Stratigraphy of the Lower Paleozoic Haima Supergroup of Oman

Henk H.J. Droste
Petroleum Development Oman

ABSTRACT

Following the discovery of significant gas/condensate reserves in Lower Paleozoic clastics in Central Oman a regional geological review using all available well data and a set of regional seismic lines was carried out by Petroleum Development Oman. The objective of this study was to support further appraisal and exploration activities. A chronostratigraphic framework of regional correlatable major flooding surfaces improved the understanding of the stratigraphic relationship between the different units and the regional distribution of the reservoir seal pairs. The interval of interest, the Cambrian to Lower Silurian Haima Supergroup, is a late syn- to post-rift siliciclastic infill of an extensive graben system. The depositional setting was initially continental but higher in the sequence of marine deltaic setting prevailed. The sequence is characterised by the occurrence of laterally extensive sand sheets typical of pre-vegetational times but difficult to interpret sedimentologically. At least six major transgressive regressive cycles can be recognised which can be regionally correlated. Marine intercalations are limited to Central and North Oman. The clastic influx into the grabens was initially of local origin but as the grabens filled up the sediments were predominantly derived from a southern source.

INTRODUCTION

Since 1989 significant gas/condensate discoveries have been made in the Lower Paleozoic Haima clastic reservoirs of North Oman. Until this time, the stratigraphy of the Haima was poorly understood and loosely defined because of lack of well penetrations and the limited number of cores and sidewall samples available. With the recent drilling campaign a significant amount of new data has become available improving our understanding of the Haima. This paper provides an overview of the Haima stratigraphy and the tectono-stratigraphic evolution of this unit and summarises the results of several review studies carried out by the exploration department of Petroleum Development Oman (PDO). The lithostratigraphic definitions of the Haima currently in use by PDO is an update and revision of that presented by Hughes Clarke in 1988.

The study area covers the whole subsurface of Oman south of the Oman Mountains (Figure 1). A regional set of composite seismic lines was selected from which seismic facies, lateral thickness variations and principal tectonic elements were determined. All the lithological, sedimentological and biostratigraphical data were examined and calibrated for approximately 200 Haima penetrations. Borehole Image data of selected intervals were interpreted for paleocurrent directions. Results from outcrop studies (Millson et al., 1996; Buckley, 1997) were also included in the review. Using the above data the stratigraphic framework was established, lithofacies and isopach maps were constructed for selected intervals and a tectonostratigraphic model for the Haima reservoir/seal distribution was developed.

GEOLOGICAL SETTING

The Cambrian to Lower Silurian Haima Supergroup of Oman forms the late syn- to post-rift siliciclastic infill of a northeast-southwest trending Precambrian to Paleozoic graben system and overlies pre- and syn-rift carbonates and evaporites of the Huqf Supergroup (Figure 2). The rift system consists of three north-south to northeast-southwest trending basins separated by basement highs (Figure 1; see also Loosveld et al., 1996). The asymmetrical South Oman Salt Basin is bordered by the Western Margin High and separated in the north from the Ghabra Salt Basin by the Central Oman High (Figure 3). The symmetrical Ghaba Salt Basin is bordered to the east by the Huqf axis and separated in the west by the Mabrouk Makarem High from the shallower Fahud Salt Basin in northwest Oman (Figure 4). The sediments of the Haima Supergroup completely fill-up and cover the margins of these graben systems, forming a classical “steer’s head” basin geometry in the Ghaba Salt Basin reaching a thickness in excess of 6 kilometers (km) along the central axis.
Figure 1: Simplified tectonic map of Oman showing in pink the outline of the Precambrian to Cambrian salt basins of the subsurface, in green the Huqf area where Precambrian to Upper Cambrian sediments are outcropping and in yellow the Oman Mountains formed by the Late Cretaceous continent-ocean collision and obduction (modified from Loosveld et al., 1996).
Figure 2: Tectonostratigraphy of the Oman subsurface showing the major stratigraphic breaks and transgressive-regressive supercycles. The studied interval has been highlighted and the Petroleum Development Oman stratigraphic nomenclature has been used.
Figure 3: Schematic geological section across South Oman (see Figure 1 for location).
Figure 4: Schematic geological section across North Oman (see Figure 1 for location).
The pre-existing, highly variable topography caused major variations in the early sedimentary infill of the basins. In addition, synsedimentary movement of underlying Huqf evaporites and differential subsidence across basement highs strongly influenced the thickness and lateral extent of stratigraphic units. The depositional setting was initially continental, becoming progressively more marginal marine to deltaic in nature for the upper part. The marine incursions are more pronounced in the Fahud and Ghaba Salt basins, suggesting that some connection to the open ocean existed in the north. On a regional scale, the main source of the siliciclastics was from the south.

The rift system and its infill was regionally tilted to the west in Late Silurian-Carboniferous (pre-Haushi Group) times, resulting in progressive truncation of the formations towards the east. Further erosion occurred above areas with active salt movement which continued during post-Haima to pre-Haushi times and various phases of post-Paleozoic deformation.

LITHOSTRATIGRAPHY

A stratigraphic subdivision for the Haima Supergroup has been published by Hughes Clarke in 1988. As relatively few wells penetrated this interval at the time, many units, especially in North Oman, were informally subdivided. In the last decade however, understanding of the Haima was significantly improved by an increasing number of well penetrations and cores, improved seismic imaging and outcrop studies in the Huqf area. This paper presents a revised stratigraphy of the Haima of Oman and is based on a number of recent reviews carried out by PDO.

It has to be realised that the existing knowledge of the Haima is from a biased dataset, all wells have been drilled on local highs and intervening low areas are undersampled. Seismic evidence indicates the occurrence of expanded sections and the presence of truncated and/or onlapping packages in these areas. The present Haima stratigraphy is therefore incomplete part and additional units may have to be defined in the future when more data are available.

The updated stratigraphy of the Haima Supergroup is shown in Figure 5 where it is compared to that of Hughes Clarke (1988). A detailed description of all the stratigraphic units is provided in Appendix-1. The Haima is subdivided into three Groups represented by the Nimr, Mahatta Humaid and Safiq each separated by major regional unconformities. Although these units are regionally extensive, lateral variations exist between the different basins, especially in the lower part of the sequence. All units are only known from the subsurface, with the exception of the Amin, Miqrat and lower part of the Andam Formation which are exposed in the Huqf area (Buckley, 1997).

The late syn-rift continental clastics of the Nimr Group are best known from the Eastern Flank area in South Oman, and have relatively few penetrations in North Oman where they are restricted to the deeper part of the basins. The contact with the overlying Mahatta Humaid Group is formed by the rift-sag Angudan unconformity (Loosveld et al., 1996) which is developed as a clear angular unconformity in southwest Oman. The Mahatta Humaid Group consists of laterally extensive continental to marginal marine sediments. These sediments were deposited on an essentially flat topography and small-scale depositional cycles of 10 to 20 meters (m) thick can often be confidently correlated over distances of more than one hundred kilometers. The Safiq Group contains deltaic to marine sediments and has a patchy distribution as a result of truncation below the base Carboniferous unconformity.

BIOSTRATIGRAPHY

Because of the general absence of fossils in the predominantly continental Haima sediments, the ages of most units can only be roughly estimated. The main tool for biostratigraphic dating of the Haima sediments in wells are palynomorphs. Other biostratigraphic information has been derived from trilobite fragments recovered from Haima outcrops in the Huqf area (Fortey, 1995). Figure 6 shows the present palynological zonation used and its relationship with the chrono- and lithostratigraphy. Four zones, 1098, 1005 and 1003, and one informal Assemblage Unit, 1012, have been recognised.
Figure 5: New Haima lithostratigraphy compared to that of Hughes Clarke (1988).
| SYSTEM | SERIES | STAGES | GROUP | FORMATION | BIOZONE | PALYNOLOGICAL MARKERS |
|--------|--------|--------|-------|-----------|---------|-----------------------|
|        |        | EUROPEAN |        |           |         | First appearance datum |
|        |        |        |       |           |         | Last appearance datum  |
|        |        | CHINESE |       |           |         |                       |
|        | SILURIAN |        |       |           |         |                       |
| (PARS) | LOWER  |        |       |           |         |                       |
|        |        | Llandovery |       |           |         | D. murusdensa          |
|        |        |        |       |           |         | Dyadospora sp. 2       |
|        |        |        |       |           |         | A. syringosagis (common)|
|        |        |        |       |           |         | Tetrahedraletes? sp. A |
|        | ORDOVICIAN |        |       |           |         | O. bispinosum          |
|        | MIDDLE  |        |       |           |         | Stellachinatum sp.     |
|        |        | Ashgill    |       |           |         | Dyadospora sp. 2       |
|        |        |        |       |           |         | A. syringosagis        |
|        |        | Caradoc     |       |           |         | E. cabottii           |
|        |        | Llandeilo   |       |           |         |                       |
|        |        | Llanvirn    |       |           |         |                       |
|        |        | Arenig      |       |           |         | Incertae sedis No. 20  |
|        | LOWER  |        |       |           |         | Stelliferidium spp.    |
|        |        | Tremadoc    |       |           |         | S. principalis        |
|        | CAMBRIAN |        |       |           |         | Acanthodiacrodium spp. |
|        | UPPER   |        |       |           |         | V. dumontii            |
|        |        | Dolgellian  |       |           |         | Cambrian palynoflora   |
|        |        | Festiniogian |       |           |         | (as yet undated)       |
|        |        | Maenwrogian |       |           |         |                       |
|        | MIDDLE  |        |       |           |         |                       |
|        |        | Menevian    |       |           |         |                       |
|        |        | Solvanian   |       |           |         |                       |
|        | LOWER   |        |       |           |         |                       |

Figure 6: Haima palynozonation of the lower paleozoic in Oman compared to the lithostratigraphy. Condensed intervals are expected to be present at major Marine Flooding Surfaces (MFS) while major time gaps may occur across the unconformities.
The 1108 Zone contains generally poor assemblages that are characterised by *Acanthodiaceododium* spp. and rare *Vulcanisphaera* spp., * Baltispaeridium* spp., *Veryhachium dumontii* and cf. *Priscotheca* spp. No chitinozoans have been recorded. The rare palynofloras from the 1108 Zone are all marine. The 1108 Zone is considered to be of Late Cambrian to Early Arenig age. Poor sample material limited a more precise age assignment.

