Ancient coral reefs, long buried in sedimentary rocks, are an important source of oil in the Middle East. These carbonate rock formations, created from the skeletal remains of diverse marine species, have been around for at least 600 M years. Some reefs formed in shallow coastal waters, while others developed around volcanic islands a long way from any large continent. What factors controlled the occurrence of these coral reefs, and which have the best reservoir potential?

In common with modern coral reefs, ancient reefs (figure 1.1) thrived in warm, shallow water with very little associated sediment. Over geological time many different types of organism have dominated the reef environment, but all have achieved their best growth rates in shallow equatorial waters. Consequently, the diversity and abundance of coral species decrease with distance away from the equator.

The typical island reef, developed around an oceanic volcano, has little potential for oil and gas accumulation. In these reef ecosystems almost all the organic material present is in the form of living organisms. Nutrients from dead organisms are recycled very rapidly. As a result, reefs do not generally produce enough 'excess' organic material to generate oil and gas. However, some reefs do contain hydrocarbons, and the best oil and gas targets are reefs which developed close to ancient continental margins. Here, organic input from a nearby continental shelf may have generated hydrocarbons or been incorporated in shales which can act as trap rocks.

The Arabian Peninsula spans a range of latitudes, so that in the south - the Gulf of Aden and the Red Sea - conditions are, currently, favourable for coral growth, while the Eastern Mediterranean and The Gulf are marginal areas, with few coral species. The Red Sea is particularly rich in modern coral reefs, especially along the edges of fault blocks.

Over geological time the Arabian Peninsula has passed through the equatorial belt a number of times (figure 1.2). Optimum conditions for reef growth occurred during the Precambrian, Jurassic, Cretaceous and Middle Tertiary.

During the Miocene, between 5 M and 20 M years ago, abundant coral structures formed at shallow depths on the highest points of rotated fault blocks in the Gulf of Suez. Oil is produced from these reefs but the complex pattern of faulting precludes the development of supergiant (over 1 billion bbls) reservoirs.

Exploration drilling in the eastern part of the Mediterranean, on similar fault blocks, may lead to more Miocene reef discoveries. For example, in the Red Sea, Miocene oil accumulation occurred when evaporites were deposited on the reef, forming an excellent seal, trapping hydrocarbons in the porous reef rock. However, in some cases the evaporite layers developed too early, preventing oil and gas migration into the carbonate highs.

Tertiary rocks contain many of the most productive reefs found in the Middle East. The reefs of the Precambrian also contain important oil accumulations, while the reservoir potential of the Jurassic is still under investigation.
A number of Tertiary reef prospects are being developed across the Middle East. There are Eocene-Oligocene (early Tertiary) reefs in northern Syria and Iraq and part of the Asmari reefs facies in Iran produces hydrocarbons. More Tertiary reefs have been discovered in Oman and in the Gulf of Aden. These discoveries may develop into important reservoirs in the future, although they are not, as yet, in commercial production.

The oldest reefal reservoirs in Arabia are located in the Precambrian rocks of southern Oman which contain algal stromatolitic reefs. Stromatolites are large accumulations of carbonate sediment and skeletal material bound together by algae. They are often dome-shaped and have a distinctive, finely-laminated appearance. In addition, deep drilling projects in marginal areas of the Ara and Hormuz salts are expected to reveal additional oil and gas in stromatolitic reservoirs.

Recently, reef-forming stromatolites have been discovered in Belize and Honduras, in Central America. Studies of these stromatolites should clarify the role which these organisms play in the development of modern reef communities.

During the Jurassic, environmental conditions in Arabia meant that oolitic carbonate sands were more common than reefs. Oolites are rocks composed of carbonate grains (ooloids) which form in tidal deltas and other shallow environments or 'shoals'. They are not produced by biological processes, rather the carbonate in each ooid precipitated directly from calcium carbonate (CaCO₃) saturated seawater. However, some 'patch reefs' did occur in the Jurassic. These small carbonate structures were scattered across the shallowest parts of the continental shelf. The patch reefs found to the west of Riyadh, in Saudi Arabia, provided good reservoirs on salt domes and anticlinal structures in the Gulf and along its southern shore.

The hydrocarbon potential of the relatively large Jurassic marginal reef in the Gotnia Basin, has not been examined in detail. However, a recent discovery in the Kuwait/Saudi Neutral Zone (South Umm-Guadir DW-1) by the Kuwait Oil Company (KOC) and Saudi Arabia Texaco should renew interest in this potential reef target. Good dolomitization of the shelf-edge reef trend has been found, with one of the best source-rock sequences down dip in the Gotnia Basin. However, effective seals are present which may separate source from reefal facies, and could have hindered oil and gas migration.

Fig 1.2: Reefs have come and gone throughout geological history. The presence of well-developed reef facies (a) is linked to sea level fluctuations. The times when reefs have been almost absent from the geological record show a rough correlation with periods of rapid sea level change (b). Another factor controlling the development of coral reefs is the movement of Arabia relative to the equator through time (c). Although close to the equator during the Devonian, Arabia was completely above sea level at that time, so no coral reefs developed on the Arabian peninsula. The development of ooids (which are chemical rather than biological carbonates) is controlled by seawater chemistry. As ocean chemistry fluctuated through time (d) the changes influenced the relative stability of calcite and aragonite cements and the dissolution of ooids. This diagram is based on concepts developed by David Raup, M.W. Hughes Clarke, Peter Vail and Bruce Wilkinson.
Darwin’s other discovery

Charles Darwin, the naturalist whose theories revolutionized our understanding of biological science, made a significant contribution to the study of reefs. In 1842, while engaged on a scientific voyage on the research ship HMS Beagle, Darwin proposed his subsidence theory for the development of coral atolls. He speculated that reef atolls had, at some time in their development, been marginal or fringing reefs (figure 1.3a) around an island. Darwin believed that as the island started to subside, the fringing reefs continued to grow upwards at a rate equal to, or greater than subsidence. Consequently, as the area of the central island decreased, a shallow lagoon formed between the island and the growing reef (figure 1.3b). When the island finally dropped below sea level, all that remained was a large lagoon fringed with upbuilding reef material (figure 1.3c). Seismic surveys and drilling carried out as part of the 1991 Ocean Drilling Program (Leg 143) appear to have confirmed Darwin’s theory on atolls.

Darwin also speculated on the characteristics of a specific group, the Maldivian atolls. He suggested that subaerial erosion and subsidence were the most important factors in their development. However, recent studies suggest that Darwin’s sea level fluctuations alone cannot account for all the complexities of carbonate deposits in the Maldives.

Seismic surveys and drilling in both the Maldives and the Seychelles have confirmed existing plate tectonic reconstructions of the Indian Ocean. In the Maldives, carbonate deposition began in the early Eocene with shallow water sediments resting on hot-spot basalts (figure 1.4) related to the slightly older Deccan Trap basalts of India. Very little is known about the early development of the islands, but the limited evidence suggests that early rifting coincided with development of a graben system along the transform fault on which the Maldivian carbonate platform and atolls grew. The overall structure of the platform was probably influenced by crustal cooling effects.

