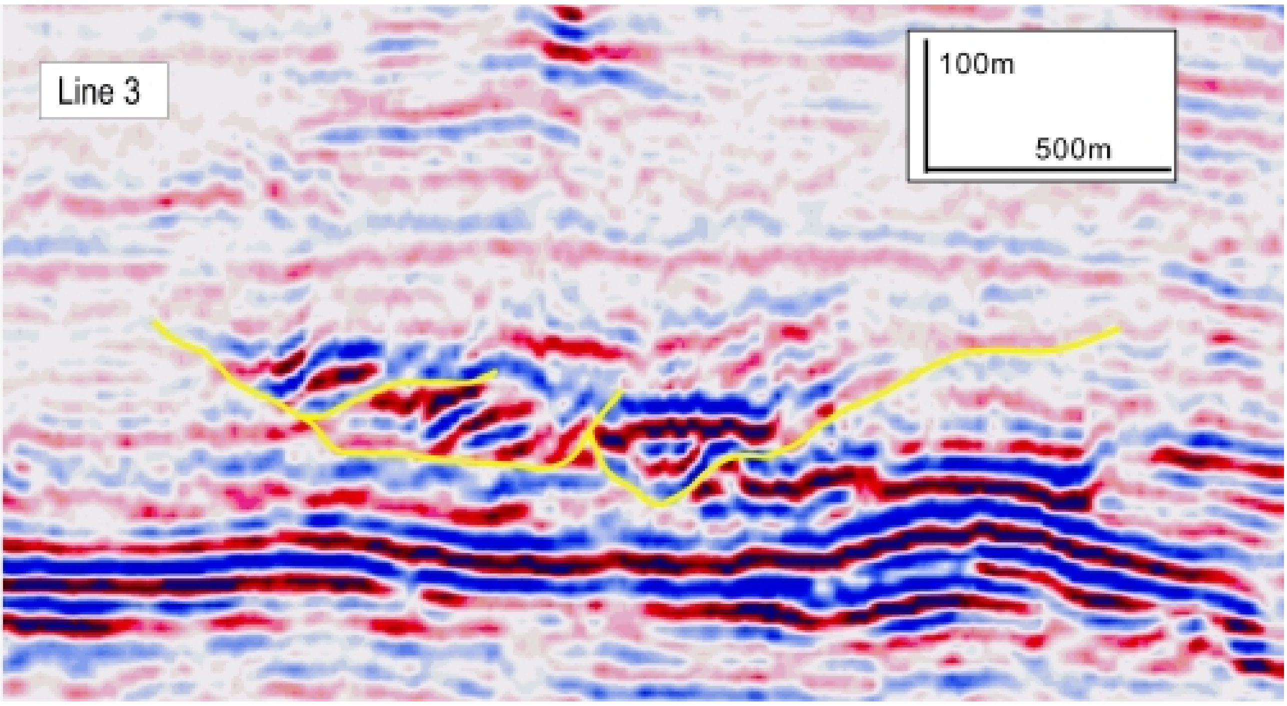
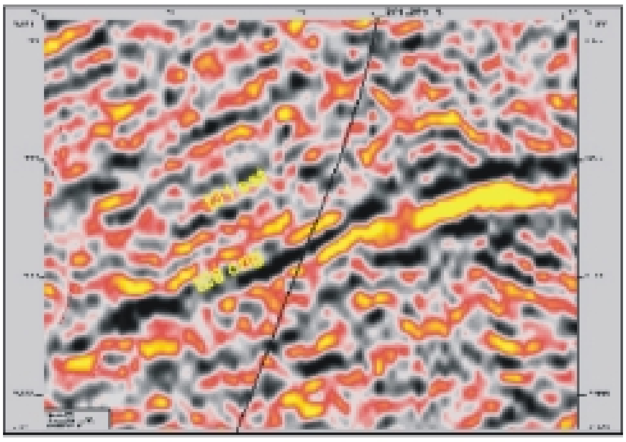
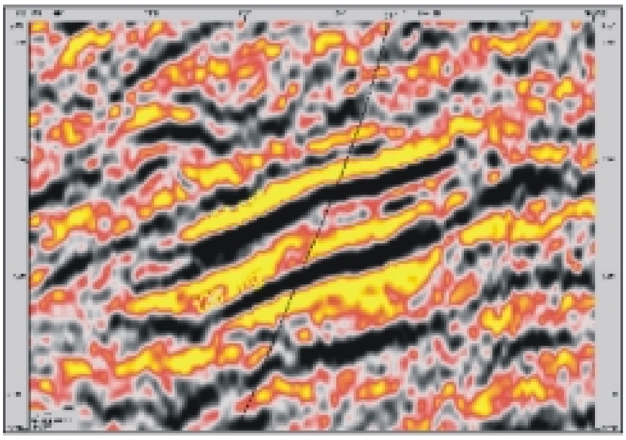


Fig. 51: Seismic line 3 traverses the meandering channel displayed in Fig. 50. The inclined reflections in the centre of the line indicate migration of channel and associated point bar from right to left (reproduced with permission of BP).



