This paper reports on the sedimentology and stratigraphy of the mid-Cretaceous Mishrif Formation, one of the principal carbonate reservoirs in Central and Southern Iraq. The Cenomanian Mahilban, Maotsi and Fahad Carbonate Formations of Central Iraq are the lateral chronostratigraphical equivalents of the Mishrif and underlying Rumaila Formations of Southern Iraq. Together, these units represent a single mid-Cretaceous carbonate succession in the Mesopotamian Basin.

The Mishrif Formation in Central Iraq reflects the continuous deposition of shallow-shelf carbonates; periodic rises in sea level led to episodes of deeper-water sedimentation, during which the outer-shelf and basinal deposits of the Rumaila Formation were laid down. A ramped platform was the principal depositional setting for the entire Cenomanian-early Turonian carbonate succession.

The best reservoir conditions in the Mishrif Formation occur in rudist-bearing facies, such as rudstones and rudistid packstone/grainstones. Reservoir units are characterised by porosities of >20% and by permeabilities of 100 mD to 1 Darcy. Other carbonate facies, such as pelagic mudstone/wackestones, bioclastic wackestones and peloidal packstones, are less significant as reservoir rocks. All the carbonates were affected by a range of diagenetic processes, among which dissolution and dolomitization led to the formation of secondary porosity; porosity was reduced by compaction, stylolitization, micritisation, neomorphism and cementation.

The Mishrif Formation is divisible by a prominent unconformity into two large-scale regressive sequences, which are particularly distinguishable in the east of the Mesopotamian Basin. Multiple reservoir units are present in both sequences. The west of the basin is

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The shallow-water reservoir units in the east of the basin are thick, reflecting relatively high subsidence rates throughout the Cenomanian (e.g. in the Amara oilfield and nearby areas). Subsidence rates in the western side of the basin were lower, and reservoir units are thinner and more limited. The Mishrif Formation carbonates wedge-out in the western and SW deserts of Iraq.

INTRODUCTION

The Mishrif Formation of Cenomanian-early Turonian age includes rudist-bearing units which are important reservoir rocks throughout the Middle East (Al-Khersan, 1975; Reulet, 1982; Harris and Frost, 1984; Videtic et al., 1988; Alsharhan and Nairn, 1988 and 1993; Burchette, 1993; Alsharhan, 1995). In Central and Southern Iraq, the formation provides the reservoir in oilfields such as Buzurgan, Amara, Halfaya Majnoon, Rumaila, West Qurnah and Nasiriyya. These carbonates contain up to 40% of Cretaceous oil reserves in Iraq, and about 30% of total Iraqi oil reserves (Al-Sakini, 1992).

The Mishrif Formation has been studied in many oilfields in Central and Southern Iraq over the last two decades by both oil companies and individual researchers (Gaddo, 1971; Al-Khersan, 1975; Sherwani, 1983; Al-Rikabi et al., 1987; Kareem et al., 1988; Aqrawi et al., 1988). However, much of this work has been in the form of internal reports and little has been published. The object of this paper is to review the sedimentology and regional stratigraphy of the Mishrif Formation in the oilfields of Central and Southern Iraq (Fig. 1), and to define the petrology, depositional and diagenetic history, and reservoir quality of this important reservoir sequence.

The Mishrif Formation, part of the Wasia Group (Alsharhan and Nairn, 1988), is a carbonate succession widespread throughout the Arabian Gulf. It was deposited on the passive margin which existed in the east of the Arabian Craton throughout much of the Mesozoic. This passive margin was generally covered by shallow waters; however, a number of deeper-water intra-shelf basins had been formed during the Cretaceous (Murris, 1980). Rudist-bearing units in the Mishrif Formation were deposited in carbonate ramps and low-gradient shelves which rimmed these basinal areas (Burchette, 1993). The Mesopotamian Basin occupies most of SE and Central Iraq (Fig. 2a). It is bounded by the Abu Jir fault zone to the west and SW, the Zagros Mountains to the east, and the Hamrin Mountains to the NE (Figs. 2a and b). Tectonically, it is located mainly on the Mesopotamian block and adjacent parts of other blocks to the NW and SE (Fig. 2b).

Materials and Methods

More than 40 boreholes in Central and Southern Iraq were studied (Fig. 1). About 400 core samples were described, in addition to more than 200 cuttings samples. Thin-sections of core and cuttings samples, together with several hundred thin-sections previously prepared by the Iraq Oil Exploration Co. (OEC), were studied petrographically. X-ray powder diffraction analysis (to determine the mineral composition) and scanning electron microscopy (to study microfabrics and micrite crystallography) were also applied to a number of samples. Additional lithological information was provided by Spontaneous Potential (SP), Sonic (S) and Gamma-Ray (GR) logs.