Island reefs and reef platforms are not potential exploration targets, since they generally lack a source rock or sealing layer, or both. Reef environments such as the modern Maldives platform contain large volumes of porous and permeable rock, but the Maldives are too far from sources of organic material to generate hydrocarbons and too small to generate the sealing layers necessary for oilfield development.

Island records

The subsidence history of a small volcanic island and subsequent growth of an Eocene coral reef has been reconstructed using geochemical logging carried out as part of the Ocean Drilling Program. Experts from Columbia University’s Borehole Research Group studied a composite volcanic-carbonate sequence in the Indian Ocean, using a Geochemical Logging Tool (GLT*) to unravel the geological history of the area. The volcanic rocks proved to be mainly vesicular olivine basalts which showed weathering effects. This suggested that they may have formed the surface of a volcanic island. These rocks were overlain by plagioclase basalts with high concentrations of titanium (Ti) and iron (Fe). Basalts can be assigned to geochemical ‘families’, with the chemical composition of the rocks indicating...
probable tectonic setting. High concentrations of iron, aluminium and silicon (figure 1.5) are typical of basalts found in volcanic island settings. The aluminium 'spikes' in the lower part of the log correspond to weathered 'soil' layers deposited between the basalt flows.

A thin calcarenite zone, interpreted from core as a beach deposit, is followed by a distinctive, titanium-rich basalt layer which marks the end of volcanic activity on the island.

The reef proved more difficult to sample, with a core recovery rate of only 5%. However, this was enough to indicate a transition from high-energy grainstones to low-energy packstones. This, together with successive faunal changes, confirmed that the water above the reef was getting deeper. Carbonates, in stark contrast to basalts, are characterized by low concentrations of aluminium, iron and silicon and, of course, a high calcium content.

The sulphur curve in this log shows zones of high sulphur concentration within the reef. These sulphur peaks have been interpreted as sulphate evaporites. Experts have speculated that the log shows sea level changes with low stands marked by relatively high sulphur content. Sulphur peaks at wavelengths of 25 ft and 50 ft could be related to the Eocene low sea level stands (at 36 M, 40 M, 42 M, 49 M and 54 M years ago) recorded in the Vail eustatic sea level curve. This example illustrates the value of geochemical techniques in determining the geological history of a sequence from raw element data recorded direct from logs.

The karst (subaerial weathering of limestone) features found in many ancient reefs underline the importance of fresh water diagenesis, which caused leaching of less stable carbonate minerals. Fresh water zones fluctuate through time as sea level rises and falls in relation to the atoll islands and the platform. Geothermally-heated fluids, which rise along crustal fracture and fault systems, mix with cooler seawater and fresh water lenses which are scattered within upper parts of the atolls and the platform.

Permo-Triassic 'exotics' - large rock masses which have been structurally emplaced into a sedimentary sequence - were thrust onto the slope/shelf at the eastern edge of Arabia during the Cretaceous. These may be fragments of ancient atolls and platforms similar to those in the Maldives. Although the exotics seen at the surface contain no hydrocarbons, there may be oil and gas-filled reef blocks beneath Tertiary shales off the east coast of Arabia. If these deeper blocks could match the productivity of similar reefs in the Gulf of Mexico, they would represent a major new exploration target in the Middle East. However, the overpressured Tertiary seal, which may also be the source rock, is a serious obstacle to deep drilling operations.

Sorting out the salt

The salt dome structures which underlie prolific reservoirs in The Gulf - including the Permo-Triassic Khuff carbonates, the Jurassic grainstone reservoirs and Cretaceous grainstone/reefal reservoirs - sometimes form islands, but have very little in common with the ocean atolls. Formations overlying the salt domes are closely interlinked and continuous with formations which surround the dome. Hydrological studies suggest that these reefs often form part of regional aquifers. The numerous evaporite layers found in Permo-Triassic and Jurassic formations, and the thick clay-rich shales deposited during phases of low sea level, are widespread and form effective seals: ideal for the development of giant oil and gas reservoirs.

Fig 1.5: WHERE'S THE BEACH? Geochemical logging is proving a powerful tool for stratigraphic interpretation. The geochemical data retrieved from this borehole show a calcium-rich carbonate (reef) deposit overlying an iron-rich basalt (volcanic complex). A separate calcium-rich layer, identified from core material as a beach deposit, occurs in the middle of the volcanic sequence. Columbia University, Borehole Research Group, 1990.
Diagenesis, dissolution and dolomite

Porosity evolution in rocks is a complex, but vital part of reservoir development and a clear understanding of this process is crucial in the search for oil and gas. Porosity varies within rock layers. Where the porosity of a reservoir layer falls below a threshold, or cutoff, it ceases to be a viable reservoir. This cut-off value varies from reservoir to reservoir.

A picture of the porosity distribution in each reservoir zone depends on a clear understanding of reservoir geochemistry (figure 1.6).

Other elements in the porosity equation are sedimentary geochemistry, pressure and temperature of burial, fluctuating sea level and changing pore fluid composition. Reservoir analysts must build a composite picture of porosity, extrapolating and interpolating data between wells from the start of drilling.

Dolomite makes a difference

Dolomite mineralization can play a major part in influencing reservoir properties such as porosity and permeability. The conversion of pure limestones ($\text{CaCO}_3$) to dolomite ($\text{CaMg(CO}_3\text{)}_2$) is a gradual process which can start almost as soon as the carbonate sediments have been deposited. Dolomite crystallization is caused by seawater interacting with fresh water lenses or pore water in carbonate rocks. This dolomitization process can take place in hypersaline ponds where there are freshwater lenses in the sediment or in coastal lakes which are subjected to intense evaporation.

While dolomites can be produced in a number of ways, the chemical changes involved do not vary. Magnesium from the seawater replaces some of the calcium present in the original limestone. The concentration of magnesium in dolomite is much higher than in the seawater from which it was derived. Dolomite crystallization and dissolution processes often control porosity development in carbonate reservoirs. Early dolomitization can preserve porosity which might be lost by compaction effects and calcite cementation. Dolomitization often occurs as a result of repeated sea level changes and the mixing of hypersaline basinal brines and normal seawater which accompanies these changes. At the same time, leaching of less stable skeletal components (aragonite) occurs, along the platform margins, increasing porosity. During long periods of rising sea level (marine transgressions) dolomite mineralization may spread to carbonates at the centre of the platform. The extent of dolomitization, and its effect on reservoir properties, depends on the volume and salinity of the hypersaline brines. Large volumes of mouldic, vuggy and intercrystalline porosity can be created by marine transgressions.

Changing sea level and water chemistry also influence the composition of common pore-filling cements. Calcite cementation is retarded because the calcium carbonate in solution is incorporated into the precipitating dolomite. When calcite cementation is inhibited, the development of anhydrite cements is the most important porosity-reducing mechanism. In some cases, both primary porosity and early-generated secondary porosity have been filled by anhydrite cements.