The 1098 Zone contains assemblages characterised by the common presence of *Duvernaysphaera* cf. radiata, *Stelliferidium* spp. and abundant acantomorph acritarchs. Additional characteristic but more rare species are *Actinotodissus* sp. and *Striatotheca* principalis. Chitinozoans are quite common in many samples with *Desmochitina* spp. and *Desmochitina minor* as typical species for the 1098 Zone. The 1098 Biozone generally contains marine indicators, though palynofloras may be dominated by an indeterminate palynomorph. A Late Arenig-Llanvirn and possibly Llandeilo age has been interpreted for this zone.

The 1005 Zone is characterised by the presence of *Dyadospora* sp. 2, *Nodospora* sp. A and abundant *Nodospora* and *Dyadospora* spp. More rare types are *Dyadospora* sp. 1, *Arenoricanium syringosagis*, *Villosacapsula setosapelicula*, *Othosphaeridium chordrododora*, *Othosphaeridium bispinosum* and *Stelliginatum* sp. Chitinozoans are rather rare, characteristic are *Conochitina* species. The palynofloras of the 1005 and also the 1003 Biozones are dominated, sometimes totally, by cryptospores, considered to be derived from the earliest land plants. The marine acritarchs and chitinozoans which are also recovered indicate a near-shore and or marginal marine depositional environment. In the absence of these marine indicators, however, it is not clear if the depositional setting is really non-marine or that it represents a marginal marine situation with a high surface run off. The 1012 Sub-Zone of the 1005 Biozone is defined on the occurrence of marine acritarchs such as *Orthosphaeridium chordrododora*, *Othosphaeridium bispinosum* and *Stelliginatum* sp. Although it is in effect a facies related assemblage, it is always encountered below sediments containing normal 1005 assemblages and therefore it still has stratigraphical value. The 1005 Zone is considered to be of Caradoc-Ashgil, the 1012 Assemblage Unit of Caradoc age.

The assemblages of the 1003 Zone are not very diverse and are characterised by abundant presence of *Nodospora* spp. and *Dyadospora* spp. and fairly rare *Dixallophtysis denticulata*. Chitinozoans are quite common with as characteristic species as *Conochitina* cf. senta, *Conochitina* sp., *Ancyrochitina spongiosa* and, very rare, *Cyathochitina kuckersiana*. The palynofloras are dominated, sometimes totally, by cryptospores. The 1003 Zone is considered to be Llandovery in age, however an Ashgill age cannot be completely ruled out on the available data.

The only units in the Haima Supergroup with biostratigraphic control are the Upper Cambrian-Lower Ordovician Andam Formation in the Mahatta Humaid Group and the Middle Ordovician to Lower Silurian formations in the Safiq Group. A further control point is provided by scarce biostratigraphical markers that have been determined in the upper part of the underlying Huqf Supergroup (Mattes and Conway Morris, 1990). These correlate with similar associations from Siberia and Mongolia, where they are indicative of the earliest Cambrian (Tommotian). The ages of the other Haima units have been inferred and should be considered as rough estimates. With the limited biostratigraphic control points and the coarse zonation scheme it was not possible to resolve the time gaps in the sequence across the stratigraphic discontinuities shown by seismic evidence and well data.

The Nimr Group is inferred to be of Early Cambrian age, based on the Tommotian age of the underlying Huqf (Mattes and Conway Morris, 1990) and the assumption that the overlying Amin correlates with the Lalun sandstone sequence of Central and Southern Iran which is overlain by Lower Cambrian marine horizons (Hughes Clarke, 1988). Trilobite fragments from exposures of the Al Bashair and lower Barik Sandstone Member of the Andam Formation in the Huqf area (Fortey, 1995) and palynomorphs in subsurface samples suggests that the Andam Formation spans the whole of the Upper Cambrian and possibly the Lower Ordovician. From this, a Middle Cambrian age has been inferred for the underlying unfossiliferous Miqrat and equivalent Mahwis formations. Palynofloras and graptolites show a Middle Ordovician to Early Silurian age for the Safiq Group. The underlying Ghudun Formation, which is in facies very similar to that of the Barik sandstone, is considered to be still Early Ordovician in age.
SEISMOSTRATIGRAPHY

The Haima section has a very low internal seismic reflectivity and is overprinted by multiples from the carbonates in the overburden. Although 2-D and 3-D seismic data quality has been significantly improved over the last years with the acquisition of long cable (4.4 to 6 km) seismic and processing techniques to minimise multiple interference, mapping of the Haima units remains a challenge (Figures 7 and 8). Reflectors which can be followed on a more regional scale include the Mid-Al Bashair, top Amin and top Andam. The Nimr Group is clearly infilling pre-existing Huqf topography while the overlying Amin is widespread and completely covers and onlaps the remaining Huqf topography. Major wedging occurs within the overlying Miqrat and Andam formations which is related to movement of underlying Huqf salt and differential subsidence across major Huqf fault lineaments. The seismic resolution at these depths does not allow a clear picture of the nature of the bounding surfaces of these wedges but it is considered that these represent mainly onlap surfaces with only minor truncation.

SEDIMENTOLOGY

The absence of land plants during pre-Silurian times had a major influence on the organisation of fluvial and shoreface systems (McCormick and Grotzinger, 1993; Galloway and Hobday, 1983). Plants promote stabilisation and trapping of sediment and decrease the effect of aeolian processes. In addition, the production of organic acids in soils promotes the formation of clays. Therefore, depositional systems in the pre-Silurian are expected to show major differences with those that we observe today (Figure 9). In continental settings the meandering river systems, favoured by vegetation and by a low sand-to-clay ratio of the sediments, are absent and river systems will be braided and very sandy.

In the absence of physical barriers the channels will be shallow and wide and can easily migrate laterally to form extensive sheets of sands. Intercalated with these fluvial deposits aeolian sediments can be expected. In deltas and shoreface systems larger volumes of sands would be supplied by rivers, causing rapid progradation. Deltas are expected to occur scattered along the coast and show frequent lateral migration. Sedimentary bedding tends to be very well preserved as the intensity, depth and tiering of burrowing by benthos was very low before the Middle Ordovician (Sepkoski et al., 1991). The unvegetated coasts would also be easily and rapidly modified. Storms could erode large quantities of sand and transport offshore while transgressions are expected to be rapid and very erosive. All these factors promote the occurrence of thick, widespread sandy quartzose successions including fluvial, aeolian and shallow marine sediments that are so characteristic of the Precambrian and earliest Paleozoic.

The interpretation of the depositional setting of the Haima sediments as determined from cores and well log patterns is shown in Table 1. A detailed description of the facies is provided in Appendix 1.

PROVENANCE

Provenance studies suggest a recycling of older sediments and low-to-medium grade metamorphic rocks, including metaquartzite and quartz mica schists, as the main source of the Haima sediments. Plutonic igneous rocks including granites were also significant sources. The source area was probably the Precambrian basement of northern and eastern Yemen which contains a variety of metamorphic and intrusive igneous rocks (Ellis et al., 1996). Facies trends and paleocurrent directions observed on Borehole Images and in outcrops of the Haima Supergroup in North Oman also suggest a southern source for the sediments. The recycled sediments may have been derived from erosion of the underlying Huqf Group which was exposed on regional highs and by intra-Haima reworking (Nimr Group). Changes in provenance have been observed across the boundaries of the Nimr Group and Mahatta Humaid Group, a change of heavy mineral suit, and the Amin and Miqrat formations by an increase in feldspar content suggesting a closer source, possibly the Mirbat Massif, in southeastern Oman. The sediments of the Haima Supergroup show an overall increasing trend of compositional maturity upwards indicating a higher proportion of recycled sediments.
Figure 7: Composite seismic section through the Ghaba Salt Basin (see Figure 1 for location).
Figure 8: Seismic section through the South Oman Salt Basin (see Figure 1 for location).
Lower Palaeozoic Haima, Oman

**TABLE 1**
Depositional Facies of Haima Supergroup in North and Central Oman.

| STRATIGRAPHIC UNIT | DEPOSITIONAL SETTING |
|--------------------|----------------------|
| Safiq Group        | cyclic alternation of marine offshore to deltaic/fluvial deposits |
| Mahatta Humaid Group | braid delta, marine influenced at base |
| Ghudun Formation  | braid delta, marine influenced at base |
| Andam Formation    | marine, shoreface at base to shallow marine at top |
| Barakat Member     | marine, shallow marine at base, in places possibly intertidal to sabkha at top |
| Mabrouk Member     | marine influenced, braid delta |
| Barik Sandstone Member | marine, tidal flat deposits with common carbonate |
| Al Bashair Member  | continental, inland sabkha |
| Miqrat Formation   | continental, alluvial fan at base to aeolian at top |

Nimr Group

continental, alluvial fan

Figure 9: Model for Cambrian depositional environments.
LATERAL CORRELATIONS

The construction of a chronostratigraphic framework (Figure 10) for the Haima Supergroup is hampered by the very poor biostratigraphic control, low seismic resolution and the mainly continental nature of the sediments. Several regional disconformities and major marine flooding surfaces can however be recognised and have been used as time lines for stratigraphic correlations. The main surfaces are listed in Table 2.