1995 Data
pre-injection



1998 Data
after 12bcf injection

Fig. 52: Visualisation of gas injection. Top: the seismic appearance of the reservoir before gas injection. Bottom: the reservoir architecture is visible in greater detail after injection of 12 billion scf of gas.

returning signals, and the close sampling of the recorded signal (Fig. 49 to 51). Very promising also is the 3-dimensional acquisition and processing of multi-component seismic. This means a pressure (p)-wave component and three shear (S)-wave components (4components = 4-C) are being recorded in seismic surveys. Since s-waves do not propagate through water, 4-C seismic in offshore areas needs to be recorded with cables/ receivers which lay on the sea bottom or by means of well to well seismic. Because p-waves capture information about the rock matrix of sediments and their pore fluids, and s-waves provide additional information about the properties of the rock matrix, this so-called **3-D/4-C seismic enhances our knowledge of the distribution of lithofacies and pore fluids in the deep subsurface**. If we acquire 3-D/4-C seismic after some time interval at the same location (time lap 3-D = 4-D), the resulting 4-D/4-C pictures allow to trace the flow of oil, gas, and water through the reservoirs during the life time of a hydrocarbon field (see also Fig. 52). This results in high success rates for infill drilling.

We are now able to illuminate the subsurface in ways unthought of only a few years ago. Based on interdisciplinary team efforts we not only accurately map in three dimensions subsurface structures like anticlines, normal, and reverse faults. We also are able to map sedimentary bodies and their pore contents (oil, gas, or water) in great detail. This gives industry the confidence to drill extremely expensive wells (costing $ 50 million plus each) in more than 1500 m of water aiming for a gas bearing turbidite channel sand, which is located underneath a salt overhang at a depth of more than 6000 m below the seabed. Sedimentologists can be proud of making this possible.

3.4. Sequence Stratigraphy

Before 1970, interpretation of deep reflection seismic in sedimentary basins was generally focused on the recognition and mapping of structural features such as anticlines, fault blocks, salt domes, etc. Since then, acquisition and processing methods have sufficiently advanced to map sedimentary features such as carbonate platforms, channels (see also chapter 3.3. - Figs. 13, 14) and 'seismic sequences'. Vail and others of Exxon introduced sequence stratigraphy as seismic stratigraphy in the early 1970's (Vail & Mitchum 1977). They were driven by the petroleum industry's desire to predict lithofacies from seismic before drilling. They recognised certain reflection patterns, which characterise the internal and external geometrics of packages (Figs. 53, 54), and wisely correlated them to sedimentary sequences related to changes in relative sea level (Fig. 55).

Sequence stratigraphy is now a preferred method to analyse and comprehend the architecture of the sediment fill of basins. It allows us to map genetically related depositional packages based on their **internal facies characteristics and the characteristics of their boundaries** (Miall 1997). The boundaries are unconformities or their correlatable conformities. The internal architecture of the depositional packages and their external boundaries are the result of the - at times very complex - **interplay of subsidence** (which may be caused by tectonics, thermal cooling, or sediment loading), **sediment supply, and eustatic sea level changes**; all these factors together determine the accommodation space, i.e. the space available to be filled by sediments. In aquatic environments this means the space between top and the bottom of the water body.

Large scale sequences (first and second order) are generally defined as starting with lowstand erosion on the continent and shelf, followed by sediments of a **lowstand systems tract,** which usually accumulate in the lower parts of a basin (LST, Fig. 55); sediments of the overlying **transgressive systems tract** (TST) indicate rising relative sea level and often exhibit backstepping stacking patterns. Large scale sequences often culminate in the progradational sediment patterns of the **highstand systems tract**, which are usually found building from the higher continental and shelf) portions of the basin towards deeper water (HST, Fig. 55).