The Egyptian experience

The Belayim carbonate facies, and the equivalent Gemsa Formation, developed along Egypt’s Gulf of Suez as scattered and separate carbonate deposits. In the northern part of the Darag Basin, the Belayim carbonates were deposited in a very shallow marine sabkha environment. In the west central part of the Gulf of Suez, in the Ras Gharib and Ras Fanar fields, the Belayim was deposited as a reef complex. In the southern Gulf of Suez these carbonates are represented by reefal limestones, such as those in Gemsa Field, and also sabkha carbonates.

Structural factors control the distribution of the Belayim carbonate facies, which were deposited on tilted and eroded pre-Miocene fault blocks (figure 1.7). These fault blocks developed during the opening of the Gulf of Suez and are formed by NW-SE oriented Clysmic faults. Fractures associated with the structures have enhanced secondary porosity, permeability and hydrocarbon potential.
Impermeable salt and anhydrite which surround carbonate deposits in the southern Gulf of Suez, for example at Gebel al Fessayan, prevented hydrocarbon migration into potential reservoir zones. Clearly, the position of salt and anhydrite layers is crucial in any evaluation of reservoir potential in carbonates. Miocene carbonate facies vary throughout the Gulf of Suez. The supratidal sabkha deposits at the northern end of the basin, around Ras Fanar Field and in the Darag Basin, generally have poor reservoir potential. In contrast, the reef complexes of Nullipore facies found in the Ras Gharib, Ras Fanar, Ras Bakr and Gmsa fields are excellent reservoirs.

Early dolomitization and subsequent dissolution of the dolomite crystals were vital steps in porosity development in Gulf of Suez carbonates. Other factors favouring the development of high-porosity rocks included; skeletal aragonite dissolution coupled with late corrosion of anhydrite, and fine grained sediments. The porosity of Miocene carbonates could reach values between 15% and 30% following deep burial, and associated fracturing and late dissolution of anhydrite cements, carbonate grains and even, in some cases, the rock matrix. The corrosive fluids capable of a large-scale, late-stage dissolution were probably associated with source rock maturation or basinal shale compaction.

Dolomite mineralization develops gradually (figure 1.8) and chemical changes can halt the process at any stage. Unfortunately, some of the major fields (e.g. along the Shoab Ali Trend and the Kareem Formation of the Zeit Bay Field) contain chalky microporosity and are only partly dolomitized. Marly-shaly units, which overlie potential reservoir zones, probably kept the dolomitizing fluids out of the carbonate.

Modern dolomitization effects can be seen in the Gulf of Suez (figure 1.9) where freshwater from the surface and from the basement mix with seawater.

Fig. 1.7: The reef reservoirs which developed in Egypt’s Gulf of Suez are found in a variety of positions along the trend of Miocene fault blocks.

Fig. 1.8: Dolomite mineralization develops gradually; spreading grain by grain through the reservoir rock. The progressive growth of dolomite crystals within a Miocene reservoir is shown in these microscope photos (a-c). In the final stages of dolomitization pore space can be filled by dolomite (d).

Fig. 1.9: The interaction of seawater with fresh water (arrows) provided an ideal environment for the replacement of calcite by dolomite after deposition of the older reef. The upper limit of dolomite development coincides with maximum sea level. The younger reef is presently undergoing dolomitization. Radioactive dating indicates the older reef cycle is between 350,000 and 270,000 years old. The younger reef cycle was deposited between 140,000 and 60,000 years ago (Strasser et al., 1992).
Dolomite close up

At any given depth, dolomite sequences seem to have greater porosity than a limestone sequence. Most of this porosity difference is due to 'porosity retention' in the dolomite.

The factors which encourage dolomitization are reduced sulphate content in seawater (which typically occurs during gypsum and anhydrite precipitation); dilution of seawater where the ionic concentration is lowered while the molar Mg:Ca ratio is maintained; raising of the Mg:Ca ratio by evaporation; and temperature increases during burial. Climate is a factor, since dolomitization commonly occurs in arid depositional systems. Sea level fluctuations also mix fresh water and marine fluids in subsurface pore systems - another cause of dolomitization.

Studies in the Khuff, Arab and Asmari formations and in Miocene carbonates from the Gulf of Suez, indicate that all of the factors mentioned above played a part at some stage in the development of dolomite in these major reservoirs.

In most Cretaceous reservoirs the dominant factors were groundwater and seawater mixing.

Pleistocene sea level fluctuations in the Gulf of Suez and Red Sea are believed to be the main factors in stratigraphic variations of reef dolomites, although the climate and tectonics of any area will always influence dolomite mineralization.

Age dating of dolomitized sequences indicates that major cycles of dolomite development correlate well with the 100,000 year cycle of eccentricity in the Earth’s orbit (Milankovitch cycles). This eccentricity affects the amount of solar radiation reaching the Earth and, therefore, has a profound effect on global climate. Climatic variations may, in turn, control dolomite development. The smaller sequences which comprise the individual reef sequences are believed to be controlled by sea level fluctuations every 21,000 years, a cycle which relates to movement of the Earth’s axis. These smaller depositional sequences have reefal and lagoonal facies which represent transgressive stages and coral rubble and siliciclastics associated with sea level highstands.

At the southern end of Sinai, around Sharm el Sheikh, studies of Pleistocene and younger reefs by Andre Strasser et al. (1992) underline the importance of seawater and groundwater mixing in the dolomitization of the reefs and associated sediments (figure 1.10).

The carbon and oxygen isotope values in the older (Pleistocene) reefs (figures 1.11 and 1.12) indicate a fresh water influence on carbonate mineralization, whereas the younger reef samples show values typical of dolomite mineralization in normal marine waters. Results from the Sinai reefs resemble findings from Pacific atolls and reefs in Latin America where mixing zone dolomitization is the most important mechanism.

However, evidence for other mechanisms has emerged recently. Thermal pumping - hot water rising from depth to mix with seawater is the focus of current research - while small-scale seawater fluctuations, such as tides, may also promote dolomite mineralization.


Fig. 1.10: Pointed aragonite crystals growing into pore space in the younger reef, Red Sea, southern end of the Sinai Peninsula.

This image and those opposite were provided by Andre Strasser, Institut of Geology, University of Fribourg, Switzerland.

Fig. 1.11 (above): This Scanning Electron Microscope (SEM) image shows rhombs of dolomite growing over crystals of calcite which contain high concentrations of magnesium. This rock is from the Pleistocene (older) reef.

Fig. 1.12 (below): Dolomite and high-magnesium calcite crystals are invaded by small needle-like crystals of aragonite. This change in the older reef is in response to changing water compositions as seawater and groundwater mix.
Developing Dolomite

In the Cretaceous and Tertiary rocks of the Middle East there is patchy development of algal and foraminiferal limestone, with some coral and associated detrital limestones. These were not connected with true fringing reefs, barrier reefs or reef banks. Some modern examples can be seen in The Gulf today.