MID-CRETACEOUS STRATIGRAPHY IN CENTRAL AND SOUTHERN IRAQ

The Cretaceous sequence in the Middle East is usually divided into three parts, due to the existence of two regional intra-Cretaceous unconformities of late Aptian (or early Albian) and early Turonian ages (Harris et al., 1984). The mid-Cretaceous (early Albian-early Turonian) sequence in the Mesopotamian Basin of Southern and Central Iraq consists of two sedimentary cycles (Buday, 1980). The older cycle, of early Albian -
Fig. 1. Map of South and Central Iraq with the location of the boreholes studied. Profile of the fence-diagram in Fig. 8 is marked, as is the line of Fig. 12 on which wells AAm-I (Fig. 9), Ns-1 (Fig. 10) and Hf-1 (Fig. 11) are located.
early Cenomanian age, includes the Nahr Umr and Mauddud Formations and their equivalents. The upper (Cenomanian-early Turonian) cycle in the Mesopotamian Basin begins with the transgressive Ahmadi Shale Formation, overlain by the chalky/marly limestones of the Rumaila Formation. These grade upwards into the regressive Mishrif Formation (middle Cenomanian-early Turonian), which in turn grades up into the Kifil Formation evaporites in a number of oilfields in the west of the basin (Fuloria, 1976) (e.g. the Kifil and Afaq areas; boreholes Kf-1 and Aq-1 in Fig. 1).

The Mishrif and underlying Rumaila Formations were originally described in southern Iraq by Rabanit (1952) in Well Zubair No. 3 at the Zubair oilfield. This well was later chosen by Owen and Nasr (1958) as the type section for these two (and many other) Cretaceous formations in southern Iraq (Dunnington, 1959). However, a very limited amount of data has been preserved about this type section. Aqrawi (1983) suggested an additional type section for the Rumaila Formation in Well Zb-13 at the Zubair field, while Sherwani (1983) described the Mishrif Formation in detail from cores at Well WQ-1 (West Qurnah oilfield) (Fig. 3).
Fig. 2b. Basement tectonic framework of Iraq (compiled from Buday and Jassim, 1987). The basement is divided into blocks and sub-blocks by a series of major lineaments striking NW-SE and NE-SW, which subdivide the main zones and subzones. The basement beneath the Mesopotamian Basin includes the Euphrates, Tigris and Zubair sub-zones of the Mesopotamian Block.

The contact between the Mishrif and Rumaila Formations is gradational (Aqrawi, 1983), as is the contact between the Mishrif and Kifil Formations. However, in many oilfields (such as West Qurnah: Fig. 3), the Mishrif Formation is unconformably overlain by the Khasib Formation where the Kifil Formation is absent (Dunnington, 1959; Sherwani, 1983; Aqrawi, 1996). The lower contact of the Rumaila Formation can be recognised clearly on gamma-ray logs by the appearance of the black, fissile shales of the underlying Ahmadi Formation.

The Mishrif Formation is encountered in most oilfields in Central Iraq as far north as the Hamrin Mountains and throughout SE Iraq. The thickness of the formation varies according to the location within the Mesopotamian Basin (Fig. 4). It reaches a thickness of about 350 or 400m in SE Iraq (Al-Siddiki, 1978) (the Amara, Halfaya, Majnoon and Buzurgan oilfields near the Iranian border: boreholes Am-1, Hv-1, Mj-1 and Bu-1, respectively); and thins or wedges out in the west and SW (for example, at Shawiyah and Ghalaisan: boreholes Sw-1 and Gh-1).
Petrography of the Mishrif Formation

The carbonates of the Mishrif Formation in Southern Iraq consist of micrite and various skeletal grains such as foraminifera (of different sizes), echinodermal plates, ostracods and the shells of molluscs (mainly rudists). Non-skeletal components are restricted to peloids, intraclasts and ooids, and are less abundant.
Skeletal grains

Planktonic foraminifera are common, but are mainly restricted to the outer-shelf depositional units (Fig. 5a). *Hedbergella washiensis*, *Hetrohelix globulus* and various Oligosteginids are the dominant planktonic forms, and are very common in the lower parts of the Mishrif Formation which rests gradationally on the underlying Rumaila Formation (Ahmed, 1979; Aqrawi and Khaiwka, 1986 and 1989). These planktonic faunal assemblages are usually interpreted to indicate a low-energy, open-marine, outer-shelf depositional environment below wave-base (Flugel, 1982).

Benthic foraminifera of various sizes (Fig. 5b) are the most common skeletal grains in the Mishrif Formation, particularly in inner-shelf depositional units. Alveolinids such as *Praealveolina*, *Dicyclina*, *Ovalveolina* and *Alveolina* are dominant, whereas *Anomalina*, *Nezzazata*, *Textularia* and Miliolids are less common. Most of the benthonic foraminifera were complete, but were usually highly altered by diagenesis, making them difficult to identify.