The unconformities can be recognised by truncation and/or onlap geometries on seismic and/or on detailed log correlation panels of marine flooding surfaces. Maximum flooding surfaces can be picked on well logs by recognising intervals that show maximum ‘shaleyness’. Often these are associated with an increase in bioclast/microfossil abundance and diversity and glauconite. Usually the maximum flooding surface shows a peak on the gamma log, maximum separation of the Density and Neutron Logs and low resistivities. In Figure 11 the major flooding surfaces and shallowing/deepening trends are shown with the log response in a well located in the Ghaba Salt Basin. A regional correlation panel of the Mahatta Humaid Group in the Ghaba Salt Basin using these surfaces is shown in Figure 12.

| REGIONAL UNCONFORMITY | INTERPRETED AGE | MAXIMUM FLOODING SURFACE |
|------------------------|----------------|--------------------------|
| Llandovery (Early Silurian), palynozone 1003 | | Basal Sahmah Formation (highly radioactive shale interval) |
| Intra-Hasirah incision related to glaciation? | Caradoc (Late Ordovician), palynozone 1012/1005 | Basal Hasirah Formation |
| Base Saih Nihayda Formation (truncation of underlying Ghudun) | Llanvirn (Middle Ordovician), palynozone 1098 | Basal Saih Nihayda Formation |
| Base Barakat Member (?low angle truncation of underlying units) | Tremadoc? (Early Ordovician), palynozone 1098 | Middle Barakat Member (MFS-3) |
| Base Al Bashair Member (onlap/truncation surface) | Early Tremadoc? (Early Ordovician), palynozone 1108 | Basal Mabrouk Member (MFS-2) |
| Base Miqrat/Mahwis (onlap surface) | Maentwrogian to Menevian (Late to Middle Cambrian), palynozone 1108 | Menevian to Solvanian? (Middle Cambrian) |
| Base Amin Formation (clearly angular truncation) | Early Cambrian? | Base Amin Formation (clearly angular truncation) |
Figure 10: Schematic chronostratigraphic cross-section of the Haima Supergroup in North Oman.
Figure 11: Well log of Mahatta Humaid Group in the Central Ghaba Salt Basin showing the interpretation of the sedimentology and depositional trends.
Figure 12: Regional correlation panel for Mahatta Humaid Group in Ghaba Salt Basin (see Figure 1 for location).
Within the Andam Formation of North Oman several other, smaller scale, marine flooding surfaces can be recognised and correlated over many tens of kilometres. Regional correlations of these time lines clearly show that the boundaries between the Al Bashair, Barik Sandstone and Mabrouk members and between the Barakat Member and the Ghudun Formation are diachronous and that these lithostratigraphic units represent lateral facies variations.

The major marine flooding surfaces and regional unconformities define major transgressive-regressive cycles on a second-order scale with a duration of 3 to 50 million years (Ma) (Vail et al., 1991). Recognition of third-order sequences of 0.5 to 3 Ma duration, with systems tracts is hampered by the poor biostratigraphic control, the generally wide well spacing and difficulties in the recognition of non- to marginal marine mudstone from the open marine mudstone intervals.

A correlation of the Oman subsurface stratigraphy with that of surrounding areas using the regional unconformities and flooding surfaces as time lines is shown in Figure 13. A good correlation can be made between the Haima of the subsurface and the outcrops in the Huqf area. The Cambrian Strata in the Huqf represent the Amin and Miqrat formations and the Al Bashair and Barik Sandstone members of the Andam Formation (Millson et al., 1996; Buckley 1997) and are truncated by the base Haushi Group unconformity.

The Ordovician Amdeh Formation of the Saih Hatat area in the Oman Mountains consists of a sequence of shallow marine sandstones and mudstones (Lovelock et al., 1981) that correspond to the lower part of the Safiq Group based on biostratigraphic dating. It is, however, possible that the undated Lower Quartzite Member and the Lower Siltstone Member corresponds to the Ghudun Formation of the subsurface. It is not clear how the outcrops of the Saih Hatat area fit into a regional paleogeographic model of this part of this part of the Haima Supergroup.

An excellent correlation exists with the shallow marine Lower Paleozoic clastics reported from Saudi Arabia which have good biostratigraphic control (Stump et al., 1995). The biostratigraphy and major transgressive-regressive trends show the Hanadir (Llanvirn-Llandeilo) and Ra’an (Caradoc) members of the Qasim Formation and the Qusaiba shale (Llandovery-Wenlock) Member of the Qalibah Formation to correlate with the Saih Nihayda, Hasirah and Sahmah shale intervals of the Safiq Group in Oman.

Erosional events associated with the Hasirah sandstones can be correlated with major continental glaciations that have been reported from the Ashgill to ?Lower Llandovery of Saudi Arabia that caused valley incisions with a relief of more than 200 m (Vaslet, 1989; 1990). The shallow marine sandstones of the Sahmah Member in the upper part of the Saq Formation are poorly dated, ranging in age from Middle Cambrian through Arenig and may correspond to the widespread Ghudun Formation of Oman.

The marine deposits of the Burj Formation and its lateral non-marine equivalent the Risha Member of the basal Saq Formation can be correlated to the marine-influenced Andam Formation. The thin basal transgressive marine shale of the Burj Formation may correspond to the flooding event of the Barakat Member, this being the most extensive transgression recorded in Oman. The Early Cambrian age that has been suggested for the alluvial Siq/Yatib formations (Stump et al., 1995) would make these sediments stratigraphically equivalent to the widespread Amin Formation and/or the more laterally restricted Nimr Group. The Saudi Arabian data show more complete sections of Silurian and Devonian strata which seems to be absent in Oman due to erosion below the base Haushi unconformity.

**TECTONOSTRATIGRAPHIC EVOLUTION**

**Lower to ?Middle Cambrian: Nimr Group**

Relatively little is known of the depositional setting and stratigraphic evolution of the Nimr Group. Most well and all core data are concentrated in South Oman. Seismic evidence suggests that the Nimr Group is restricted to the central parts of the salt basins showing an onlap onto the bordering Huqf
Figure 13: Correlation of Lower Palaeozoic sections in Oman and Saudi Arabia based on a framework of regional unconformities and major marine flooding surfaces.
basement highs and salt diapirs within the basin (Figure 14). Syndepositional salt movement played a major role in the distribution of the Nimr Group especially in the South Oman Salt Basin where seismic evidence shows a complicated internal sequence of onlapping wedges and seismic facies changes between salt highs. Here, several depocentres developed separated by basement and salt highs, each of which may have its own infill history. The infill shows thickness changes over short distances caused by erosion and truncation on the salt highs and shifting of depocentres by salt withdrawal. Seismic evidence in the deeper Ghaba salt basin indicates that the Nimr Group may attain a thickness of several kilometers. Syndepositional salt movement was less significant and with a lower amplitude than that of South Oman and depositional conditions of the Nimr Group seem to be laterally more extensive. The Nimr Group is relatively thin or absent in the Fahud Salt Basin.

In South Oman two formations have been recognised in the Nimr Group: the Karim Formation and the overlying Haradh Formation. The Karim Formation consists of fine- to very fine-grained sandstones representing sheet sands and channel-fill deposits in an alluvial fan setting. This is usually overlain by a shale interval with interbeds of silts and sandstones thought to be lacustrine/playa lake in origin. The Haradh Formation unconformably overlies the Karim Formation and consists of fine-grained sandstones and shales coarsening upwards into medium- to coarse-grained sandstones with chert fragments. These represent braided river channel and sheetflood deposits in a prograding alluvial apron probably sourced from highlands in the west of the South Oman Salt Basin (Heward, 1990). Major thickness changes over short distances suggest very active syndepositional salt withdrawal in this area. In Central and North Oman, limited well data of the Nimr Group indicate similar lithologies and vertical trends and likewise a continental alluvial fan to lacustrine playa lake setting is assumed.

There are indications in the Ghaba Salt Basin that thin salt beds occur in the basal part of the fine grained sands (Karim Formation?), suggesting that the contact with the underlying Huqf salt series in the central part of the basins may be transitional. This is also suggested by the absence of an apparent break with underlying clastics assigned to the uppermost Huqf (Dhahaban Formation) near the Western Margin in South Oman. On the basin margins the basal contact with Huqf carbonates is formed by an angular unconformity with, in places, large reworked clasts of carbonates and cherts in the basal Karim Formation.

The continental sediments of the Nimr Group are considered to represent a continuation of the infill of the Huqf rift basins following a complete isolation of these basins from open marine water by tectonic uplift at entrance straits or a eustatic sea-level drop, that terminated the initial carbonate-evaporite system infilling stage.