F.R.S. Henson, in his 1950 AAPG paper, suggested the term 'reef-shoals' for these small reefs which lack rigid fore-reef walls. He also recognized that there were massive rudist accumulations making up banks which he observed outcropping in north east Iraq (Upper Cretaceous between Bekhme Gorge and Aqra, and Late Middle Cretaceous at Pir-i-Mugrun). Dolomite mineralization developed in a variety of tectonic settings in northern Iraq and in Syria (figure 1.12).

The Shuaiba reef of Bu Hasa Field in Abu Dhabi may be a rudist bank, but Ibrahim Marzouk, Supervisor of Reservoir Geology at the Abu Dhabi National Oil Company (ADNOC), has indicated that wrench faulting may have affected the topography of the reef buildup.

Opportunities in Oman

Occidental has recently announced the discovery of a Lower Cretaceous reservoir in northwest Oman, near the flank of the Middle Cretaceous high situated west of Safah Field. This should lead to a re-evaluation of this reef-bearing region.

Reef facies were deposited around the Kirkuk Field during both the early Cretaceous and the Oligocene, along with Eocene nummulitic shoals. The mineralogy of the reef facies was originally calcite (limestone) but many zones were later dolomitized. Recent studies indicate that dolomitization of the Eocene bank was related to falling sea level. This occurred before development of the major unconformity which precedes deposition of the Fars evaporites.
Dolomite-related porosity typically develops in one of two ways. In the early stages individual dolomite crystals appear in the limestone matrix (a). Dolomite mineralization continues until individual crystals come into contact (b), and a framework may emerge (c). Alternatively, chemical changes may favour the dissolution of the dolomite crystals and the rock may develop leached mouldic porosity (d). If dolomite mineralization continues, the dolomite framework may prove more durable than the limestone host. Dissolution of the limestone leaves a dolomite framework with inter-crystalline porosity (e).

Fig. 1.16: Mineral analysis of this Cretaceous carbonate reservoir in the Emirates used geochemical data collected by a Geochemical Logging tool (GLT). The best porosity is found in the lower part of the sequence, but the high permeability values correlate with dolomitization.

Studies from around the Middle East show that dolomites retain their porosity longer than interbedded or associated limestones. There are a number of reasons for this, perhaps the most important being less physical and chemical compaction and reduced cementation associated with dolomites. In mixed carbonate sequences dolomites often show the highest permeability values (figure 1.16). However, shallow dolomite reservoirs with relatively high porosity values can have lower permeabilities than grainstones with similar porosities.

Core mineralogy, isotopic variations and rock examinations suggest there may have been seven stratigraphic discontinuities caused by sea level fluctuations. Detailed mineral analysis indicates that cementation variations from one sea level fluctuation to the next account for the permeability variations found in the sequence. Changing sea level also resulted in the development of calcite cementation following the dolomitization phase. The best permeability is found in dolomite intervals where blocky meteoric calcite cements have not developed. Data from the Kirkuk Field in northern Iraq (figure 1.13) shows this clearly.

Dolomitization can have a very profound influence on permeability and porosity (figure 1.14). This makes a clear understanding of the process crucial to reservoir development. Dolomitization is a complex process and dolomite-related porosity can develop in two ways (figure 1.15). Dolomite crystals appear in the limestone matrix and, as dolomitization continues, may coalesce to form a framework. At this stage chemical changes can dissolve the dolomite leaving leached porosity, or may dissolve the remaining limestone, producing inter-granular porosity and high permeability in a pure dolomite rock.

Fig. 1.15: Dolomite-related porosity typically develops in one of two ways. In the early stages individual dolomite crystals appear in the limestone matrix (a). Dolomite mineralization continues until individual crystals come into contact (b), and a framework may emerge (c). Alternatively, chemical changes may favour the dissolution of the dolomite crystals and the rock may develop leached mouldic porosity (d). If dolomite mineralization continues, the dolomite framework may prove more durable than the limestone host. Dissolution of the limestone leaves a dolomite framework with inter-crystalline porosity (e).
**Subtle traps revealed in the Middle East**

Most of the giant anticlines and large reef reservoir bodies in the Middle East have been surveyed and drilled. New reef and carbonate shoal reservoirs are likely to be smaller than those in existing fields, and will only be found through careful processing and informed interpretation of 3D seismic surveys. In the Gulf region, many Cretaceous reservoir zones are not dolomitized. Consequently, depositional characteristics are the most important factor in understanding oil and gas accumulations. Seismic surveys are therefore being evaluated for depositional characteristics as well as reservoir structure.

A team of seismic experts from Geco-Prakla/GeoQuest recently summarized an integrated seismic processing strategy which can be applied in carbonate exploration and reservoir characterization. Figure 1.17 (a to c) shows their work on a prograding carbonate platform and aggrading shoals similar to those seen in northern Iraq and Syria and northern and eastern Arabia. The first step (figure 1.17a) is a preliminary interpretation of the structure, seismic sequence analysis and interpretation of depositional facies. The next stage (figure 1.17b) produces a complete interpretation of depositional environment, using all available data from systems tracks and sequences. In the third and final stage (figure 1.17c), synthetic modelling is carried out to check the interpretation and to give an indication of the geophysical risk factors in the area.

Risk evaluation is a vital step in new exploration areas where the seismic, structural and depositional interpretations are usually based on limited datasets.

Fig. 1.17. **STEP BY STEP:** After preliminary interpretation had been carried out (a) the interpreters brought together all existing data from system tracks and sequences to present an integrated picture of the reservoir (b). This was checked and the potential risks for development assessed (c) before any major production commitment was made.

During the Cretaceous an aberrant group of large bivalves, the rudists, moved into the reef environment. These particular organisms filled the high-energy shoal so successfully that many geologists think of rudists as reef builders.

For 40M years rudists dominated the tops of shoaling highs and the edges of carbonate platforms. These unusual bivalves have one long cylindrical valve hinged with a flat 'lid' (figure 1.18). Rudists, like recent bivalves, filtered seawater for food. The elongate valve helped keep the rudist's feeding mechanism high above the sediment-rich layer which would have clogged their food gathering system. This adaptation allowed them to feed almost continuously, stopping only when very strong currents lifted muddy sediment from the sea floor.

Rudists did not replace corals completely, they simply took over part of the environmental niche which corals had exploited in the past. As rudists moved into the environments where corals had been less successful, their shape evolved to overcome the soft mud problems which had faced the corals.

The hippuritids and radiotitids formed the most striking of all in-place rudist congregations, with individuals sometimes so densely packed together that they resembled colonial organisms (figure 1.19). These dense clusters were most common in quieter water. In high energy facies, the caprinids were dominant.

The best reservoirs in the Cretaceous are typically carbonate sand grainstones or rudist shallow-marine carbonate deposits. Of the latter, the most significant are the Middle Cretaceous rudist facies which form banks, thickets and biostroms (fossil rich layers). The rudists did not build reefs, nor did they form large bioherms, but they are a vital component of many Cretaceous reservoir rocks.