Other bioclasts included shell fragments (Fig. 6a), echinoderm plates (Fig. 6b), ostracods, coral and algal fragments, sponge spicules and brachiopods. Rudists (Fig. 5d) are the most important mollusc fragments, and occur either in a distinct rudstone facies or a rudistid packstone/grainstone, or rarely (with other grains) in bioclastic wackestones and packstones. Rudists are good environmental indicators, and are interpreted to indicate patch-reef and fore-reef slope settings (Wilson, 1975; Flugel, 1982: Tucker and Wright, 1990).
Fig. 5. Photomicrographs of microfacies in the carbonates of the Mishrif Formation.
a. pelagic mudstone/wackestone with planktonic foraminifera; b. bioclastic wackestone (note the leached bioclasts which have been partially cemented by calcite cement); c. peloidal packstone (note the large intraclast); d. rudstone with compacted rudist fragments (note dissolution surfaces with oil residue).

Scale-bar is 1-mm long. All photomicrographs are under ppl.

Non-skeletal grains

Peloids are the main non-skeletal grains in the Mishrif Formation (Fig. 5c), and range in size from silt to sand grade. Some peloids are probably micritized ooids; ooids were recorded in the Mishrif Formation in Southern Iraq by Al-Khersan (1975) and Sherwani (1983). Peloids occur in packstones and wackestones, and are characteristic of shoal and subtidal environments, respectively (Flugel, 1982; Tucker and Wright, 1990).

Intraclasts are less common than peloids (Fig. 5c) and are present in low percentages in peloidal and bioclastic wackestones and packstones. Intraclasts are interpreted to be reworked grains within the subtidal and intertidal parts of the Mesopotamian Basin arising from current agitation.

Micrite

In most of the boreholes studied, the Mishrif Formation carbonates are mainly composed of mud-supported fabrics such as lime mudstones and wackestones (Figs. 5a and 5b). In some eastern oilfields such as Amara, however, grain-supported fabrics are dominant. Lime muds dominate matrix-supported limestones such as pelagic and dolomitic mudstones. Micrite in the Mishrif Formation is microcrystalline, and is generally neomorphosed to microspar and rarely to pseudospar.
DEPOSITIONAL MICROFACIES

The Mishrif Formation carbonates were classified following Dunham's (1962) classification (modified by Embry and Klovan, 1971) into mud- or grain-supported textural types. Each type consists of three principal microfacies, as follows:

**Mud-supported microfacies**

(i) *Pelagic mudstone/wackestone*

This microfacies occurs at various levels throughout the sections studied, but was particularly common in the lower parts. Micrite is the main component (Fig. 5a), but planktonic foraminifera also occur (mostly oligosteginids or calcispheres, *Heterohelix*, *Hedbergella washitensis*, etc.) in various proportions usually less than 50%. This microfacies dominates the underlying Rumaila Formation (Aqrawi, 1983; Aqrawi and Khaiwka, 1986 and 1989). Pelagic lime mudstone/wackestones are usually interpreted as outer-shelf or basinal deposits (Wilson, 1975).
(ii) **Bioclastic wackestone**

Bioclastic wackestones comprise one of the most common microfacies in the Mishrif Formation carbonates (Fig. 5b), and may locally be dominated by a specific type of bioclast at various levels within the succession. Bioclasts (such as Praealveolinids, algae and echinoderms) comprise between 10 and \(<50\%\) of the lithology, and limited pelagic foraminifera also occur. The microfacies is characteristic of shallow, open-marine environments (Flugel, 1982).

(iii) **Wackestone/packstone**

Wackestones/packstones are quite common in the successions studied. Benthic foraminifera (such as Miliolids, Textularia and *Nezzazata*), sponge spicules, green algae, small mollusc fragments and echinoderms occur in this microfacies in proportions up to about 50\%. The microfacies is typical of lagoons (Flugel, 1982) or restricted subtidal zones (Reulet, 1982) with warm shallow waters and moderate circulation (Tucker, 1985).

**Grain-supported microfacies**

(i) **Peloidal packstone**

This microfacies is principally composed of peloids of various sizes, many of which have an uncertain internal structure (Fig. 5c). In addition, benthic foraminifera, rudist fragments and ostracods also occur. The microfacies is common in the upper parts of the Mishrif Formation successions studied, and is interpreted to indicate shoals and subtidal zones with moderate agitation.

(ii) **Rudistid packstone/grainstone**

This microfacies is characterised by a high content of rudist fragments, which are associated with other bioclasts such as algal débris, benthic foraminifera and peloids (in smaller proportions). It is one of the two principal reservoir facies of the Mishrif Formation. Rudist grainstones are interpreted to be a reef-bank or shoal deposit, and rudist packstones to be a back-reef deposit. Lime mud may be present in small proportions in intergranular pore spaces, indicating highly-agitated depositional conditions.