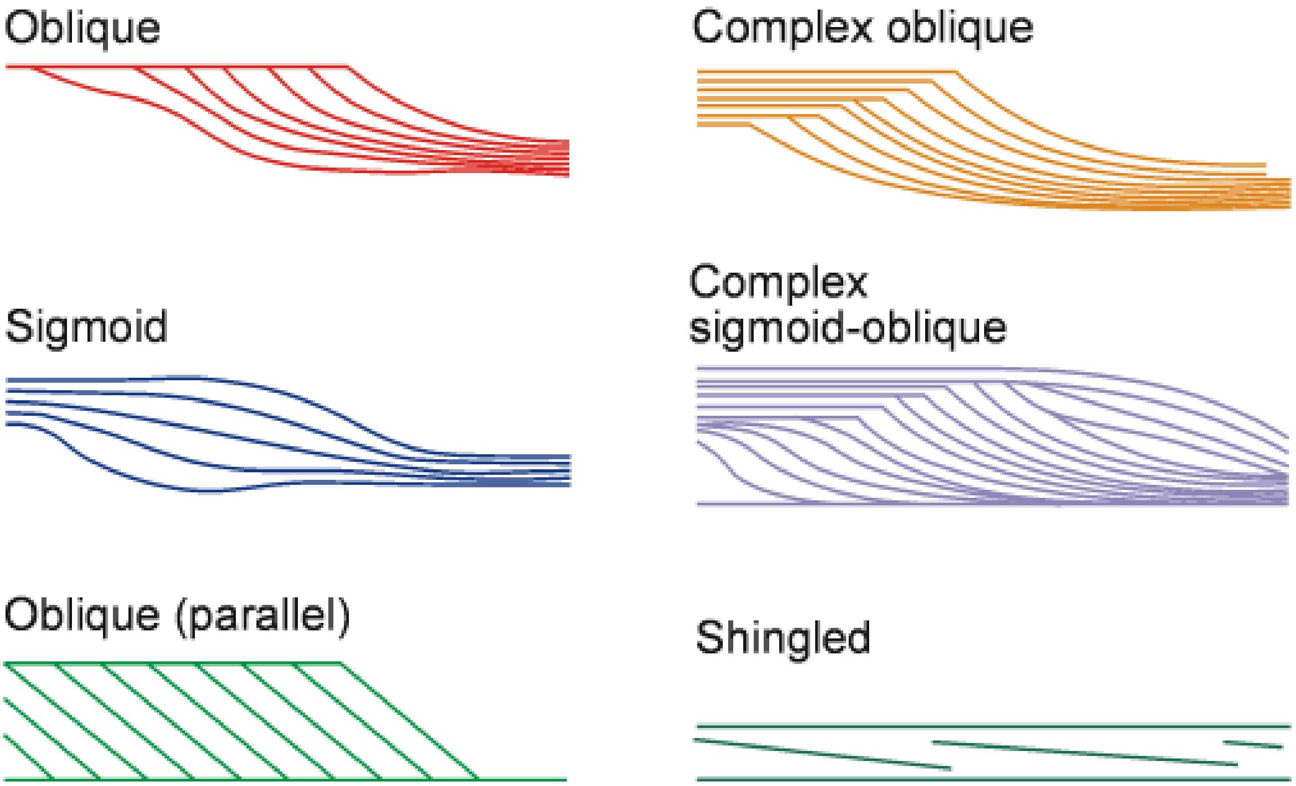


Fig. 53: Sequence stratigraphy: examples of reflection patterns as seen on seismic section. See also Figure 54 (reproduced with permission from Schlumberger).

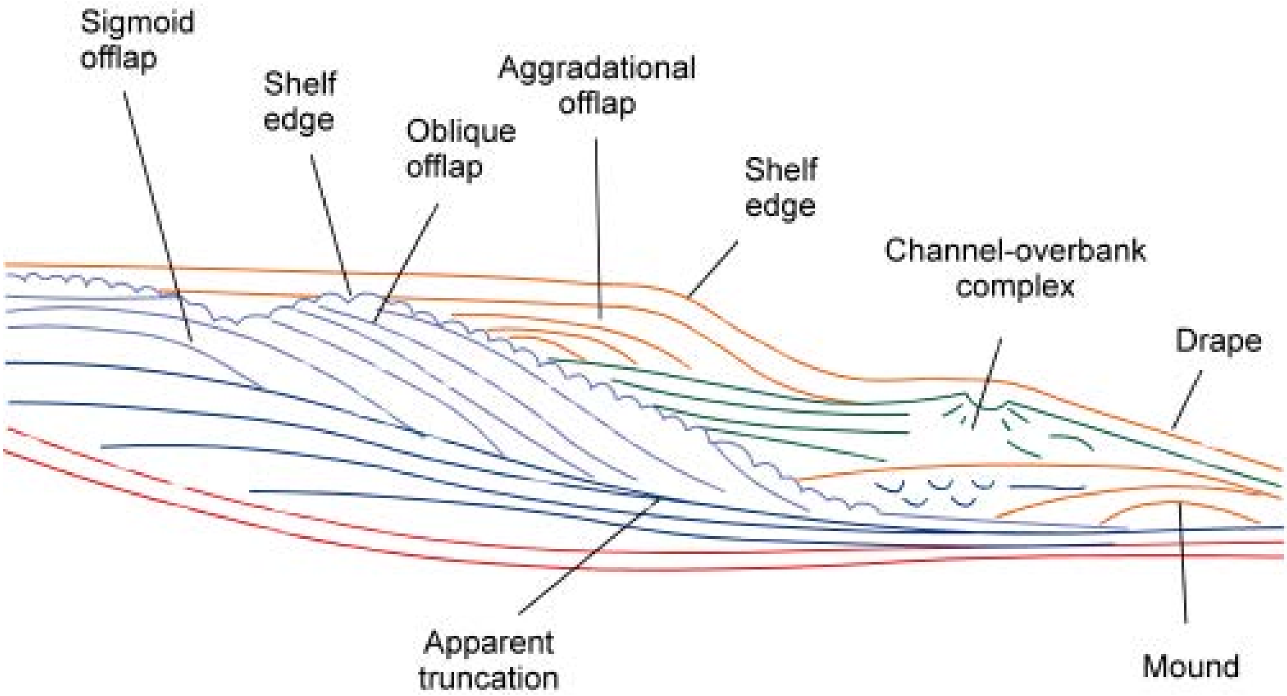


Fig. 54: Sequence stratigraphy: delineating packages of reflectors based on their internal reflection patterns and their depositional or erosional external boundaries, is an important step in interpreting lithofacies from seismic before drilling. See Figure 53 for colour key (reproduced with permission from Schlumberger).