The best rudist reservoir facies are those which contain a high proportion of skeletal aragonite (from Caprinid) shells. The leaching (dissolution and removal) of aragonite, an unstable carbonate, has produced important, secondary porosity in the form of large 'vugs' or cavities in the limestone. The reservoir potential of a horizon is often enhanced if the aragonite intervals were subaerially exposed after deposition. Increased porosity related to this type of exposure can be seen in the Natih reservoir, in Oman. The leaching associated with fresh water lenses during subaerial exposure is often high in the carbonate reservoir, but not necessarily at the very top of the sequence.
**Pictures of the prospect**

Explorationists often have to deal with very complex sedimentological and structural problems in prospective areas. Their aim is to understand the detail of reservoir variations, while drawing all of the information together into a comprehensive picture of reservoir development and overall hydrocarbon potential.

Petroleum Development Oman (PDO) carried out an evaluation study of the Sirat structure, making use of sequence stratigraphic techniques.

The Sirat Prospect, in the Natih Formation of Oman, has been the focus of intensive seismic and geological modelling. This formation consists of stacked limestone cycles separated by relatively thin shaly beds. The depositional environment of the Natih Formation has varied from deep water shales, with characteristic marine fossils such as ostracods and planktonic foraminifera, to very shallow marine packstones, grainstones and rudstones with abundant larger foraminifera and rudists.

In the upper part of the Natih ‘e’ Member a number of sedimentary lobes developed (figure 1.20). These prograded from the shallowest parts of the shelf, building out to deeper water at the edge of the shelf. Maximum water depth during this progradation was probably no more than 100 m.

Each lobe contains a cycle of rock types changing from deep water deposits at the base to shallow sediments at the top.

Sequence stratigraphy attempts to classify sediments and sedimentary packages by their relationships to changing sea levels (rise, fall, rate of change) for local and worldwide (eustatic) changes. This allows us to define different packages or sequences consisting of a Transgressive Systems Tract (TST), a Highstand Systems Tract (HST) and, in deeper areas, a Lowstand Systems Tract (LST). Sequences are separated by sequence boundaries (SBs) created by sea-level fall. During times of maximum rate of sea-level rise, a Maximum Flooding Surface (MFS) is deposited. Sequences with their systems tracts and surfaces can all be recognized on seismic lines, giving vital clues to the structure and likely composition of sediments. Micropalaeontology provides important, additional information about the sequences.

Sequences are ranked, according to their importance and the type of changes which they represent. The 1st-order sequence boundary is more important than a 2nd-order boundary and so on.

The cyclic response from the Gamma-Ray log has been used to define two 2nd-order sequences (Sequence I and II) and a number of smaller 3rd-order sequences (figure 1.21). The top of the Natih ‘e’ Member is identified as an important sequence boundary. The shorter period cyclicity defines the various members (a - g) which constitute the Natih Formation. In shallow areas only the TST and the HST are present. In the basin at the southwestern end of the seismic section (figures 1.20 and 1.21) a LST developed.

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*Fig. 1.20: This seismic line shows the facies changes which occur across the platform edge and into the basin. The sedimentary lobes developed during the High Stand Systems Tract (HST) of the Natih ‘e’ Member are remarkably clear on this seismic section. During this period of high and stable sea level sediment was prograding from the NE towards the SW. This sedimentation was terminated by a sea level drop, creating a sequence boundary (SB).*

Fig 1.21: Sequence stratigraphic analysis of the area revealed two 2nd-order sequences (Sequence I and Sequence II) and a number of 3rd-order sequences. Two maximum flooding surfaces have been identified and the top of the ‘e’ Member is an important sequence boundary. By correlating seismic lines with this analytical approach to sedimentary structures, experts can assess the structural history of the area and determine the risks associated with any given prospect.

The sequence stratigraphic reconstruction has a number of implications for the prospectivity of the Sirat structure. The prograding lobes of Sequence I, as seen on the seismic section, contain excellent reservoirs. Porosity and reservoir permeability were enhanced by the exposure of the sediments which occurred during low sea level phases. This reservoir quality, coupled with the clear images available using seismic technology, suggest that this would be an excellent prospect. However the sediments at the top of the Natih ‘e’ level were deposited in a shallow environment and are of poor sealing quality, thereby downgrading the prospect.

LST deposits are present but will probably be low value reservoirs. These sediments normally contain a high proportion of fine clastic sediment which would reduce porosity. In addition, the absence of rudist fragments suggests that initial porosity was low.

The study concluded that despite the excellent reservoir qualities of the HST lobes, the limited sealing capacity of overlying sediments made development of the Sirat Prospect a high-risk project. A further conclusion from the study was that sequence stratigraphic methods could be used to reconstruct the detailed sedimentary history of the area and to predict the character of the rocks in the sequence.

Three important reflectors relating to the sequence stratigraphy can be seen on the seismic line:
- the maximum flooding surface of Sequence I (basal ‘e’ Member)
- the sequence boundary between I and II (near top of ‘e’ Member)
- the maximum flooding surface of Sequence II.

The seismic view

Explorationists integrated seismic lines with well data in the sequence stratigraphic model, to reconstruct the depositional environment of the Sirat Prospect.
- Deep water sediments occur around the maximum flooding surface. The relatively deep limestone-shale alternations are represented by a ‘reflective’ seismic facies containing a number of continuous, high-amplitude reflectors.
- The rudist accumulations are sometimes visible as high-amplitude discontinuous reflectors.
- Thick deposits of shallow marine carbonates appear as low amplitude ‘transparent’ seismic facies.
**Cyclic sequences**

The Middle Cretaceous is one of the main hydrocarbon producing horizons in Oman and offshore Dubai. Sediments such as the Middle Cretaceous Natih Formation were part of a Mesozoic platform carbonate succession, accumulating around intrashelf depressions on the eastern edge of the Arabian peninsula. To the north west, in the Emirates, the equivalent reservoir rocks are known as the Mishrif Formation (figure 1.22). Elf has recently discovered oil in the same formation offshore Qatar.

The Natih limestones are separated from the deeper Shuaiba reservoir carbonates by the Nahr Umr Shale. This, and the Fiqa Shale which overlies the Natih Formation, act as regional seals. The Natih Formation is cyclic, comprising a succession of coarsening-upward sequences. Each cycle consists of deep marine shales and mudstones grading up to shallow marine rudist packstones and grainstones. Emergence surfaces occur at the top of each cycle. The cyclic sequence was caused by eustatic sea level changes, although it appears that deposition of the Natih Formation was halted by tectonic uplift.

Away from the local highs, typified by shallow water deposits, the limestones interfinger with two deeper marine shales. These have significant organic content and a rich fauna of planktonic foraminifera. The cycles have formed the basis of a scheme of subdivisions (members labelled ‘a’ to ‘g’) for the Natih Formation.