(iii) **Rudstone**

Rudstones are almost entirely composed of rudist fragments (Fig. 5d), most of which are larger than sand-grade, in addition to coral fragments of a similar size. This microfacies is interpreted to be a fore-reef slope deposit (Wilson, 1975).

The rudstones and rudistid packstone/grainstones are generally over- and underlain by subtidal and outer-shelf facies, respectively, in the boreholes studied. These two microfacies are characterised by high primary and secondary porosities and permeabilities; together, they form the most important reservoir units in the Mishrif Formation throughout the Mesopotamian Basin.

**DIAGENETIC PROCESSES**

The carbonates of the Mishrif Formation have been altered by the following diagenetic processes: micritization, compaction, dissolution, neomorphism, cementation, dolomitization, and stylolitization. These processes are described briefly in turn below.

**Micritization:** Micritized skeletal fragments are very common in the bioclastic wackestones and packstones of the Mishrif Formation. Micritization is an early diagenetic process, and skeletal grains were micritized shortly after deposition.
**Compaction**: The dominance of mud-supported fabrics in the Mishrif Formation, coupled with the thick overburden, resulted in significant compaction (e.g. Zankl, 1969). Compaction resulted in both grain alignment and the development of point/line grain contacts in packstones and grainstones, respectively. Large skeletal grains in the wackestones and mudstones may be fragmented (Fig. 6a). Compaction in muddy calcareous sediments begins soon after deposition, and increases steadily in intensity as the overburden thickens.

**Dissolution**: Early diagenetic dissolution resulted in the formation of mouldic and vuggy pores as unstable (mostly aragonitic) grains were dissolved (Fig. 6c). This enhanced the pre-existing intergranular porosity, particularly in the rudist-bearing units which are rich in aragonitic shell fragments of various sizes and types. Late diagenetic dissolution may also have occurred, providing a source for the calcite which was reprecipitated during late-phase cementation.

**Neomorphism**: Micrite matrix material is often recrystallized (Folk, 1965) leading to the inversion of aragonitic micrite to microsparite, and that of calcitic micrite to microspar. Neomorphism commonly affects mud-supported microfacies in the Mishrif Formation (Fig. 6d), and is mostly early diagenetic in origin.

**Cementation**: Three types of cements have been recognized in the carbonates of the Mishrif Formation:

(i) **Syntaxial rim cements** are common (Fig. 6b), particularly in wackestones and packstones. These are usually interpreted to be early diagenetic, and to indicate the near-surface meteoric environment (Longman 1980, 1982). This cement type is characteristic of carbonates below the unconformities which divide the Mishrif Formation into two sequences (see below).

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<th>Diagenetic Process</th>
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<td>STYLOLITIZATION</td>
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*Fig. 7. Diagenetic sequence for the Mishrif Formation in the Mesopotamian Basin.*
(ii) *Druzy mosaic cements* and (iii) *granular cements* are present in various microfacies filling inter- and intragranular pores and fractures (Figs. 5b and 6d). These cements are believed to be of later diagenetic origin, although the mosaic cement may have formed during two or more phases.

Cementation has led to occlusion of primary porosity in Mishrif Formation carbonates such as packstones and grainstones. However, dissolution is a more effective diagenetic process than cementation in most of the reservoir facies.

**Dolomitization:** Scattered, fine-grained dolomite rhombs occur within the mud-supported microfacies (Fig. 6a), and are often concentrated along stylolite surfaces. The fine grain-size of the rhombs and their occurrence within the mud-supported facies indicates their early-diagenetic origin, particularly those present within intertidal mudstones. Larger dolomitic crystals, of a clear-rimmed, cloudy-centred type probably formed during later diagenesis (Sibley, 1982) but before stylolitization. Dolomitization has slightly enhanced the reservoir quality of some of the microfacies, particularly with the formation of secondary intercrystalline micropores within muddy microfacies.

**Stylolitization:** Pressure solution has resulted in the formation of dissolution surfaces (Fig. 5d), clay seams and stylolites. Stylolites in both mud- and grain-supported microfacies took the form of horse-tail and irregular anastomosing sets (Logan and Semeniuk, 1976). Organic material, and other relatively insoluble particles (dolomite rhombs, early calcite-cemented grains, and clay particles) commonly occur on the stylolite surfaces, indicating a late-diagenetic origin.

**DIAGENETIC ENVIRONMENTS**

Carbonates of the Mishrif Formation have been affected by both early and late-stage diagenesis (Fig. 7). Mudstones and wackestones were principally altered by marine phreatic and later diagenetic processes. Diagenetic features in these microfacies include occasional pyrite crystals and borings in planktonic foraminifera, in addition to the rare occurrence of calcite cement filling skeletal grains. Cloudy-centred, clear-rimmed dolomite rhombs and stylolites indicate later, burial-diagenetic processes. These diagenetic fabrics have been reported from wackestones and mudstones in the underlying Rumaila Formation (Aqrawi, 1986).