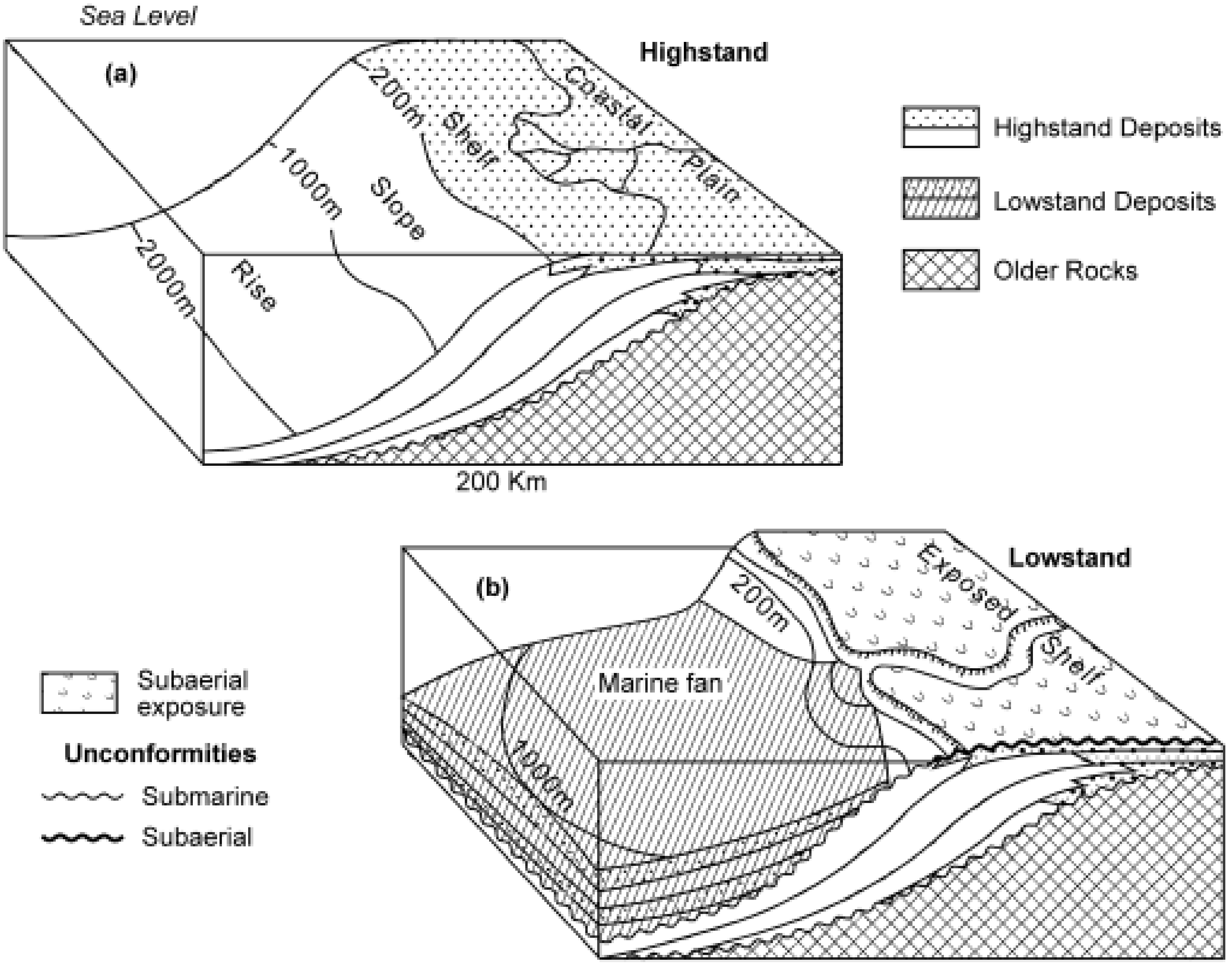
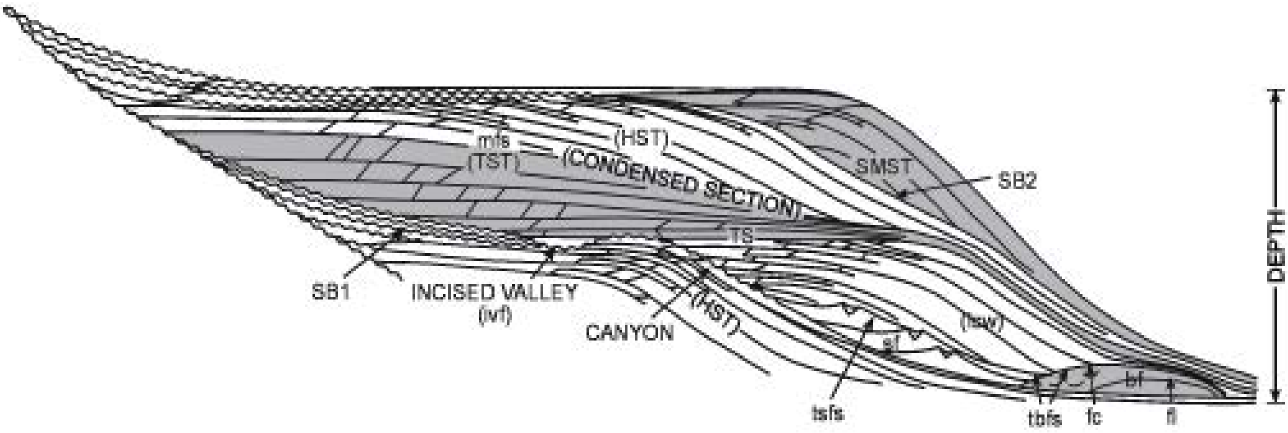


Fig. 55: Sequence stratigraphy: accommodation space and deposition during a sealevel highstand (A)and a lowstand (B). During a lowstand deposition occurs mainly in the deep (“low”) parts of the basin (e.g. on deepwater fans); during a highstand deposition takes place mainly in the shallow (“high”) portions of a basin (in prograding deltaic or non-deltaic coastal complexes).