Regional uplift during the Jurassic effectively reduced average sea level and led to the deposition of evaporites over much of the Arabian carbonate platform. In some areas uplift raised the sediment above sea level and there is evidence of subaerial erosion. Compression, as the Arabian and Eurasian plates were forced together, caused rapid subsidence along the plate boundaries. This was followed by the spread of transgressive seas across the Arabian platform (figure 1.23).

On two more occasions during the Cretaceous, uplift pushed topographic highs to a position where they were eroded. Both phases were followed by rapid subsidence and shale deposition. The transgressive seas which developed after these events became areas of deposition for the three main carbonate megasequences which cover northeastern Arabia namely: the Thamama/Kahmah, Wasia and Aruma groups. Each megasequence contains numerous depositional cycles (3rd-order or parasequences) related to small-scale sea level fluctuations.

Understanding the cycles, and defining which areas were most suitable for reef and shoal development, is an essential part of the interpretation. These depositional factors control the nature and location of the Cretaceous carbonate reservoirs.

The best reservoirs are generally found in the upper part of each megasequence. This is due to upward shallowing, the abundance of coarse grain carbonate particles, leaching caused by subaerial exposure and the presence of particularly effective seals immediately above the uppermost carbonate units in each megasequence.

**Fig. 1.22: TIME ZONES:** The study of rudist assemblages and the discovery of ammonites within the Natih Formation have provided a precise correlation of time lines within the sequence. Correlation between outcrop sections allowed explorationists to develop a conceptual sequence stratigraphic model which includes the subdivisions (‘a’ to ‘g’) used in subsurface studies.

**Fig. 1.23: PRIME SITES:** The best locations for rudist buildups were in the shelf setting as shown in this Middle Cretaceous map of The Gulf area.
Mishrif reservoirs

Rudist reefal-shoaling deposits comprising the Cretaceous Mishrif Formation, which is partially equivalent to the Natih Formations of Oman, are the major reservoirs in many fields in Dubai and eastern Abu Dhabi. The domal Fateh Field is the largest offshore Mishrif-age field in the Emirates. It was discovered in 1966, despite the absence of Mishrif rocks from the discovery well - the result of pronounced post-Cenomanian erosion on the crest of the structure. Typical structures and fabrics from wells in Fateh Field are shown in figures 1.24 to 1.27.

Other fields in the region, including the Shah Field in Abu Dhabi and the Awali Field in Bahrain, are characterized by erosion of Mishrif and equivalent rocks.

Fluid inclusion data, maturation calculations and burial history modelling indicate that cementation by blocky calcite crystals and oil migration happened about the same time, between the Late Miocene and Early Eocene. The Khatiyah Shale, which lies directly beneath the Mishrif, is believed to be the major source rock for these reservoirs.

A number of depositional cycles, locally bounded by erosional unconformities, have been identified by geologists of the Dubai Petroleum Company. These unconformities are believed to have been caused by global sea-level fluctuations and uplift of the deep, Eocambrian Hormuz Salt.

The combination of sea level fall and uplift probably led to the development of new, tectonically-controlled islands and erosion of these structures. Anticlinal fold belts and deep-seated salt deposits were raised to the surface of the Cretaceous sea which covered much of the Middle East. Having reached the surface, they were subjected to the mixing of fresh water and marine water. The results of this mixing process can be seen along the mountain fronts from Turkey to Oman.

Subsequent transgression over the subaerially exposed islands was associated with deposition of the Laffan Shales which seals the Mishrif and other, slightly younger, Cretaceous reservoirs.
Evaluating variation

Examination of drill cuttings, core and well logs reveals the vertical variation in carbonate reservoir sequences. Integrated studies of reservoir behaviour, particularly when these involve major waterflood projects, highlight the lateral variations present in all reservoirs. In some giant and supergiant reservoirs understanding the lateral variations has not been a priority. These variations were not considered a problem since the flow rates were outstandingly high and standard porosity well logs suggested lateral variations were not significant.

In addition to the hidden complexities in some major reservoir zones, there are many zones with lower reservoir potential, whose development has been delayed until now. These include chalky, high-porosity but low-permeability zones such as the Haifa and certain Thamama reservoirs. These zones must be appraised carefully and new techniques have emerged to meet the challenge. Recent 3D seismic surveys have indicated many more faults than previously seen, and 3D borehole imagery in highly deviated and horizontal wells is providing a wealth of fracture data.

The role of fractures, either helping or hindering oil production, has been examined in detail (Middle East Well Evaluation Review, Number 14) and this knowledge can be applied where fracturing affects the reservoir zones. Careful interpretation and integration of results indicates that many of the simple structures mapped over Gulf salt domes and in fold-belt anticlinal reservoirs are actually more complicated than early models suggested. On a more positive note, better models of complex structures should reveal oil-filled reservoir compartments and reservoir facies on the flanks of existing fields. This will offer new exploration opportunities.

First stop - secondary porosity

Secondary porosity is not of secondary importance in reservoirs. In fact this type of porosity, created after the reservoir rock has been buried, has often proved the most difficult to quantify and the most important for reservoir development.

Secondary porosity has caused problems in the majority of carbonate reservoirs. Even the biggest grainstone reservoirs, with intergranular porosity similar to that found in sandstone, can exhibit a surprising range of secondary porosity. This is often developed in the form of intercrystalline pores, vugs, moulds of leached shell material and micropores which may be no more than a few microns in diameter.

The abundance of micropores makes carbonates difficult to evaluate accurately. They are not visible to the naked eye, or even under a standard microscope. The very high magnifications possible with a scanning electron microscope (SEM) are usually necessary for accurate estimates of secondary porosity. The size of the micropores means they are generally filled with non-moveable water, while larger pores in the same rock contain varying proportions of water and oil. Consequently, it is possible to produce oil, without water cut, from a carbonate reservoir interval which contains more than 50% water.

Many new techniques are available for micropore imaging. Dielectric measurements, nuclear magnetic resonance and Stoneley wave sonic energy have been introduced in recent years. At the same time, computer modelling of 3D borehole electrical imagery is improving the definition of large vugs and moulds which characterize some reservoirs.

Going for the vuggy

Carbonate research projects indicate that evaluating porosity is difficult but determining permeability is impossible in the presence of large vugs and moulds (figure 1.28) - even when whole diameter cores are used. Ehrlich, in his studies of carbonate permeability, concluded that no core would be large enough to represent the full extent of interconnection in the pore system. Thus, whole diameter core or analysis of 3D borehole images must be verified using down hole well testing techniques or drill stem tests. This approach is the only way to improve our understanding of large scale interconnectivity and producibility in vuggy zones.

Recently, researchers (McNamara et al. 1991) at the University of Calgary, Canada found that porosity defined by core analysis alone could be 30% lower than the actual value (figure 1.29). However, such errors in evaluating vuggy or mouldic porosity are unavoidable in cases where the size of the vugs is comparable with core diameter.
Detecting vugs and moulds

The petroleum industry devotes a lot of time to mould and vug evaluation (figures 1.30 and 1.31). However, strict definitions of moulds and vugs are often ignored and using the two terms synonymously can lead to confusion.