Diagenetic features in the bioclastic wackestones, packstones, grainstones and rudstones indicate early and near-surface alteration in the meteoric phreatic and mixing zones. The dolomite rhombs in the wackestones and mudstones indicate mixing-zone diagenesis in intertidal flats, and the small size of the dolomite crystals (Badiozamani et al. 1977; Aqrawi, 1995b) may support their brackish-water origin. Syntaxial overgrowths on echinoderm plates and equant calcite cements are interpreted to be products of local meteoric phreatic diagenesis (Evamy and Shearman, 1965; Loucks, 1977; Longman, 1982). The development of mouldic, vuggy and channel porosity, particularly in rudist-bearing packstones and grainstones and rudstones, indicate a similar diagenetic environment. Near-surface, meteoric-zone diagenesis probably affected structurally-higher parts of the basin, particularly in areas where rudist-reefs had developed.

**RESERVOIR QUALITY OF THE MISHRIF FORMATION CARBONATES**

Porosities in the Mishrif Formation carbonates in Southern Iraq range up to 18% - 25% (Al-Hassan, 1979). Al-Rikabi et al. (1987) measured porosities and permeabilities throughout the Mishrif Formation at the Nasiriyya oilfield (Ns-3 Well). Here, the porosity was 1.8-27%, while the permeability was <0.01-73 mD.

High porosities (i.e. >15%) and permeabilities (i.e. >100 mD and up to 1 Darcy) are restricted to the rudist-bearing facies, which therefore constitute the main reservoir zones.
Fig. 8. Fence diagram showing the inter-tonguing of deep-water, outer-shelf carbonates (Rumaila Formation) with the shallow-water carbonates of the Mishrif Formation in Central and Southern Iraq (adapted from Aqrawi, 1983). Location marked on Fig. 1

in the Mishrif Formation at producing oilfields. High primary porosities, enhanced by early-diagenetic secondary porosities of various types (such as vuggy pores resulting from dissolution) characterise the reservoir units.

The formation of secondary vuggy, mouldic and intragrannular pores, which are common in the bioclastic and rudist-bearing facies, resulted from the dissolution of aragonitic skeletal grains during early diagenesis. Other types of porosity, such as intercrystalline pores between dolomitic rhombs, and microporosity in the mudstones’ matrix, have been recognized by SEM analyses.
High porosities are present in a number of facies in the Mishrif Formation, including mudstones and wackestones. However, high permeabilities are confined to rudist-bearing facies. The dissolution of aragonitic grains has critically improved the permeability of this facies. As a result, rudist-bearing units provide the principal reservoir zones in the Mishrif Formation in Central and Southern Iraq.

STRATIGRAPHIC RELATIONSHIPS BETWEEN THE MISHRIF AND RUMAILA FORMATIONS OF SOUTHERN IRAQ AND THEIR EQUIVALENTS IN CENTRAL IRAQ

Central Iraq

The stratigraphic relationships between the carbonates of the Mishrif and Rumaila Formation in Central Iraq are complex (Fig. 8). The carbonates were deposited in either (i) an outer-shelf or basinal setting — the Rumaila Formation; or (ii) a shallower-water inner-shelf setting — the Mishrif Formation. Units of the Rumaila Formation comprise fine-grained marly and chalky limestones; they alternate with the thicker units of the Mishrif Formation, which is generally composed of coarse-grained carbonates.

In Central Iraq, the deeper-water carbonates were formerly known as the Mahilban Formation, while the bioclastic carbonates were known as the Fahad and Maotsi Formations (Dunnington, 1959). It has been suggested that the Mahilban, Fahad and Maotsi Formations in Central Iraq should be renamed the Rumaila and Mishrif Formations (Aqrawi, 1983; Sherwani, 1983; Sherwani and Aqrawi, 1987) because they are the continuation of these two formations within the same sedimentary cycle.

Central Iraq was tectonically unstable due to the periodic reactivation of basement blocks (Fig. 2b; Buday and Jassim, 1989). The mid-Cretaceous carbonate succession in Central Iraq was influenced by sea-level fluctuations which were due to local tectonism and/or eustatic changes. Regressive bioclastic grainstones were laid down during periods of low relative sea-level, and uplift and emergence resulted in the formation of unconformities. Subsidence led to deeper-water, outer-shelf and basinal conditions during which the finer-grained lithologies were deposited.

Southern Iraq

Southern Iraq was tectonically more stable during the deposition of the Mishrif and Rumaila Formations. High relative sea levels accompanied deposition of the transgressive carbonates of the Rumaila Formation. These were followed by a gradual fall in relative sea level, during which the regressive, shallow-shelfal carbonates of the Mishrif Formation were deposited.