A regional angular unconformity separates the Nimr Group from the overlying Mahatta Humaid Group. This so called “Angudan unconformity” is thought to represent the rift-sag unconformity of the Huqf rifting phase (Loosveld et al., 1996).

Middle Cambrian: Amin, Miqrat and Mahwis Formations (Basal Mahatta Humaid Group)

The base of the Mahatta Humaid Group is represented by the Amin Formation, a sandstone and conglomerate package which overlies the Angudan unconformity. The Amin Formation is one of the most widespread units of the Haima Supergroup and oversteps the underlying truncated Nimr and Huqf strata onto the flanks of the Salt Basin (Figure 15). The Formation shows a variable thickness in the basins as result of salt withdrawal, and thins onto the basin flanks.

The onset of the deposition of the Amin Formation is characterised by the influx of coarse clastics into the basins. Conglomerates interbedded with sandstones typify the Conglomeratic Sandstone Member, often exceeding several hundreds of meters in thickness. Conglomeratic sandstones have been encountered at the base of the Formation along the Western Flank of the South Oman Salt Basins, the southeastern margin of the Ghaba Salt Basin and in the Fahud Salt Basin where it is only a few tens of
Figure 14: Distribution of the Nimr Group sediments.
Figure 15: Distribution and facies of the Amin Formation.
meters thick). These are interpreted as proximal alluvial fan deposits sourced from the uplifted basin margin highs and filling in topographic lows. Basinward, these deposits interfinger with alluvial and aeolian sandstones. The composition of the conglomerates is variable and reflects different sources: along the Western Margin they are polymict, with pebbles of cherts, dolomite, greywacke, igneous and metamorphic rocks, while those in the southeastern Ghaba Salt Basin and Fahud Salt Basin consist almost entirely of chert pebbles.

The upper and basinal part of the Amin Formation consist of the Sandstone Member, a widespread package of clean quartzose sandstones of interbedded aeolian (dune and interdune) and fluvial origin. In the Fahud Salt Basin the sands are slightly argillaceous containing locally siltstone streaks, while interbedded mudstones occur in the basal part of the sands in the eastern Ghaba Salt Basin. This finer grained unit may have been deposited in interdune ponds or lakes. By late Amin times, all the relict topography of the Huqf rift system was leveled, and relatively uniform depositional conditions persisted over large areas.

The top of the Amin Formation represents a major change in sedimentation and depositional differentiation between the different salt basins. In the South Oman Salt Basin the clean Amin sandstones are overlain by dirty shaly sands of the Mahwis Formation. The Mahwis Formation consists of an overall fining-upwards sequence of micaceous sandstones interbedded with conglomerates grading vertically and laterally into fine-grained micaceous shaly sandstones and siltstones. The conglomerates have a similar composition to those of the Amin Formation and the renewed influx may reflect a reactivation of the same source areas. The sediments of the Mahwis Formation were deposited in a system of extensive semi-arid alluvial fans that laterally graded into alluvial plains with sheetflood deposits and ephemeral lakes/sabkhas (Heward, 1989). Regional facies trends indicate a southwest to northeast transport direction suggesting that the sediment was derived from the southwestern and southern margins of the South Oman Salt Basin (Figure 16). The contact between the Amin and Mahwis formations is often abrupt and therefore assumed to be disconformable, however in places transitions with interbedding of the two sediment types has been reported (Heward, 1989). Seismic evidence shows the presence of wedge-shaped geometries within the Mahwis Formation as a result of syndepositional salt movement (see Figure 8).

In the Ghaba Salt Basin, the Amin Formation is overlain by red-brown micaceous shales and siltstones intercalated with fine- to very fine-grained sandstones of the Miqrat Formation. The Miqrat Formation was deposited in an inland sabkha to lacustrine setting with influxes of sheet sands. Well data in Central Oman suggest that the Miqrat Formation is a lateral, more distal, equivalent of at least the lower part of the Mahwis Formation of South Oman (Figure 16). A highly micaceous sandy siltstone marker bed can be recognised over most of the Ghaba Salt Basin and divides this Formation into two overall fining-upward units. The micaceous silts may have been deposited in an extensive lake covering a large part of North Oman.

Seismic and well data show strong lateral thickness changes in the Miqrat reflecting differential subsidence variations above unstable salt substrate and across old basement fault lineaments. The contact between the Amin and Miqrat formations is often abrupt and may be unconformable. This is also suggested by possible onlap geometries on seismic, although the seismic resolution at the depths concerned (5-6 km) does not allow distinction between onlap and stratigraphic thickening. Along the eastern edge of the Ghaba Salt Basin the boundary between these two formations is transitional. In the Fahud Salt Basin the Miqrat Formation is absent or when present, much thinner and poorly developed in a less sandy, more distal facies.

Apart from renewed uplift at the margins and reactivation of sediment source areas in South Oman, a climatic change seems to have occurred towards more humid conditions across the Amin Mahwis/Miqrat boundary. The characteristic shaly micaceous nature of these formations suggests a common occurrence of ephemeral lakes/inland sabkhas in contrast to the well-sorted, clean, more “arid” Amin sands.
Figure 16: Distribution and facies of the Mahwis and Miqrat formations.
Late Cambrian to Early Ordovician: Al Bashair, Barik Sandstone and Mabrouk Members of Andam Formation

A further differentiation in depositional environments between the north and south Oman Salt Basins occurred in the Late Cambrian to Early Ordovician with marine incursions in the North Oman while continental conditions continued in the South Oman Salt Basin. In North Oman the marine influenced units are grouped in the Andam Formation. The marine incursions in the Andam Formation diminish towards the south of the Ghaba Salt Basin and the Formation becomes more continental in character. It is thought that the Andam Formation is the stratigraphic equivalent of the upper part of the Mahwis Formation of the South Oman Salt Basin. Subtle onlapping geometries on regional seismic lines in North Oman, and truncation of the underlying Miqrat and Amin formations in the Fahud Salt Basin, indicate that the base Andam is a regional unconformity.

The Andam Formation has a very poor internal seismic reflectivity and only a few reflectors can be confidently picked between the multiples from the overburden and correlated over larger regions.

Lateral continuity of marker beds formed by marine flooding surfaces between wells over a few hundred kilometers suggests a nearly flat topography. Well and seismic data show very gradual but substantial thickness increase of units towards the center of the Ghaba Salt Basin. Subtle changes in subsidence above unstable salt substrate and across Huqf fault lineaments also caused lateral thickness variations. Well correlations show that a large part of the thickening is taken up by stratigraphic expansion. Onlap or truncation of sediment packages within the Andam Formation are suspected, but are not clearly recognisable on seismic and from the biased well dataset. Wedging on seismic profiles suggest that it is likely that additional stratigraphic units are present in the undrilled lows between the structural highs. In the Fahud Salt Basin the Andam Formation is much thinner than in the adjacent Ghaba Salt Basin.

The first clear indications for marine conditions since Huqf times are found at the base of the Al Bashair Member. The lower part of this member contains an overall transgressive stacking of very shallow marine to inter- and supratidal shallowing-upward cycles with clastic and carbonate sediments. Log correlations show a subtle onlap/stratigraphic thinning towards the Central Oman High in the south. The overall deepening trend of the basal Al Bashair Member reaches a maximum flooding surface with open marine, storm-influenced conditions. Following this maximum flooding surface (MFS-1, Figure 11) an overall coarsening-upward progradational trend can be recognised all over the basin towards the sandstones of the Barik Sandstone Member. These represent the progradation of a braid delta system with the upper Al Bashair Member representing marine prodelta deposits grading into braid delta front, platform and plain deposits of the Barik Sandstone Member.

Palaeocurrent directions and facies distribution suggest that the main development of this delta system followed the axis of the Ghaba Salt Basin from south to north (Figure 17). A braid delta plain setting predominated in the south and progressively developed into a more distal braid delta front to shelf setting in the north. In the upper part of the Barik Sandstone Member the delta cycles are stacked in an overall transgressive trend towards a major flooding surface (MFS-2, Figure 11) in the basal part of the Mabrouk Member.

The relationship of the Barik Sandstone Member along the western margin with the delta system described above is not clear. Possibly these represent shallow marine sediments deposited laterally from the main delta system. Open marine conditions were established in the basal part of the Mabrouk Member. Intertidal sabkha conditions are suggested for the upper Mabrouk Member in cores from the Ghaba Salt Basin. The transition from the underlying marine unit is not clear, however, and intermediate shoreface sands are missing. It may be possible that, in places, the major unconformity now placed at the base Barakat Member occurs within the upper Mabrouk Member. With the current data, however, this cannot be proven.
Figure 17: Distribution and facies of the Barik Sandstone Member of the Andam Formation.
A major regional unconformity separates the Barakat Member from the other underlying members of the Andam Formation. Previously this unconformity was interpreted to be located at the base of the Ghudun Formation (Hughes Clarke 1988). Log correlations, however, clearly show that very low angle truncation and thinning of underlying units occurs not below the base Ghudun but below the sandy interval at the base of the Barakat Member. The amount of truncation increases towards the southern, western and eastern flanks of the Ghaba Salt Basin and may be in the order of at least 300 m in the Ghaba Salt Basin to 600 m on the Central Oman High. Though it would be desirable to include the Barakat Member with the overlying Ghudun into one formation, it has been kept for operational reasons with the lithologically similar Andam Formation, because of the difficulty to recognise this unconformity (often shale on shale) on well logs, cuttings and seismic.