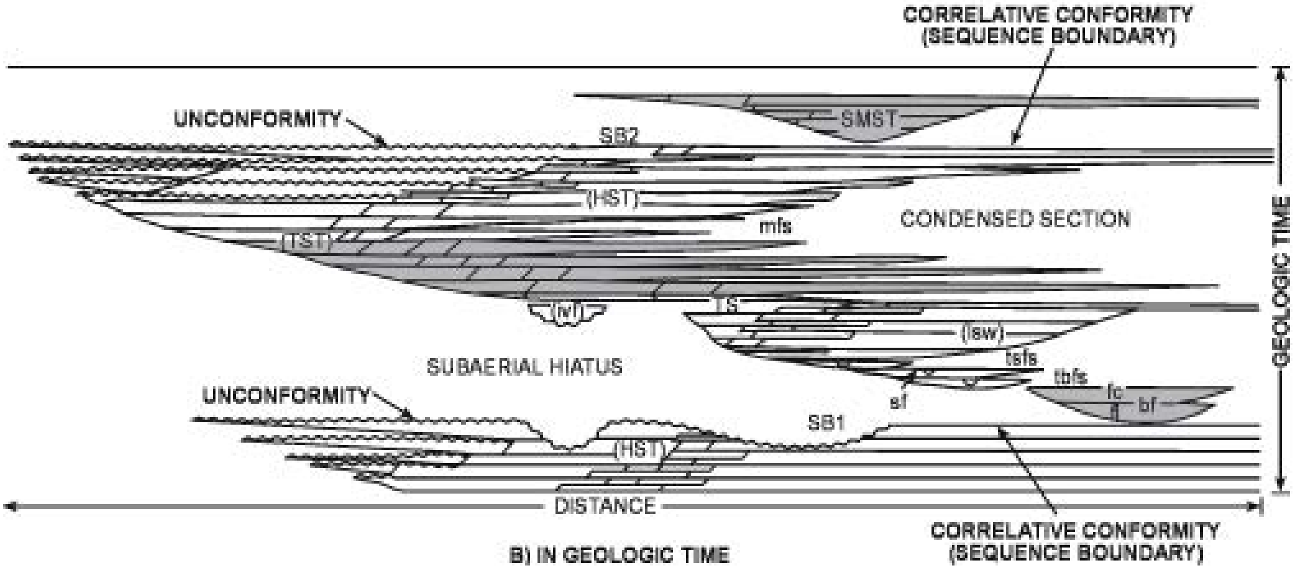
The smaller scale **parasequences** generally are bounded at the bottom and at the top by marine flooding surfaces or their correlative surfaces (van Wagoner et al. 1990). Both, sequences and parasequences are useful organising principles in sediment piles.

Wide spread and successful application of sequence stratigraphy in the energy industry has taken the edge off most of the controversial aspects of sequence stratigraphy that raised passionate discussion in the past. Early strong emphasis on world wide eustatic sea level changes as the predominant driving mechanism for sequence evolution (Vail et al. 1977) has given way to the realisation that sequence deposition and internal stratal patterns are mainly controlled by fluctuations of **relative** sea level. This means that sediment body shapes, facies stacking patterns, and boundary surface geometries are a consequence of the intrigate interplay of eustatic sea level change, subsidence (tectonic, thermally and load induced), and sediment supply. The clarification of the importance of relative sealevel changes softened considerably the earlier strong assertion that each sequence boundary reflected a change in (world wide) eustatic sea level and was therefore a perfect, globally correlatable chronostratigraphic marker. The problem is twofold: firstly, not every sequence boundary reflects a synchronous world wide event (see previous paragraph); secondly, there are so many sequences of slightly different ages within each time window that unique correlations between them are practically impossible. Experience gained from petroleum exploration shows that sequence stratigraphy in conjunction with (and not instead of) high resolution biostratigraphy is extremely effective tool in reconstructing and understanding thediscontinous events that cause the internal architecture of thick sediment piles (Fig. 56). **It is to Vail’s great merit that he re-invigorated physical (litho)stratigraphy and brought it back from the dead end street, where it was stuck before 1975**.

Pitfalls in the sequence stratigraphic interpretation of carbonates where clarified by Schlager et al. (1994),



A) IN DEPTH



B) IN GEOLOGIC TIME

Fig. 56: Sequence stratigraphy also demonstrates the episodic nature of sedimentation. Top: deposits of various system tracts stacked on top of each other as we observe them in wells/outcrops. Bottom: the same system tracts plotted against time reveal how much time is not represented by sediments, and when and where gaps in deposition occur (VAIL 1987, AAPG Copyright 1987, reprinted with permission of AAPG whose permission is required for further use).

SCHLAGER (1999b), and others. Very helpful was the observation that rapid growth of carbonate platforms during transgressive and highstand periods leads to sediment instabilities at the edges of such platforms and to gravitational transport of shallow water carbonate clastics and mud into otherwise starved basins. This creates wedges at the toe of a carbonate platform, which look like lowstand wedges and turbidite fans in a siliciclastic setting.

Sequence stratigraphy is successfully applied by thousands of geoscientists throughout the petroleum industry and academia. It challenges the sedimentary geologist more than any other current stratigraphic concept to ask the right questions in order to find the right answers. It permits us to predict lithofacies distributions and their likely acoustic impedance contrast at their boundaries. This in turn enables us to improve the definition of parameters for seismic acquisition and processing. This again contributes tremendously to the brighter illumination of the subsurface. Seismic stratigraphy enables explorers to estimate the location of reservoirs, source rocks, and migration pathways ahead of the drill bit. This allows us to find more oil and gas. In addition to all this, sequence stratigraphy also provides data for safer and more cost effective drilling. **Sequence stratigraphy is not only a brilliant concept, it is also one of the petroleum industry's most useful tools**.