However, it is often not possible to delineate accurately the contact between the two formations, particularly from well logs, as a result of its gradational nature (Aqrawi, 1983; Sherwani, 1983). Also, thin packages of deeper-water sediments occur within the regressive Mishrif Formation succession. This occurs, for example, at Well AAm-1 (Abu Amood oilfield, recently renamed the Rafidain oilfield) (Fig. 9); and at Well Ns-1 (Nasiriyya oilfield) (Fig. 10).

Depositional cycles

At the Rafidain and Nasiriya oilfields, the Mishrif Formation can be divided into two large-scale regressive sequences, each comprising medium-scale sequences (Figs. 9, 10 and 11). Similar sequences have been recognised in the Mishrif Formation elsewhere, and have been interpreted in northern Oman by van Buchem et al. (1996) in terms of high resolution sequence stratigraphy. Van Buchem et al. (ibid.) proposed that the fluctuations in relative sea level which resulted in this sequence architecture were caused by eustatic changes. However, local changes in relative sea level due to tectonic instability in Central Iraq may also have been a contributory factor. High-resolution sequence-stratigraphic
Fig. 9. Lithostratigraphy of the Mishrif Formation at well AAm-1, Rafidain (formerly Abu Amood) oilfield, southern Iraq. See well location on Fig. 1. Well logs are spontaneous potential, gamma-ray and sonic. Interpretations of depositional environments are from Ahmed (1983). Two major regressive sequences are identified, each consisting of smaller-scale sequences, and are divided by an unconformity.
analyses of the Mishrif Formation in Central and Southern Iraq, supported by biostratigraphic and seismic data, will be required as the basis for further studies.

Previous stratigraphic studies of Iraq have used regional unconformities as correlative timelines (e.g. Dunnington, 1959; Buday, 1980) which separate the main depositional cycles. Aqrawi (1996) applied general sequence-stratigraphic concepts to the Upper Cretaceous Khasib, Tanuma and Sa’di Formations in the Mesopotamian Basin. However, Al-Shididi et al.’s (1995) study of Lower Cretaceous deposits at a number of northern oilfields near Kirkuk is the only detailed sequence-stratigraphic analysis yet carried out in Iraq.

In this study, we have attempted to distinguish large- and medium-scale accommodation cycles (i.e. major regressive sequences, and coarsening-up medium-scale sequences, respectively) within the Mishrif Formation. We have based this on available petrographic and electric-log data. The lack of detailed biostratigraphic and seismic data has made more detailed sequence-stratigraphic interpretation difficult. Most biostratigraphic studies in Iraq have in the past concentrated on determining a formation’s age and depositional environment, rather than on distinguishing and dating individual biozones. These biozones could be correlated with seismic marker horizons for future sequence-stratigraphic studies. In addition, most petroleum geologists in Iraq use lithological markers (regardless of their ages), as distinguished on well logs, for stratigraphic correlations and reservoir analyses.

Fig. 12 illustrates an east-west lithostratigraphic section of the Mishrif Formation in the Mesopotamian Basin. Unconformity-bound upper and lower sequences can be distinguished in the east of the section. By comparing these sequences with those recently identified in the time-equivalent Natih Formation in Oman (van Buchem et al., 1996), it appears that the unconformity which separates them is of middle Cenomanian age. An unconformity of this age has been recognised elsewhere in the Middle East. Therefore, the lower sequence in the Mishrif Formation in Iraq may be correlated with the major Natih “E” sequence in Oman; whereas the upper sequence of the Mishrif Formation may correspond to the Natih “A-D” sequences (van Buchem, pers. comm., 1997).

EVOLUTION OF THE MISHRIF FORMATION IN THE MESOPOTAMIAN BASIN

A transgression during the early Cenomanian (Fig. 13a) was responsible for the deep-water conditions in which the Ahmadi and Rumaila Formations were deposited, as well as the lower part of the Mishrif Formation in Southern and Central Iraq (Figs. 9, 10 and 11). Deposition of the lower regressive sequence of the Mishrif Formation began in the east of the Mesopotamian Basin. Continuous subsidence of the basin in the east, in the area around the Amara palaeo-high, resulted in the development of thick, reefal build-ups there before the western parts of the basin (Fig. 12).

Shallowing of the east of the basin was probably controlled both by the uplift of the Amara palaeo-high and also by a regional fall in relative sea-level. The presence of the Amara palaeo-high was described by Chatton and Hart (1962); Buday (1980) extended it to the NW (to the Dujaila area) and named it the Amara-Dujaila ridge. Basin shallowing led to a gradual change from open-shelf conditions, to fore-reef slopes and reef flats, shoals, and finally inner-shelf conditions.