The basal Barakat Member consists of marine deposits laid down during an extensive marine transgression that extended over north and south Oman. In the Ghaba Salt Basin a thin shallow marine sandstone interval is often present at the base but is missing in many other areas where the underlying Mabrouk Member consists mainly of mudstones, or cannot be recognised when overlying units are sandy, as in South Oman. A major marine flooding surface (MFS-3, Figure 11) is located in the middle of the Barakat Member. This is followed by a coarsening shallowing upward trend into the sands of the Ghudun Formation that were deposited in a braid delta complex (Figure 18). Although there is definite marine influence in the Ghudun the overall setting seems to be generally more proximal (braid plain) than that of the Barik Sandstone Member. A more distal setting is suggested in the northern part of the Ghaba Salt Basin by the overall finer grain sizes and clear evidence of marine conditions. The vertical stacking of these braid delta cycles into a widespread package of more than 1,000 m thickness without any major marine incursions suggest a very high sediment influx coupled to high regional subsidence.

A major erosional unconformity occurs below the overlying Safiq Group with removal of up to several hundreds of meters of Ghudun Formation. This unconformity is associated with uplift of the regional highs separating the salt basins.

### Middle Ordovician to Early Silurian: Safiq Group

The uppermost unit of the Haima Supergroup is formed by sediments of the Safiq Group. Apart from a major stratigraphic break the base Safiq boundary also marks a major change in the regional depositional setting. Sediments of the Safiq Group cover a wide range of depositional environments from deep open marine to alluvial plain compared to the narrow ranged restricted very shallow marine to marginal marine/continental Mahatta Humaid sedimentary rocks. Furthermore the Safiq sediments contain palynofloras that in places are dominated by cryptospores, considered to be derived from the earliest land plants. Marine acritarchs and chitinozoans, and, in cores, graptolites are also often recovered.

The depositional setting and trends and internal stratigraphy of the Safiq Group is still relatively poorly understood and the seismic resolution is very poor. The unit has a scattered distribution due to erosion associated with incisions during the Permo-Carboniferous Al Khlata glaciation, and major lateral facies variations occur related to internal erosional surfaces and incisions (Figure 10). Furthermore, the wells are located on regional highs, where most erosion is expected and the well data provide only an incomplete picture of the stratigraphy.

The Safiq Group consists of open marine to restricted marine/deltaic sediments stacked into three major transgressive-regressive cycles each corresponding to one of the three formations; the Saih Nihayda, Hasirah and Sahmah. An onlap onto the Ghudun towards the south can be observed. The Saih Nihayda Formation occurs only in the north and disappears by onlap and truncation near the Central Oman High, while the overlying Hasirah Formation is widespread over both Central and North Oman. The present day distribution of the Sahmah Formation is limited by Pre-Haushi erosion. However, a major flooding event at its base resulted in the deposition of organic-rich sediments which may suggest an even more widespread distribution than the Hasirah Formation.
Figure 18: Distribution of the Ghudun Formation.
Within the Hasirah Formation at least one major unconformity occurs that is associated with the sudden influx of significant amounts of fluvial to deltaic sands on top of deep marine sediments, and suggests a major fall in relative sea-level. This can be correlated with major continental glaciations that have been reported from the Ashgill to Early Llandovery of Saudi Arabia that caused valley incisions with a relief of more than 200 m (Vaslet, 1989; 1990). The major flooding at the base of the overlying Sahmah Formation may represent the sea-level rise resulting from the melting of the ice cap.

**POST SILURIAN**

A major time gap, in most areas more than 100 million years, separates the Haima Supergroup from the Upper Paleozoic sediments of the Haushi Group in Oman. Tilting and uplift of Early Palaeozoic strata occurred above salt pillows and regional highs in the east (Huqf axis) and north (Oman Mountains). This may be related to Late Carboniferous thermal doming preceding the break-up of Gondwana leading to the formation of the Neotethys ocean in the north and the later separation of the Arabian plate from India-Madagascar-Antarctica in the east (Loosveld et al., 1996). Erosion of the high area is further enhanced by the repeated Late Carboniferous Early Permian Gondwana glaciations during which land ice covered Oman (Levell et al., 1988).

Some sediments of Devonian age have been encountered in a small number of wells in central and southeast Oman preserved in synclines and half graben fills below the base Haushi unconformity. These consists of a variety of sandstones, siltstones, shales, some of which are organic-rich, and limestones deposited in continental alluvial fan/fan delta to marine environments and have been defined as the Misfar Group (Hughes Clarke, 1988). In Saudi Arabia more complete sections through the Devonian exist with Lower to Middle Devonian continental to shallow marine sandstones and shales and some carbonates overlying the Lower Silurian clastics. It is likely that in structural lows of the Oman subsurface, similar more complete Palaeozoic sections may be present.

**HYDROCARBON PLAY ASPECTS**

In South Oman, sandstones of the Nimr, Amin and Mahwis form oil reservoirs sealed by either Nahr Umr (Lower Cretaceous) or Rahab (Al Khlata Formation, Lower Permian) shales or in places by the intra-formational Karim shale. The structures are related to withdrawal and dissolution of underlying Infracambrian salt (Heward, 1990). Approximately 151 million cubic meter (MMm$^3$) oil has been found in these reservoirs.

In North Oman approximately 67 MMm$^3$ condensate (95 MMm$^3$ expected) and 14 trillion cubic feet (TCF) (18 TCF expected) gas have been found in Haima reservoirs. The main reservoir intervals are sandstones of the Amin and Miqrat Formations and the Barik Sandstone Member of the Andam Formation (Figure 19). Seals are provided by mudstones of the basal Miqrat Formation, mid-Al Bashair and Mabrouk members and intra-formational mudstone beds. The structures consist of gentle, faulted, dip closures over Huqf salt pillows or basement highs.

Oil source rock correlations have shown that Huqf sediments are the principle source rocks for the hydrocarbons.

**CONCLUSIONS**

The Haima Supergroup of Oman consist of predominantly siliciclastic sediments of Cambrian to Early Silurian age. These sediments form the late syn- to post-rift deposits of an extensive Precambrian graben system and overly an earlier infill of evaporites, shales and carbonates of the Huqf Supergroup.

An actualistic approach using recent examples in determining the depositional setting is severely hampered by the absence of landplants and the presence of only limited marine burrowing organisms during Early Palaeozoic times. The depositional setting was initially continental, but higher in the sequence a marine influenced deltaic setting prevailed. Marine influence is more prominent in the north while regionally the main clastic influx into the basins was from the south. Lithological units area laterally extensive and small-scale depositional cycles, 10 to 20 m thick, can be confidently correlated over more than 100 kilometers.
Figure 19: Schematic geological cross-section of the Ghaba Salt Basin showing Haima hydrocarbon play aspects.
At least six major transgressive regressive cycles can be recognised. The regional correlatable marine maximum flooding surfaces and unconformities provided a chronostratigraphic framework which improved the understanding of the stratigraphic relationships between the different units and the distribution of the reservoir seal pairs.

Seismic evidence shows numerous onlap and truncation surfaces and indicates that syndepositional movement of underlying salt was an important control on the distribution and thickness of the different units. Seismic data also show that the existing knowledge of the Haima is from a biased dataset, all wells have been drilled on local highs. The intervening lows are undersampled and additional stratigraphic units to those described in this paper can be expected in these areas.

Several intervals with laterally extensive sheets of sands sealed by mudstones have trapped hydrocarbons in structures related to underlying salt pillows or basement highs. The reservoirs in North Oman are mainly filled with gas and condensates while the Haima of South Oman contributes to the oil production.

ACKNOWLEDGEMENTS

The author wishes to thank the Ministry of Petroleum and Minerals and Petroleum Development Oman (PDO) for their permission to publish this paper. For this review, data from several unpublished company reports were used and this paper reflects many years of work by a great number of present and former PDO geologists. Special mention should go to Rashid Mohammed, John Millson, Fer Guit, Herman Priebe, Christos Kapellos, Christel Hartkamp-Bakker, Stuart Lake, Marrietta Vroon the Hove, Charlie Love, Randall Penney, Mark Bentley and Recep Kazdal. Many thanks are due to Moujahed I. Al-Husseini, Gulf PetroLink’s staff and to the anonymous reviewers for their comments that greatly improved the paper.

APPENDIX 1

LITHOSTRATIGRAPHIC DESCRIPTIONS

Introduction

This appendix describes the lithostratigraphic definitions of the units in the Haima Supergroup as they are currently being used by Petroleum Development Oman. The lithostratigraphy presented in this appendix is an update and revision of that presented by Hughes Clarke in 1988. Figures 20 to 23 show type logs for the Haima Supergroup in both south and north Oman. More type logs of the different Haima units are provided in Hughes Clarke (1988).

HAIMA SUPERGROUP

Author: Von der Weid (unpublished report, PDO, 1967), originally defined as group name for all the Palaeozoic formations above the Buah dolomite. Restricted to the Lower Palaeozoic by Winkler (unpublished report, PDO, 1975; see also Hughes Clarke 1988) and upgraded to Supergroup by Priebe and Kapellos (unpublished report, PDO, 1993; partly published in Boserio et al., 1995).