4. Sedimentology in the Future of the Oil and Gas Industry

4.1. Knowledge Management based on Integration

As demonstrated throughout this paper, progress in sedimentology comes increasingly from multidisciplinary teams that bring together sedimentologists, palaeontologists,

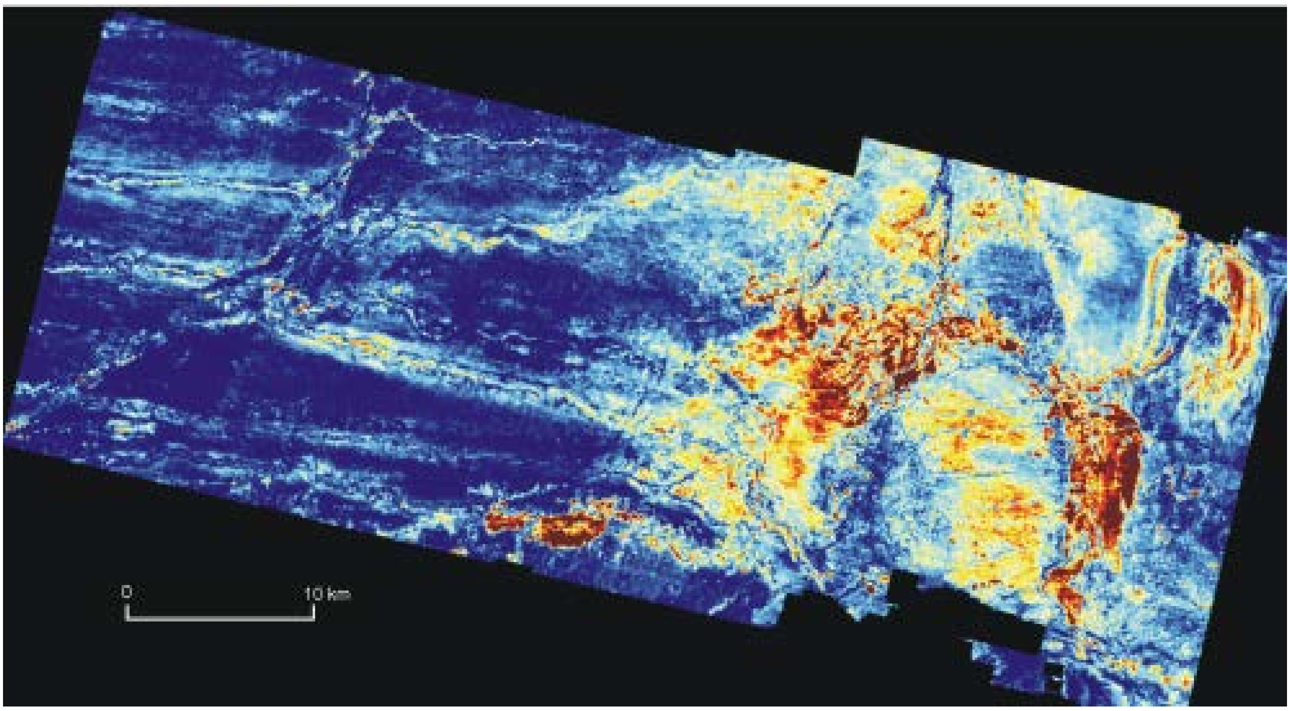


Fig. 57: A seismic time slice (map view) from a 3-dimensional seismic data set. The amplitude display illuminates several Tertiary deep water slope channels and turbidite fans (sediment transport from left to right), under >1000 m sediment cover, offshore West Africa. The fan sediments are (in yellow and brown) ponded against two salt or clay swells, one swell can be seen at the right edge of the image, the other one at about 19 km from the right edge (with permission of BP).