Continued uplift and shallowing of the basin led to the exposure of the Mishrif Formation, and its diagenetic alteration in a meteoric-phreatic environment. Dissolution in this environment improved the carbonates’ porosity, particularly that of the coarse-grained, rudist-bearing facies. Continuing fall in relative sea-level led to an intraformational unconformity, which can be traced on well logs throughout the eastern boreholes studied (e.g. Well Hf-1: Fig. 11), and may be correlated throughout the Mesopotamian Basin. Sea-level fluctuations in the SW of the basin caused a change from an inner-shelf setting
Fig. 10. Lithostratigraphy of the Mishrif Formation Well Ns-1, Nasiriyah oilfield, southern Iraq (from Aqrawi et al., 1988). For well location, see Fig. 1. Two large-scale sequences (and several smaller-scale sequences) are identified. Major sequences are divided by shales, which may be correlated to the unconformity identified in boreholes in the east of the basin.
Fig. 11. Lithostratigraphy of the Mishrif Formation at well Hf-1 (Halfaya oilfield), SE Iraq. Location on Fig. 1. Modified from OEC Study, 1995. Large- and medium-scale depositional sequences can be identified.
Fig. 12. East-west lithostratigraphic cross-section of the Mishrif Formation in the Mesopotamian Basin, showing the vertical distribution of principal depositional facies (modified from OEC Study, 1995). For location of section, see Fig. 1.

Two sequences with several pay zones can be identified in the east of the section; only the lower sequence with a few pay zones is present in the west. Pay zones are present in rudist-bearing units; these are thicker in the east than the west, indicating more rapid subsidence rates. Age of timeline is by analogy with Natih Formation in northern Oman (van Buchem et al., 1996).
Mishrif Formation, Mesopotamian Basin, Iraq

Fig. 13a. Palaeogeographic map of the Mesopotamian Basin during the late Cenomanian (modified after Buday, 1980), showing the distribution of the main depositional units. The Mishrif Formation is confined to the east of the basin; its equivalent in the west is known as the Ms’ad Formation.

to a coastal complex. This is represented at the Nasiriyya (Fig. 10) and Gharraf oilfields, and probably also in surrounding areas, by compacted terrigenous muds and shales. This unit may be considered to be correlative to the intra-Mishrif unconformity recognised in the east of the basin.

However, intermediate parts of the Mesopotamian Basin (along the basin axis) were characterised by shallow-marine conditions, and were connected to an outer-shelf zone in the east in which there were deeper-water, open-marine conditions. In Iran, this may have been the basin in which the Sarvak Formation was deposited (James and Wynd, 1965; Ala, 1982). As a result, grain-supported carbonates including rudist-bearing facies were deposited in these areas somewhat later than they were in the east.

The intraformational unconformity surface was subsequently covered by open-marine deposits, as a result of subsidence and/or a rise in relative sea level. The resulting outer-shelf deposits pass up into a second regressive sequence of shallow-water carbonates (Reulet, 1982). This sequence also contains a number of reservoir units, particularly in the east of the basin (e.g. at Well Hf-I, Fig. 11).

Continued shallowing of the basin led ultimately to the deposition of supratidal evaporites assigned to the Kifil Formation, particularly in the west (in the Afaq and Kifil areas), terminating the regression. However, in some areas such as in the SW, the top of the Mishrif Formation was exposed subaerially, resulting in the deposition of freshwater limestones which were locally eroded. In other parts of the Mesopotamian Basin (e.g. around Amara), the top of the Mishrif Formation was exposed and highly eroded, and was then covered by conglomerates (Al-Khersan, 1975). These mark the end of the regressive phase in the Cenomanian-early Turonian sedimentary cycle.

A new sedimentary cycle began during the Turonian-lower Campanian (Buday, 1980), following a lengthy depositional hiatus during the early Turonian. This cycle resulted in the deposition of the Upper Cretaceous carbonates and siliciclastics of the Khasib,
Fig. 13b. Paleogeographic map showing the distribution of depositional sub-environments within the Mesopotamian Basin during deposition of the Mishrif Formation. The shallow-water, high-energy belts to east and west constitute the most promising exploration areas. Modified from OEC Study, 1995. Line of section in Fig. 14 is marked.

Tanuma and Sa’di Formations (Aqrawi, 1996), which unconformably overlie the Cenomanian-early Turonian succession (Owen and Nasr, 1958).

In summary, depositional environments in the Mesopotamian Basin during the deposition of the Mishrif Formation (Fig. 14) were dominated by a ramped platform with a variety of inner-shelf sub-environments. A shallow, open-marine connection led to a deeper-water basin. Intertidal (and occasionally supratidal), subtidal, lagoonal and reefal (including reef-slope and back-reef) facies were deposited during regressive phases of sedimentation, and usually overlie deeper-water facies. In most oilfields in Central and Southern Iraq, restricted lagoonal/supratidal facies marked the end of Mishrif Formation deposition.