Definition: A major siliciclastic-dominated unit of Cambrian to Silurian age unconformably overlying the siliciclastics, carbonates or evaporites of the Huqf Supergroup and unconformably overlain by sediments of the Devonian Misfar, Permo-Carboniferous Haushi or younger groups. The Haima Supergroup is widespread in both south and central Oman and can attain a thickness over 6 km in the Ghaba Salt Basin of central Oman. The Haima is subdivided into three groups (from base to top): the Nimr, Mahatta Humaid and Safiq.
**NIMR GROUP**

Authors: Priebe and Kapellos (unpublished report, PDO, 1993; partly published in Boserio et al., 1995). This unit has been informally described as “Lower Haima of South Oman” by Hughes Clarke (1988).

**Type Area:** Eastern Flank of South Oman, particularly Nimr, Karim West, Amal and Amin fields.

**Definition:** Red-brown to light grey, either very fine- or fine- to coarse-grained, unfossiliferous and often micaceous clastics. In South Oman (Eastern Flank area) a lower Karim and upper Haradh Formation are clearly recognisable (Figure 20). In North Oman the Nimr Group is undifferentiated (Figure 21). The Nimr Group is bounded at the top by an angular unconformity of regional extent which has been observed on seismic and dipmeter logs. Lithologically, this upper boundary is in some areas difficult to define as the basal Amin may have similar lithological character.

**Distribution:** The Nimr Group is restricted to the central parts of the Oman Salt Basins. In south Oman there are numerous penetrations of this unit which was deposited in a complex of peripheral sinks between Huqf salt pillows and ridges (see Heward, 1990). In the north Oman Ghaba Salt Basin there are only a handful of Nimr penetrations by wells but seismic data shows that the undrilled deeper
| Depth (m) |
|-----------|
| 3,600     |
| 4,000     |
| 4,500     |
| 5,000     |
| 5,500     |

### Figure 21: Type log of the Haima Supergroup in North Oman.

| GR (API) | LITHOLOGY | FORMATION | GROUP |
|----------|-----------|-----------|-------|
| 0.0  | 200.0 | Hasirah | SAIFI |
|        |         | Saih Nihayda |       |
|        |         | Ghudun | MAHATTAL |
|        |         | Barakat Mbr | HUMAID |
|        |         | Mabrouk Mbr |       |
|        |         | Barik Mbr |       |
|        |         | Al Bashair Mbr |       |
|        |         | Upper Mbr | NMR |
|        |         | Lower Mbr |       |
|        |         | Amin |       |
|        |         | Undifferentiated in North Oman | HUQF |
parts of the basin contains a thick package of Nimr equivalent sediments. Towards the flanks of the basins the Nimr Group disappears by onlap and truncation and on basement highs the Nimr is absent. In the Fahud Salt Basin the Nimr Group is relatively thin and poorly developed.

**Karim Formation**

*Author:* Wiemer (unpublished report, PDO, 1981; see also Heward 1990).

*Type Area:* Eastern Flank of the South Oman Salt Basin.

*Definition:* A lower predominantly sandstone interval overlain by a shale unit with interbeds of silt- and sandstones.

*Distribution:* The Karim Formation is only recognised in south Oman where several depocentres with different facies distributions can be recognised. The Karim is only known from subsurface data.

*Lithology:* The basal sandstones consist predominantly of fine- to very fine-grained, well to moderately sorted, light grey, occasionally red sandstones. They are interbedded with silts and shales. Locally large lithoclasts of carbonates and chert, derived from the underlying Huqf sediments occur at the base. The sediments show a variety of structures: low angle lamination, convolute lamination and trough cross-bedding in the sandstones, ripple and horizontal laminae and mudcracks in the mudstones. Soft sediment deformation features such as sand dikes ball and pillow structures are common in the finer-grained lithologies. Erosionally based packages up to a meter thick and sometimes fining-upward can be recognised. Intra-formational siltstone clasts may occur especially at the base of these units. A variable amount of dolomite cement has been encountered in these sediments.

The overlying shales are predominantly red, occasionally greyish/green, and micaceous with interbeds of red-brown micaceous siltstones and sandstones.

*Wireline logs response:* The basal sandstone shows a serrated, 50 to 110 API, gamma-ray response which shows a barrel-shaped profile. The upper interval has a higher gamma-ray response and a typical Density and Neutron Log separation for shales.

*Boundaries:* In most parts of the Eastern Flank the lower boundary is a hiatus or an angular unconformity with the underlying Huqf sediments. However near the western margin of the South Oman Salt Basin the transition into the underlying clastics of the Dhahaban Formation (Huqf Supergroup) seems to be continuous without an apparent break. The nature of the upper boundary with the sandstones of the Haradh Formation is not clear, in the past it was assumed to be conformable (see Boserio et al., 1995) but recent studies suggest that the Karim has been eroded before deposition of the Haradh (Hartkamp-Bakker, unpublished report, PDO, 1995).

*Age:* The Karim Formation has not itself been dated, but an Early Cambrian age is assumed based on the age interpretation of over- and underlying units.

*Depositional Setting:* The fine- to very fine-grained sandstones of the Karim Formation are interpreted as sheet sands and channel fill deposits in an alluvial fan setting. The interbedded and overlying shale intervals with interbeds of silts and sandstones are thought to be lacustrine/playa lake in origin. Several depocentres can be recognised and the internal stratigraphy of the Karim Formation is variable.

**Haradh Formation**

*Author:* Wiemer (unpublished report, PDO, 1981; see also Heward, 1990).

*Type Area:* Eastern Flank of the South Oman Salt Basin.

*Definition:* A siliciclastic unit which, when fully developed, represents a coarsening upward sequence.
**Distribution:** The Haradh Formation is only recognised in South Oman and best developed in the Eastern Flank area. The distribution is patchy due to erosional truncation and syndepositional salt movement. The Haradh is only known from subsurface data.

**Lithology:** The lower part consists of fine-grained, well-sorted, light grey to occasionally red quartzose sandstones with streaks of grey micaceous siltstones and reddish shales. These sediments grade upwards into lithic and sublithic cross-bedded, porous sandstones that are grey, medium to coarse grained and frequently rich in chert fragments. The cherts are laminated and it is thought they were sourced from exposed siliceous mudstones of the Huqf Group.

**Wireline logs response:** The gamma-ray response is very spiky and overall funnel shaped with values between 50 and 120 API. The spiky response reflects the micaceous nature of the sands, and intercalated shales shown by thin (2-5 m) Density and Neutron Log separations.

**Boundaries:** The nature of the lower boundary with the Karim Formation is not clear. In the past it was assumed to be conformable (see Boserio et al., 1995) but recent studies suggest that the Karim has been eroded before deposition of the Haradh (Hartkamp, unpublished report, PDO, 1995). The upper boundary is formed by an angular unconformity with the Amin or younger formations.

**Age:** The Haradh Formation has not been dated, an Early Cambrian age is assumed based on the age interpretation of over- and underlying units.

**Depositional Setting:** The Haradh Formation is interpreted as braided river channel and sheetflood deposits in a prograding alluvial apron probably sourced from highlands in the west of the South Oman Salt Basin (Heward, 1990). Major lateral thickness changes over short distances suggest very active syndepositional salt withdrawal in this area. In North Oman limited well data of the Nimr Group indicate similar lithologies and vertical trends and likewise a continental alluvial fan to lacustrine playa lake setting is assumed.

**MAHATTA HUMAID GROUP**

New group name introduced here for North and South Oman. Originally the Mahatta Humaid was the formation name used by Kassler (unpublished report, PDO, 1966) for the outcropping Cambrian to Ordovician clastic sediments in the Huqf area.

**Type Area:** the outcrops in the Qarn Mahatta Humaid area of the northern Huqf (see Millson et al., 1996; Buckley, 1997) and the Ghaba Salt Basin.

**Definition:** A composite clastic rock unit of Cambrian to Lower Ordovician age. The lower part of this Group is dominated by continental clastics, the upper part comprises largely marine to coastal deltaic sediments (Figures 11 and 21). Some carbonates may be present in the middle part of this unit. This Group is separated from the underlying Nimr or Huqf and the overlying Safiq Group by major unconformities. In North Oman, the Mahatta Humaid Group consists of four formations (from base to top): the Amin, Miqrat, Andam and Ghudun.

**Amin Formation**

**Authors:** Winkler and Rácz (unpublished report, PDO, 1978), revised by Oprinsen (unpublished report, PDO, 1986), published by Hughes Clarke (1988). The original definition was based on subsurface data.

**Type Area:** Southern part of the Haima outcrops in the Huqf area (Buckley and Harbury, 1996). Originally these sediments have been described as “Lower Haima” by Millson et al. (1996). Further study (Buckley and Harbury, 1996; Buckley, 1997) has shown that these sediments are equivalent to the Amin known in the subsurface and that the ‘Amin’ of Millson et al. (1996) belongs to the overlying Miqrat Formation.
Definition: The Amin Formation forms the lowermost part of the Mahatta Humaid Group and is characterised by the occurrence of very clean, quartzose sandstones. Three members are recognised: (1) Sandstone, (2) Interbedded Siltstone and Sandstone, and (3) the Conglomeratic Sandstone Member. The last two members occur at the base of the formation, the boundaries between the three members are diachronous.