Moulds are pores formed by the selective removal, normally by solution, of an existing rock particle such as a shell fragment, crystal or grain. The resulting porosity is referred to as mouldic porosity and is described according to the type of particle removed; e.g. oomouldic for an oolitic rock where ooids have been dissolved.

If the leaching of the original particle goes beyond the point at which it can be identified the hole is referred to as a vug (figure 1.32). The condition of the hole, not its size, determines whether it is a mould or a vug.

The authors of the basic reference on carbonate porosity, Philip Choquette and Lloyd Pray, suggested that a vug which is large enough to be examined from the inside should be referred to as a cave. They also defined micropores as those which have a diameter or cross-section which averages less than 1/16 mm whether the pores are equidimensional, platy or tabular.

The full capabilities of the Modular Dynamic Tester (MDT)* tool include the definition of vuggy reservoir zones which cannot be characterized by core or borehole imagery even when combined with other well logs. Even the RFT tool has limited applications for vuggy intervals. Tests often fail due to lack of seal or the presence of a tight patch resulting in a dry test. Fractures in low porosity patches further complicate the situation. However, the MDT tool has inflatable packers which can be placed above and below the vuggy zone to isolate it. The zone can be defined by FMI/FMS tools or core data.

While testing vuggy zones the MDT tool can be configured to include a conventional probe and an inflatable packer module. The tool can then provide probe measurements, and allows the operator to use the inflatable packers when a seal is not possible in the best fractured or vuggy interval.

The MDT tool’s pumpout module can be used for the dual packer approach which often succeeds where RFT attempts fail. Packer spacing can be set to match the small intervals defined in FMI/FMS (or UBI in oil-base muds) or core data, to a minimum of 3 ft. This minimum size actually provides a surface area thousands of times greater than the standard RFT or MDT probe. In this respect it can be thought of as a small-scale DST-type test which provides a pressure buildup with a radius of investigation just under 100 ft into the formation. This figure varies with the pore system in the formation.
Evaluation of isolated zones is normally achieved by pressure tests. However, fluid samples for evaluation can be taken from vuggy zones or even low permeability or thin bed intervals. This benefit is derived from the large seal and sample area created by the dual packers. Tough sampling situations require use of the MDT tool’s pumpout module, fluid analyzer and sample throttling; an approach which relies on the tool’s modular design.

Since pressure and fluid content read-out is done at the surface, the test need only continue until the formation fluid is detected. This appears after the flow of drilling fluid which invaded the formation has been pumped out. This type of arrangement can replace the more expensive drill stem test and offers a high degree of safety. The MDT tool has been used for production testing for wells with high hydrogen sulphide (H₂S) concentrations.

Revealing reservoir permeability

Measured slowness, derived from low frequency Stoneley waves, can be used to evaluate the permeability of hydrocarbon reservoirs. At low frequencies the Stoneley wave produces fluid flow which is related to the connectivity of pore space. By comparing observed slowness with elastic slowness computed for a formation with no fluids we can calculate permeability (figure 1.33). Elastic slowness is calculated using three factors which have a direct effect on Stoneley wave propagation: formation density, borehole fluid density and shear slowness.

Stoneley attenuation provides an alternative to permeability estimates based on slowness. In permeable formations Stoneley waves are attenuated by fluid moving in the pore space (figure 1.34) to a degree proportional to fluid mobility in the formation. From this value engineers can derive the quality factor, Q (inverse attenuation), which is directly related to reservoir permeability. The calculation used to derive permeability from the quality factor involves values for pore fluid and bulk elastic moduli, and for porosity and borehole diameter.

The technique was tested on a dataset collected from a high porosity, pure carbonate reservoir in Saudi Arabia. The slowness and attenuation techniques were applied to data gathered using a Dipole Shear Sonic Imager (DSI*) tool. The predicted permeability was modified to simulate a synthetic flowmeter profile. Agreement between slowness-derived permeability and the flowmeter profile was very good.

Thick deposits of shallow marine carbonates appear as low-amplitude ‘transparent’ seismic facies.
Imagery + Stoneley analysis + OH Logs Reservoir data for well testing strategy and optimum MDT tool configuration

(FMI) (DSI) (ELAN) (UBI) Lithology (ARI) Porosity Saturation

**Permeability progress**

Permeability measurements in carbonate reservoirs present a major challenge to well logging analysts. A group of expert analysts and geophysicists in Dubai, Abu Dhabi, Egypt, Saudi Arabia and at the Oil and Natural Gas Commission (ONGC)-Schlumberger Joint Research Council in India, have tested carbonate reservoir permeability using Stoneley wave data. Present efforts are concentrated on sample analysis and Stoneley frequency using the DSI tool which samples at lower frequencies than the earlier Array Sonic tool (figure 1.35).

The permeabilities found in shoaling sequences, where coarse particles overlie fine chalky facies with micropore systems, have been characterized using the DSI tool. The tool has also found success in reservoirs where there are a variety of secondary porosity types.

RFT tool permeability data can be used to calibrate permeability profiles defined by Stoneley wave data. In the example, core permeability data from one inch diameter plugs, taken at one foot intervals, compare favourably with the DSI tool and RFT tool profiles. However, in carbonate reservoirs where the pore system is heterogeneous, the match is often poor, despite accurate permeability measurements.

This situation typically arises when each measurement relates to a different rock volume. Whole core analysis is recommended for permeability characterization in the heterogeneous pore systems found in many carbonate reservoirs.

The MDT tool has already succeeded in defining pressure, permeability and fluid content within complex carbonate reservoirs in the Middle East. The tool’s modular design allows the operator to select the optimum configuration for each task (figure 1.36). The MDT tool is reliable in challenging reservoirs, such as those where permeability ranges from hundreds of millidarcies to hundredths of a millidarcy. To devise a high-quality MDT tool test we require information from several sources (e.g. electrical imagery and Stoneley). Only by combining data from several sources can we be sure of maximizing test efficiency.

**Fig. 1.35**: At low frequencies the Stoneley wave produces fluid flow which is related to the connectivity of pore space (permeability). This plot shows the sensitivity of Stoneley slowness to frequency - in the range measured by the DSI tool - for a water-saturated sandstone. From Cheung and Liu (1988).

**Fig. 1.36**: The MDT tool can define pressure, permeability and fluid content within complex carbonate reservoirs. The tool’s modular design allows the operator to select the optimum configuration for each task. The MDT tool is reliable in reservoirs, where permeability ranges from hundreds of millidarcies to hundredths of a millidarcy.

**Fig. 1.37**: The main types of carbonate porosity heterogeneity revealed by borehole imagery.
Chemical timing

Geochemistry is finding new applications as a tool for explorationists and reservoir analysts. A few years ago, most geochemical surveys were directed at identifying source rock. This led to new applications in maturation and migration studies. Today, laboratories are using petroleum geochemistry to tackle reservoir problems such as assessing heterogeneity.