STRATIGRAPHIC DISTRIBUTION OF THE RESERVOIR UNITS

The two major sequences in the Mishrif Formation can be subdivided into parasequences, according to the precise location within the Mesopotamian Basin, reflecting minor episodes of sea-level change. Each parasequence contains a number of oil-producing zones. The lenticular geometry of these rudist-bearing units is clear on the lithostratigraphic cross-section (Fig. 12). This section also indicates that rudist-bearing units occur in both sequences in the east of the basin, whereas they are confined to the lower sequence in the west (Wells Ga-1 and Ns-1: Gharraf and Nasiriyya oilfields). In fact, the shallow-water deposits of the Mishrif Formation wedge-out towards the west.
In the west (e.g. Well Ns-1: Fig. 10), rudist-bearing units in the lower sequence, which overlie fine-grained, open-marine deposits, are overlain by shales. The shales act as local seals, and represent interruptions to carbonate sedimentation due to the input of fine-grained siliciclastic material from the SW. These shales may be correlated with the unconformity marking the top of the lower sequence in the east of the basin.

The shallow-water reservoir facies (rudistid packstone/grainstones and rudstones) in both sequences are generally overlain and sealed by fine-grained lagoonal or subtidal deposits.

**Palaeogeography**

The areal distribution of the Mishrif Formation in the study area (Fig. 13a and b) indicates two high-energy belts oriented NW-SE, parallel to the axis of the Mesopotamian Basin. The first belt occurs where the Mishrif Formation is thickest in the east of the basin (Fig. 13b) along the Amara palaeo-high. Here, the formation includes three rudist-bearing units with several pay zones. Two of these units are located within the upper sequence, while the third is in the lower sequence.

The second belt of high-energy facies is located in the west of the basin, and consists of only a single rudist-bearing unit (with a few pay zones) within the lower sequence (Fig. 12). This facies belt is near to and parallel with the palaeo-shoreline (Fig. 13b); subsidence rates on this side of the basin appear to have been relatively low.

The two belts are separated by an intervening area dominated by shallow, open-marine conditions. This area was connected to deeper-water, basinal areas to the NE. This connection led to the deposition of thick, open-marine, outer-shelf deposits, rich in planktonic foraminifera, which overlie inner-shelf bioclastic deposits, for example in the Dujuilu and Gharraf oilfields (Wells Du-2 and Ga-1: Fig. 1).

In the western and SW wedge-out belt, rudist-bearing units in the lower sequence form reservoir rocks where structural traps are present. By contrast, structural traps dominate the east of the basin, which is characterised by a multitude of reservoir units within both upper and lower sequences. A number of oilfield structures appear to have grown actively during deposition of the rudist-bearing units. As a consequence, these units may have undergone early meteoric diagenesis, improving their reservoir characteristics.

**CONCLUSIONS**

Our sedimentological and stratigraphical studies of the Mishrif Formation in Central and Southern Iraq can be summarised as follows:

The Mishrif Formation (Cenomanian- early Turonian) consists mainly of shallow-water carbonates and six principal depositional microfacies have been identified: (i) pelagic mudstone/wackestones; (ii) bioclastic wackestones; (iii) wackestone/packstones; (iv) peloidal packstones; (v) rudistid packstone/grainstones; and (vi) rudstones. These carbonates have been affected by a variety of diagenetic processes. In particular, early diagenetic dissolution improved the reservoir quality of the rudist-bearing grainstones and rudstones which constitute the principal reservoir facies. These units have porosities of >15 %, and permeabilities of between 100 mD and 1 Darcy or more.

The principal depositional environment in which the Mishrif Formation was laid down was a ramped platform, dominated by shallow-water inner-shelf environments (e.g. rudist patch-reefs or barriers, shoals, lagoons, and subtidal and intertidal flats). Deeper-water (outer-shelf and basinal) conditions arose periodically as a result of a rise in relative sea-level and/or local tectonism; Central Iraq was particularly tectonically unstable. High-resolution sequence-stratigraphic studies will be required to assess the relative importance of these factors.

The eastern part of the Mesopotamian Basin appears to have subsided more rapidly during Mishrif Formation deposition than the western side. Hence, the formation is
Fig. 14. Schematic east-west cross-section showing the depositional setting of the Mishrif Formation in the Mesopotamian Basin during the Cenomanian-early Turonian. The general setting is a ramped carbonate platform on which various depositional sub-environments were developed.
thicker in the east than the west. Shallow-water conditions were maintained in the east, however, above the Amara palaeo-high, resulting in the development of thick rudist-dominated build-ups.

Uplift and emergence of the Mishrif Formation resulted in an intraformational unconformity, which can be recognised particularly in the east of the Mesopotamian Basin. The unconformity divides the Mishrif Formation into two regressive sequences. By analogy with northern Oman, the unconformity is suggested to be of middle Cenomanian age.

In the east of the basin, both of the regressive sequences comprise a number of separate pay zones within coarsening-up medium-scale sequences. In the west, only the lower sequence is present, containing relatively few pay zones.

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