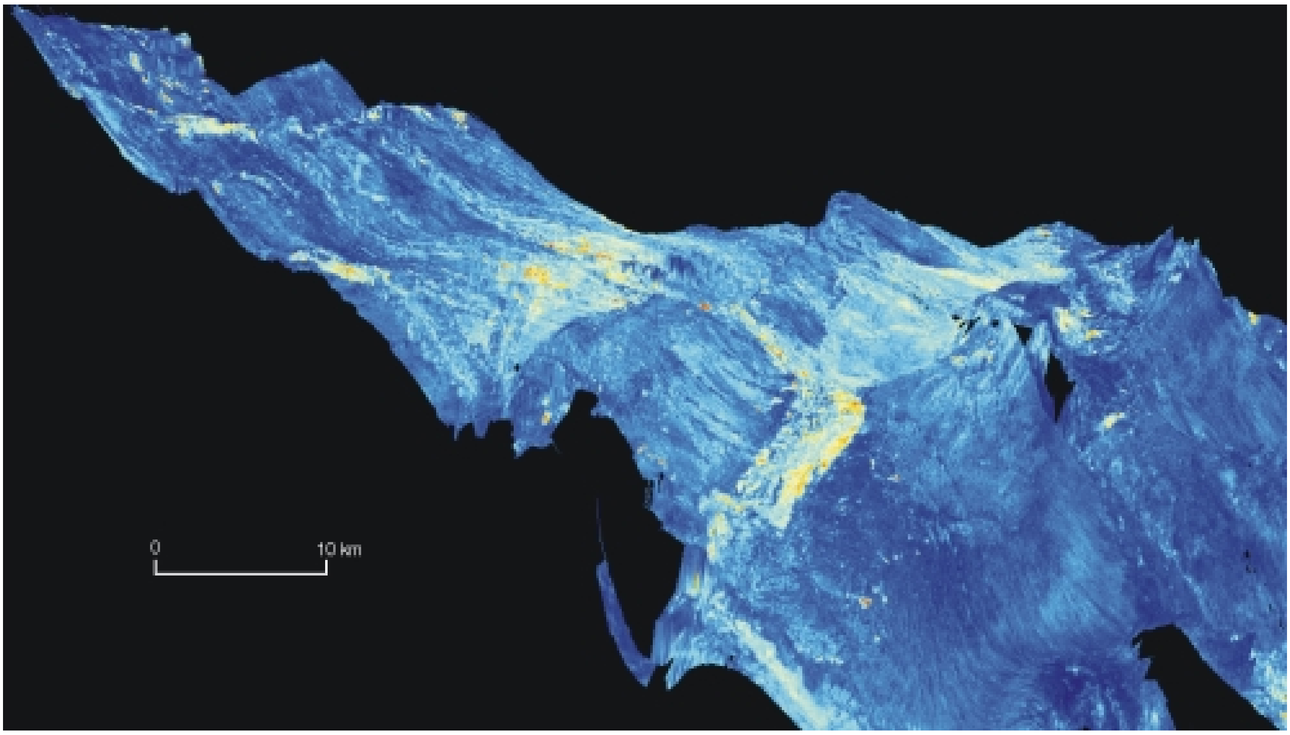


Fig. 58: A 3-dimensional display of the same scene as in Figure 57. The power of advanced visualisation techniques becomes evident. An elongated swell is prominently visible across the centre of the image, another one along the right edge. Turbidity currents ran down along slope channels (in the left half of the picture) and dropped their sediment load on deep water fans, which gradually filled the depression up-current of the salt or clay swell in the centre. Eventually turbidity currents cut through this barrier and filled the depression up-current of the salt or clay swell (at the right edge of the image) with fan turbidites. The feeder channel of this second fan system then cut back through the higher fan system (in the centre of the image) and into the basinslope (in the left part of the image) (reproduced with permission of BP).

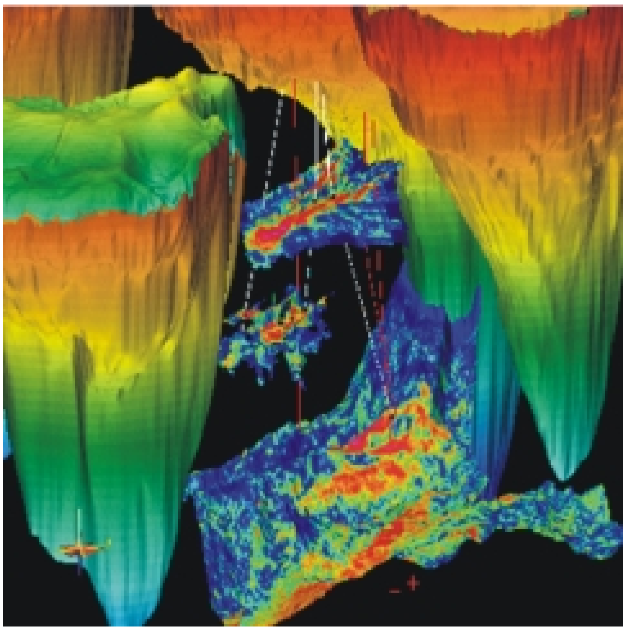


Fig. 59: Today's immersive 3-dimensional visualisation capabilities are only the primitive pre-cursors of fantastic things to come. Shown here are reservoir horizons between salt domes. Future sedimentologists will routinely climb paleoslopes and crawl through pore space in virtual reality (reproduced with permission of BP).

geochemists, petrophysicists, and seismologists. The daily relentless effort in industry to link and integrate the seismic properties of sediments (such as p- and s-wave velocity, density, amplitude, coherency, frequency, and phase) to the rock properties of sediments (such as mineralogy, magnetic susceptibility, gamma emanation, lithofacies, porosity, permeability, pore fill, pressure, and environment of deposition) and back to the seismic properties in thousands of iterations (inverse and forward modelling) is paying off in the form of higher finding rates and safer and more cost effective exploration and production operations. Many universities are part of these exciting developments, we wish even more would join.

Oil and gas have become commodities in the world markets. As long as hydrocarbons are the energy source of choice, the hydrocarbon industry will need to find ways to keep finding costs, development costs, and lifting costs as low as possible, even as oil and gas operations expand into high cost areas, such as deep water. In the future, the industry will need to accurately predict subsurface lithofacies variations, thermal maturity, pore content, and fluid flow in three and four dimensions with resolutions of less than 10 metres at a depth of more than 10 kilometres below the sediment surface. Sedimentology will have to describe and catalogue examples and models of 3-dimensional sediment distribution spanning all scales from microscopic to basin wide. We will need age dating with an accuracy of better than 10,000 years in sediments more than 500 million years old.

The linkage and integration of sedimentology with 3-dimensional multicomponent seismic (3-D/4-C) appears very promising for the future. High resolution and high accuracy would be wasted, if we would not also develop our capabilities for 3-D visualisation (Figs. 57 and 58). Today's immersive visualisation systems are just a modest beginning (Fig. 59). In future, multidisciplinary teams of geoscientists and engineers will be jointly diving and climbing through the 3-D virtual reality of sediment bodies and their pore spaces while seeing every minute detail. Sedimentology will not only be a useful component of subsurface exploration programs, but it also will be essential in predicting the fine anatomical detail within oil and gas reservoirs that influences the production behaviour of oil and gas fields (SCHLAGER 2000).

So far, we have advocated **the need for sedimentology to be "horizontally" integrated with other geoscience and engineering disciplines**. We will now argue **the usefulness of "vertical" integration to applied sedimentology, which progresses from data to information to knowledge and finally to wisdom**.

Around the world, more and more countries adopt the principles of very flexible and open market economies. Oil and gas are increasingly traded as commodities, not as speciality products. **In open markets, time is money, and commodities have to be cheap.** For the oil and gas industry to flourish in such an environment, it needs to be able to take wise decisions quickly. Any wise and, at the same time, fast decision - in industry, in applied sedimentology or otherwise - requires sound knowledge management, i.e. the capability to move and integrate from raw data to wisdom almost instantaneously. Relevant data needs to be filtered from noise before it can be integrated to information. Information needs to be interpreted and compared to a standard (more than, less than, higher than, lower than, etc.) to become knowledge. Relevant knowledge needs to be integrated and applied towards reaching certain strategic goals (e.g. of a government, a municipality, a professional society, a company) to become wisdom (SCHOLLNBERGER & NELSON 2000).