Geochemical methods include determining ‘biomarkers’ in a sequence and then using isotopes to ‘fingerprint’ different oils present in a reservoir. Recent studies have investigated hydrocarbon variation within reservoirs and clarified the extent of compartmentalization caused by tar mats, shale barriers and sealing faults. This data is vital in establishing models for development and production phases.

Rock geochemistry is especially useful where the reservoir rocks are not composed of the usual quartz, limestone or dolomite lithologies on which log interpretations are based. Problems can even arise where mixtures of these basic lithologies are being investigated for basic formation evaluation. This has encouraged the spread of geochemical well logging and core studies.

Well-to-well correlation can be enhanced by applying geochemical techniques to core or well log data. In this way, we can identify geochemical variations in major lithologies or the presence of minor minerals in adjacent wells.

Log analysts who routinely use the lithology indications from density/neutron variations in simple lithology mixtures are defining lithology by comparing a single element, hydrogen, to the bulk density of the formation. Interpretations from geochemical logs are based on much more information.

At present, the gamma ray log is most widely used for correlation in carbonate sequences: the elements identified are uranium (U) thorium (Th) and carbon (C). Geochemical logging analyses use a further nine elements for correlation.

Ocean chemistry

Ocean chemistry influences the composition of minerals being deposited on the sea floor. However, the chemical composition of the oceans varies through time and these variations control mineral stability. Ocean chemistry is crucial in determining the proportions of aragonite or calcite present on the sea bed and, consequently, in the accumulated sediment which reservoirs contain. This proportion influences ultimate reservoir porosity and permeability.

Weighing the evidence

Isotopes are atoms of the same element having different numbers of neutrons in the nucleus and, therefore, different atomic weights. The weight difference is important, and useful, because natural processes such as evaporation, condensation and photosynthesis cause significant variations in the distribution of isotopes within the various geochemical cycles.

For example, the light oxygen isotope, $^1$H$^16$O, is concentrated in water vapour when seawater evaporates. The $^1$H$^16$O-enriched vapour travels through the atmosphere towards the poles where it condenses and is incorporated in the polar ice sheets. The differential evaporation of oxygen atoms which occurs at the equator means that the $^1$H$^16$O / $^1$H$^18$O ratio in polar ice caps is much lower than in sea-

Fig. 1.38: NAME THE DATE. This simplified curve for global Sr isotope ratios in seawater illustrates the principle of the isotopic dating methods. For a known $^{87}Sr/^{86}Sr$ ratio a vertical line can be drawn. Wherever this line crosses the curve, the sample ratio matches the seawater ratio for that particular time. However, some isotopic ratio values occur at two or more places in the curve. When this happens age must be defined by alternative dating methods.

Fig. 1.39: This series of logs (a) from the Upper Jurassic shows the Asab Oolite at well A. Strontium isotope dating indicates that rocks of the same age are also found in well B, but have been lost from the sequence at well C to the north east. The unconformable contact between the Jurassic and Cretaceous beds in the third well marks a period of erosion or non-deposition. Core taken from this level (b) confirms the unconformity.
These stable isotope ratios have varied systematically over time and can, therefore, be used to date rock samples and correlate sequences. The stable isotopic ratios of strontium (Sr) and sulphur (S) are used in chronostratigraphic studies, confirming time gaps at unconformities and determining sedimentation rates. They can even be used to date diagenetic events such as dolomitization.

The principle of strontium dating relies on changes in $^{87}$Sr/$^{86}$Sr through time and the assumption that the ratio within seawater is uniform worldwide at any given time. Seawater curves for strontium ratios have been plotted and calibrated against the geological time scale (figure 1.38). This was done by analyzing the Sr isotope ratio in carbonate and phosphate from fossils of known ages.

Strontium dating, and correlations based on strontium ratios, can be used when there are few fossils and when biostratigraphic zonation is poor. Independent of facies and fossil occurrence, this technique can even be used to date evaporite sequences. Very small samples are required (as little as 0.1 mg) to provide a reliable age, with uncertainty normally being ±1 million years, or less. The technique can be applied worldwide and, unlike fossil correlations, is completely objective.

While the benefits of this technique are obvious, there are some limitations. Weathering affects all isotopic systems, and Sr isotope ratios can be modified by contamination from meteoric / mixing and Sr isotope ratios can be modified by weathering affects all isotopic systems, and Sr isotope ratios can be modified by contamination from meteoric / mixing. Depending on the modifying mechanism, the $^{87}$Sr/$^{86}$Sr ratios can be shifted towards values typical of younger, or older, rocks. If unaltered carbonate samples are not available for Sr isotope studies then adjustments must be made to account for sample impurities.

Brachiopods and belemnites, with their low-magnesium calcite skeletons, are little affected by diagenesis and the best samples come from these and from the phosphates which make up fish and conodont fossils. Whole rock samples, with the exception of anhydrites, usually give less accurate dates since their $^{87}$Sr/$^{86}$Sr ratios have frequently been altered by diagenetic processes.

The final problem occurs when one $^{87}$Sr/$^{86}$Sr value corresponds with two or more ages in the seawater curve. Ratios recorded from rocks in the Kimmeridgian have the same $^{87}$Sr/$^{86}$Sr ratio as found in Bajocian rocks which are 10 M years older. This problem occurs on both large and small scales throughout the geological record. Isotope values recorded in the Upper Permian can be identical to those in Cretaceous rocks, although there is less chance of confusion between these units. Matching the isotope ratio to a position on the curve is normally a problem only if the age of the sample layer is very poorly constrained.

In 1991, the Abu Dhabi Company for Onshore Oil Operations (ADCO) carried out an isotopic pilot study to resolve some of the uncertainties in Jurassic stratigraphy. Early results were encouraging and the study expanded. Today, the database consists of Sr isotope analyses from ooid grainstones, belemnites, lime mudstones, anhydrites and bivalves.

Sr dating has provided evidence of a direct stratigraphic correlation between the pelagic transgressive belemnite lag deposit and the unconformity (a type II sequence boundary) of the Jurassic-Cretaceous contact and the intraclassic belemnite horizon in the Asab Oolite (figure 1.39a and b). This type of geochronological correlation has helped to refine regional stratigraphy. For example, anhydrites which had been included in the lowermost Cretaceous Habshan Formation, were re-assigned to the Upper Jurassic while the Manifa Member (150.5 M years) was correlated with the Asab Formation (151.2 M years) and with the lateral equivalent Qatar Formation (150.5 M years) using this technique.

A new logging technique (figure 1.40) which relies on reversals of the Earth’s magnetic field through geological time, has proved very successful for cross-well correlation. Rocks can retain the magnetization from previous magnetic fields, a phenomenon called natural remanent magnetism (NRM). The magnetic field through geological time, has proved very successful for cross-well correlation. Rocks can retain the magnetization from previous magnetic fields, a phenomenon called natural remanent magnetism (NRM). The logging techniques which record this magnetic ‘memory’ are very accurate and can be used worldwide. Absolute age correlations derived from reversals have been made between three wells drilled by Total in the Jurassic sediments of the