Distribution: The Amin Formation has a wide distribution in Oman and can reach a thickness in excess of 700 m. Seismic evidence suggests that an even thicker development can be expected in the center of the Ghaba Salt Basin. The formation shows a varying thickness in the basins as result of salt withdrawal and thins onto the flanks of the salt basins by onlap and possibly some truncation at the top. Two members show a restricted distribution: the Conglomeratic Sandstone Member has its main occurrence along the Western Margin and the north-northwestern parts of the South Oman Salt Basin, in the southern Ghaba Salt Basin, north of the Central Oman High, possibly extending into the central parts of the basin, and the Fahud Salt Basin. The Interbedded Siltstone and Sandstone Member is mainly developed on the Eastern Flank Area of the Ghaba Salt Basin. The Sandstone Member has a very wide distribution both in North and South Oman.

Wireline log response: The Amin Formation is characterised by its very low gamma-ray values (less than 30 API) either with a spiky or undifferentiated monotonous pattern.

Boundaries: A major unconformity occurs between the Amin Formation and the underlying Huqf or Nimr (Super) groups that can be clearly recognised on the dipmeter logs. This angular unconformity has also been observed on seismic lines and in the Huqf outcrops. Lithologically the boundary with the Nimr Group is difficult to define as the basal Amin may have similar lithological character. Seismic and well log correlations suggest that the Amin Formation is bounded at the top by an onlap surface and possibly an erosional unconformity. Lithologically the top of the Amin Formation is defined by the onset of a fining upward trend and the appearance of the argillaceous and micaceous facies of the Miqrat Formation in North and the Mahwis Formation in South Oman.

Age: The Amin Formation is unfossiliferous and no biostratigraphic data are available. The Middle to Late Cambrian age established for the stratigraphically higher Andam Formation and the Early Cambrian age suggested for the underlying Huqf Supergroup (Maties and Conway Morris, 1990) would constrain the Amin to the Early to Middle Cambrian. An Early Cambrian age has been inferred on assumed equivalence to the Lalun Formation in Iran (Hughes Clarke, 1988).

Depositional Setting: The Amin Formation was deposited in an arid continental setting and contains alluvial fan, fluvial and aeolian (dune and wet interdune) deposits.

Amin Sandstone Member

Authors: Priibe and Kapellos (unpublished report, PDO, 1993; partly published in Boserio et al., 1995). This member corresponds to Unit 2 shown in Figure 6 of Hughes Clarke (1988).

Type Area: Subsurface of the Eastern Flank and the Ghaba Salt Basin.

Definition: A uniform package of clean quartz-rich sandstones.

Distribution: The Amin Sandstone Member is widespread over Oman. The thickness is variable and can be more than 700 m has been recorded in wells. Thicker intervals are expected in the central part of the Ghaba Salt Basin.

Lithology: Uniform package of clean light grey to greyish-brown coloured quartzose sandstones which are either fine- to medium- or occasionally coarse-grained. The sandstones are consolidated to friable/loose, very well-sorted, with rounded to subrounded sometimes frosted grains and classify as sublithic arenite to quartz arenites. The lithics are mainly represented by chert and metamorphic fragments. Locally traces of greenish-grey to reddish coloured shales with internal deformations features and

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desiccation cracks are present. No fossils have been observed. More argillaceous and siltstone streaks occur in the Amin on the Mabrouk Makarem High and in the Fahud Salt Basin. The sandstones are predominantly horizontal and low angle cross-stratified, in places steep 25-30° sedimentary dips occur (Heward, 1990) and also trough cross-bedding has been observed. Bed contacts often are erosive. In finer grained silty intervals adhesion ripples occur.

**Wireline log response:** The Amin Sandstone Member is characterised by a typical uniform low gamma-ray signature with values of 20 to 30 API. The argillaceous sandstones on the Mabrouk Makarem High and Fahud Salt Basin have a more spiky gamma-ray log response with peaks of 50 to 100 API. Dipmeter logs may show high sedimentary dips of 25-30°.

**Boundaries:** The lower boundary of the Amin Sandstone Member is a sharp-based contact when overlying the more shaly Interbedded Sand- and Siltstone Member. The contact with the Conglomeratic Sandstone Member is less sharp and may be gradational. The boundary is picked at the base of the interval with monotonous very low API gamma log values of non-conglomeratic sandstones. The top of this Member with the overlying Miqrat or Mahwis Formation is characterised by the first appearance of very micaceous sediments which give very high API gamma log values. This boundary is thought to be unconformable and onlap of the overlying Miqrat and Mahwis Formation has been observed on seismic and well log correlations.

**Age:** The Amin Sandstone Member is unfossiliferous and no biostratigraphic data are available. The Middle to Late Cambrian age established for the stratigraphic higher Andam Formation and the Early Cambrian age suggested for the underlying Huqf Supergroup (Mattes and Conway Morris, 1990) would constrain the age to the Early to Middle Cambrian. An Early Cambrian age has also been inferred on assumed equivalence to the Lalun Formation in Iran by Hughes Clarke (1988).

**Depositional Setting:** The good sorting, rounding, presence of frosted grains, lack of shales and mica and high sedimentary dips suggest aeolian influence. The horizontal to low angle cross-stratification observed on the dipmeter log of many wells may be related to the fact that only the basal part of the dunes is preserved. The silty streaks occurring within the sandstones and intervals with adhesion ripple sandstones are interpreted as wet interdune deposits. These seem to be more frequent on the Mabrouk - Makarem High and in the Fahud Salt Basin. Some fluvial sedimentation is suggested by the occurrence of trough cross-bedding. Fluvial influence in this member may vary regionally and is expected to increase towards the base and at the transition into the Conglomeratic Sandstone Member.

**Amin Conglomeratic Sandstone Member**

**Authors:** Priebe and Kapellos (unpublished report, PDO, 1993; partly published in Boserio et al., 1995) based on subsurface data. Sediments of this member outcropping in the Huqf area have been described as “Lower Haima” by Millson at al., 1996 (see discussion Buckley and Harbury, 1996; Buckley, 1997).

**Type Area:** Southern Haima outcrops in the Huqf area (Buckley and Harbury, 1996; Buckley, 1997) and the Western Margin of the South Oman Salt Basin

**Definition:** Conglomerates and conglomeratic sandstones with some interbedded mudstones.

**Distribution:** The Amin Conglomeratic Sandstone Member has its major occurrence along the Western Margin and the northwestern parts of the South Oman Salt Basin, in the southern Ghaba Salt Basin, possibly extending into the central parts of the basin, and the southern Huqf area. Conglomerates also occur in a much thinner interval of only a few tens of meters thickness in the Fahud Salt Basin. It is not known whether these conglomerates belong to the same depositional unit.

**Lithology:** Alternation of white to light grey coloured, fine- to medium-grained sandstones, medium to very coarse-grained conglomeratic sandstones, with a sand to silt matrix and red to reddish brown shales. The poorly sorted conglomerates are polymict and contain pebbles and granules of chert, silicilite, quartz, metamorphic rock and occasionally dolomite. The sandstones and conglomerates...
show various scales of trough and tabular cross-bedding. Large-scale fining upward trends (over more than 100 m) with an increasing number of mudstone intercalations occur.

Wireline log response: The conglomerates and conglomeratic sands show a slightly spiky monotonous low gamma-ray response with values 25 to 75 API. Muddy parts show higher values of 50 to 100 API.

Boundaries: The upper boundary of this member with the Amin Sandstone Member is thought to be conformable and transitional. The contact with the overlying Amin Sandstone Member is characterised by the disappearance of the conglomerates and a gamma-ray log change to even more undifferentiated very low API values. In the absence of rock samples this boundary may be difficult to pick. The base of this member is unconformable and a clear dipmeter break can be recognised with the underlying Nimr or Huqf sediments. Also the gamma-ray log shows a sharp break to much lower values compared to those of the underlying Nimr sediments.

Age: The Amin Conglomeratic Sandstone Member is unfossiliferous and no biostratigraphic data are available. The Middle to Late Cambrian age established for the stratigraphic higher Andam Formation and the Early Cambrian age suggested for the underlying Huqf Supergroup (Mattes and Conway Morris, 1990) would constrain the age to the Early to Middle Cambrian. An Early Cambrian age has been inferred on assumed equivalence of the Amin Sandstone Member to the Lalun Formation in Iran by Hughes Clarke (1988).

Depositional Setting: The coarse-grained nature of the sediments and absence of fauna suggest an alluvial setting. The thick conglomerates are interpreted as proximal- to mid-alluvial fan deposits sourced from the uplifted basin margin highs and filling in topographic lows. Basinward these deposits interfinger with sandy conglomerates and sandstones of a mid- to distal alluvial fan environment and aeolian sandstones of the Sandstone Member. The regional variation in the composition of the conglomerates reflects different source areas: along the Western Margin they are polymict, with pebbles of cherts, dolomite, greywacke, igneous and metamorphic rocks, while those in the southeastern Ghaba Salt Basin and Fahud Salt Basin consist almost entirely of chert pebbles. Large-scale fining upward trends may result from waning sediment supply due to erosion of the source area without tectonic rejuvenation. The local occurrence of the conglomerates and the variable palaeocurrent directions in the Huqf area suggest that here these sediments fill in a palaeotopography in the karstified and truncated Huqf carbonates (Buckley and Harbury, 1996; Buckley, 1997).