In summary, **sound knowledge management based on instantaneous integration is essential for the future oil and gas industry and for applied sedimentology**. It is useful to remember that **instantaneous integration** in sedimentology proceeds in two directions, **horizontally** between technical disciplines such as sedimentology, paleontology, geochemistry, petrophysics, seismology, reservoir engineering, drilling engineering, etc., and **vertically** from data to information to knowledge and finally to wisdom.

4.2. Future Applications of Sedimentology

Exploration and production activities are now targeting large oil and gas fields located in deep (> 200 m) and ultra deep (>2000 m) waters. This trend will continue into the future. Operations in deep and ultra deep waters have inherently high finding costs, development costs, and lifting costs, whereas operations in the land areas of the oil and gas rich Arabian Peninsula are less expensive. In order to keep deep

water oil and gas projects economically competitive with the ones in Arabia, drilling programs, well construction, well completions, subsea, and surface facilities need to be designed and executed **right the first time around**. **Later interventions are very expensive** and may render a deep water project uneconomic. A well work-over to shut off produced water down hole may cost $ 30 thousand on land, but $ 30 million in ultra deep water. Thus, interventions need to be minimised or avoided all together in deep water. The need to get everything right the first time around means that important decisions concerning the exploitation of oil and gas reservoirs have to be taken already during the exploration phase, even if the information base is still very incomplete. This 'front end loading' of reservoir studies into the exploration process has blurred the traditional boundaries between exploration geology and production geology. We anticipate separate exploration and production departments to disappear from the organisation charts of successful oil and gas companies during the next few years. We expect **sedimentologists** to become **members of integrated and multidisciplinary teams** and to be essential contributors to reservoir studies on all **scales ranging from small compartments within producing fields to entire basins**.
Sedimentology will contribute to the oil and gas industry for many years to come (see chapter 1.0 above). However, shape and content of the energy industry of the future, will ultimately depend on the price humankind is willing to pay for power, light, mobility, and comfort in terms of greenhouse gas emissions and climate change.

We believe that there is a future for applied sedimentology **beyond petroleum**, as a major ingredient in humankind's strife for **sustainable development**. As we emphasised throughout this paper, many sedimentological methods, which are currently used in the oil and gas industry, are well suited to predict fluid flow through porous rocks. Sedimentologists therefore will play a major role in finding **water** in the subsurface and producing it, as well as in harnessing geothermal energy. Sedimentologists also will be essential contributors to finding solutions for **waste management**, i.e. safely storing waste in the subsurface (incl. CO_2) and at the same time preventing waste from spreading to places where it could be harmful (e.g. aquifers). Above all, sedimentologists have many of the tools needed to understand past and present **climate changes** and to predict what is in store for us all in future. Climate change is of enormous relevance for the **sustainable development of humankind** and at the same time it is an issue to which sedimentologists can and have to provide precise answers and solutions.

4.3. Industrial Sedimentologist of the Future

These are the best of times for sedimentologists and at the same time, it feels to many like the worst of times. Important issues, such as the energy supply to the markets of the world and the effect of human activity on the climates of the future await solutions. Sedimentology can offer answers. Sedimentology's relevance to society is arguably higher than ever before and the sedimentologist's tool box is full with new and exciting gadgets. So why do sedimentologists not feel better about themselves and about what they are doing? Leo P. Kadanoff, professor for physics at the University of Chicago, recently noted well the uncertainties facing all scientists (not only sedimentologists) today (Treitel et al. 2000):
"We have already seen 15 years of considerable change - and can expect more changes to come. These developments leave the individual scientist with a substantial problem in planning a career in science. This planning must be done in circumstances of very considerable uncertainty about the structure of the institutions that will employ scientists and the nature of the jobs within them. Change is certain. The direction is unclear."

To cope well in a future in which the only certainty is change, I offer some well intended advice to sedimentologists, who wish to work in industry:
+ Be conscious of your and other people's safety, be conscious of the impact of your actions on the natural environment. (I am convinced that the responsible use of hydrocarbons as energy source and sustainable development of humankind are compatible).
+ Keep your technical knowledge reasonable up to date in at least one other earth science next to sedimentology, may this be in seismology, petrophysics, paleontology, geochemistry, etc.
+ Be able to work in integrated mutidisciplinary teams.
+ Be able to talk with reservoir engineers, drilling engineers, and process engineers.
+ Try to understand (at least in a rudimentary way) the financial drivers of both, open market economies and centrally planned economies.
+ Find solutions.
+ **Above all, have passion for sedimentary geology!**

So called S-curves are being used by economists to examine at what maturity level a certain technology is. Sedimentology is generally seen by economists (H. Wintersteller of McKinsey, pers. communication) as having reached the upper flat part of the S-curve, which would mean that sedimentology is a mature science with few break-through innovations to be expected. But it are not the economists who drive progress in sedimentology. Having contributed to technology development in Shell, Amoco, and BP, I have learned that only those, who do **not** know much about a certain field in science, believe that a state of maturity - the upper flat part of the S-curve - has been reached in that field. The passionate researcher, who actually creates new knowledge in that field, always sees him/herself as climbing the steep part of the S-curve, fully aware that **the surface of understanding has been barely scratched** and that many discoveries still have to be made and many applications still need to be invented.

Passion for sedimentary geology and a relentless drive towards precise, quantifiable, and integrated solutions shall carry sedimentologists and sedimentology to a long and prosperous future!

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