Amin Interbedded Siltstone and Sandstone Member
New name, this member corresponds to the upper part of Unit 1 shown in Figure 6 of Hughes Clarke, 1988.

Type Area: Subsurface of the Eastern Flank of the Ghaba Salt Basin.

Definition: Interbedded fine, occasionally up to coarse-grained quartz sandstones and red-brown mudstones.

Distribution: The Interbedded Siltstone and Sandstone Member has been only encountered in the Eastern Flank area. In the central part of the Ghaba Salt Basin the well penetrations are not deep enough to establish the presence of this unit. The recorded thickness ranges from a few tens up to 90 m.

Lithology: Interbedded fine, occasionally up to coarse-grained quartz sandstones and red-brown mudstones. The sandstones are sublithic with scattered chert fragments, red to red brown and moderately hard. No fossils have been observed.

Wireline log response: Spiky log response with gamma-ray values of 50 to 100 API for the sandy intervals and 100 to 150 API for the mudstones.

Boundaries: This member forms the base of the Amin Formation on the Eastern Flank and is unconformably overlying Nimr or Huqf sedimentary rocks. This contact often corresponds to a break on the dipmeter logs. The base is best expressed by the shift of gamma-ray log to much higher values.
in the Interbedded Siltstone and Sandstone Member. The contact with the overlying Amin Sandstone Member is sharp and is characterised by the disappearance of the mudstones and the onset of the undifferentiated low gamma-ray log reading.

Age: The Amin Interbedded Siltstone and Sandstone Member is unfossiliferous and no biostratigraphic data are available. The Middle to Late Cambrian age established for the stratigraphic higher Andam Formation and the Early Cambrian age suggested for the underlying Huqf Supergroup (Mattes and Conway Morris, 1990) would constrain the age to the Early to Middle Cambrian. An Early Cambrian age has been inferred on assumed equivalence of the Amin Sandstone Member to the Lalun Formation in Iran (Hughes Clarke, 1988).

Depositional Setting: The absence of fossils and the predominance of fine-grained sediments suggest a low-relief continental setting possibly a playa to distal alluvial fan environment. Some of the intercalated sands may be of aeolian origin.

**Mahwis Formation**

**Author**: Oprinsen (unpublished report, PDO, 1985), see Hughes Clarke (1988) and Heward (1989) revised by Priebe and Kapellos (unpublished report, PDO, 1993) see also Boserio et al. (1995).

**Type Area**: South Oman Salt Basin.

**Definition**: A sequence of micaceous to highly micaceous clastics unconformably overlying the Amin Formation. The Mahwis Formation shows a distinctive fining-upwards sequence of several hundred’s of meters in thickness and is subdivided into two members: the lower Sandstone/Conglomerate Member consisting of fine- to coarse-grained, micaceous sandstones with interbeds of conglomerates and the upper Sandstone/Siltstone Member with predominantly fine-grained, micaceous to strongly micaceous shaly sandstones.

**Distribution**: The Mahwis Formation only occurs in South Oman. The Sandstone/Conglomerate Member is developed in the central and western parts of the South Oman Salt Basin. Towards the north and northeastern part of the basin this member grades into the Sandstone/Siltstone Member. Seismic lines show a complex pattern of internal wedging and several erosional and onlap surfaces seem to occur within this formation related to movement of underlying Huqf salt. Regional correlations show that towards North Oman the Mahwis passes into the Miqrat Formation. However, given the presence of intra-Mahwis unconformities it may be possible that also parts of the North Oman Andam Formation are stratigraphic equivalents to the Mahwis in South Oman.

**Boundaries**: The contact between the Amin and Mahwis is often abrupt and therefore assumed to be disconformable; however, in places, transitions with interbedding of the two sediments types has been reported (Hughes Clarke, 1988; Heward, 1989). Seismic lines show the presence of wedge-shaped geometries within the Mahwis Formation as a result of syndepositional salt movement. The contact with the overlying Ghudun clastics is a hiatus or unconformity.

Age: No biostratigraphic data are available. An Early to Middle Cambrian age has been inferred from the assumed Early Cambrian age of the underlying Amin Formation and the Middle to Late Cambrian age of the Al Bashair Member of the Andam Formation which overlies the Miqrat Formation, the stratigraphic equivalent to the Mahwis Formation in North Oman.

Depositional Setting: The Mahwis was deposited in a system of extensive semi-arid alluvial fans that laterally graded into alluvial plains with sheetflood deposits and ephemeral lakes / sabkhas (Heward, 1989). Regional facies trends indicate a southwest to northeast transport direction suggesting that the sediment were derived from the southwestern and southern margins of the South Oman Salt Basin. The influx of coarse clastics at the base of the Mahwis is thought to indicate a reactivation of these margins.
**Droste**

**Sandstone/Conglomerate Member**

*Authors:* Priebe and Kapellos (unpublished report, PDO, 1993; partly published in Boserio et al., 1995).

*Type Area:* Central and western parts of the South Oman Salt Basin.

*Definition:* Generally fine-grained micaceous to highly micaceous sandstones interbedded with conglomerates and siltstones.

*Distribution:* The Conglomerate/Siltstone Member is present throughout the central and western parts of the South Oman Salt Basin. Towards the north and northeastern parts of this basin this member grades into the Sandstone/Siltstone Member.

*Lithology:* Fine-grained, locally medium- to coarse-grained, micaceous to highly micaceous sandstones which are interbedded with conglomerates and red to green siltstones. The conglomerates are up to ten meters thick and contain pebbles of igneous and metamorphic rocks, cherts and dolomite. These conglomerates are very similar to those of the Amin Formation. No fossils have been observed in the Mahwis Formation.

*Wireline log response:* Generally a highly irregular, serrated gamma log response. The conglomeratic beds show high densities and low porosities, while the more micaceous sandstones show a typical spiky, high (80 API) gamma response.

*Boundaries:* The contact with the underlying Amin is often abrupt and therefore assumed to be disconformable, however, in places transitions with interbedding of the two sediments types has been reported (Hughes Clarke, 1988; Heward, 1989). The contact with the overlying Sandstone/Siltstone Member is transitional and diachronous.

*Age:* No biostratigraphic data are available, an Early to Middle Cambrian age has been inferred from the assumed Early Cambrian age of the underlying Amin Formation and the Middle to Late Cambrian age of the Al Bashair Member of the Andam Formation which overlies the Miqrat Formation, the stratigraphic equivalent to the Mahwis Formation in North Oman.

*Depositional Setting:* The Sandstone/Conglomerate Member represent the proximal part of a system of extensive semi-arid alluvial fans that laterally grade into alluvial plains with sheetflood deposits and ephemeral lakes/sabkhas (Heward, 1989). Regional facies trends indicate a southwest to northeast transport direction suggesting that the sediment were derived from the southwestern and southern margins of the South Oman Salt Basin.

**Sandstone/Siltstone Member**

*Authors:* Priebe and Kapellos (unpublished report, PDO, 1993; partly published in Boserio et al., 1995).

*Type Area:* Eastern and northeastern parts of the South Oman Salt Basin.

*Definition:* A sequence of fine-grained micaceous shaly sands characterised by a high spiky gamma-ray response.

*Distribution:* The Sandstone/Siltstone Member of the Mahwis Formation is a distinctive unit of up to 600 m thick along the Eastern Flank of the South Oman Salt Basin (Heward, 1989). It is partly the stratigraphic equivalent of the Sandstone/Conglomerate Member in the western part of the basin.

*Lithology:* The Sandstone/Siltstone Member consists of fine-grained shaly sands in which several lithofacies have been recognised from cores (Heward, 1989; Purvis unpublished report, PDO, 1994): erosively based intra-formational shale clast conglomerates, trough cross-stratified fine-grained sands, horizontally stratified fine- to very fine-grained sands, massive sands, current ripple cross laminated fine sands to silts, wavy laminated fine- to very fine-grained sands with possible adhesion ripples and...
intervals of interbedded greenish-grey shales and sands with possible desiccation cracks and soft sedi-
ment deformation features. The facies are stacked in fining upward sequences of on average 0.7 m 
thick stacked into larger fining upward units of 25 - 50 m thick (Heward, 1989). Locally a distinctive 
green-red, laminated micaceous sandy shale interval is a prominent intra-Mahwis marker bed. Also 
thinner shale beds seem to be laterally extensive and can be used for correlation. No fossils have been 
observed in the Mahwis Formation.

**Wireline log response:** This member is characterised by its high spiky gamma log response in the range 
of 80 - 100 API. Large scale fining upward sequences show on the Borehole Image and Neutron logs 
indication an upward increase in shaliness and decrease in porosity and permeability (Heward, 1989).

**Boundaries:** The contact with the underlying Sandstone/Conglomerate Member is transitional and 
diachronous. The top of this member is truncated by younger unconformities.

**Age:** No biostratigraphic data are available. An Early to Middle Cambrian age has been inferred from 
the assumed Early Cambrian age of the underlying Amin Formation and the Middle to Late Cambrian 
datings of the Al Bashair Member of the Andam Formation which overlies the Miqrat Formation, the 
stratigraphic equivalent to the Mahwis Formation in North Oman.

**Depositional Setting:** Sandstone/Siltstone Member represent sheetflood deposits in the distal parts of a 
system of extensive semi-arid alluvial fans (Heward, 1989). Regional facies trends indicate a southwest 
ward to northeast transport direction suggesting that the sediment were derived from the southwestern 
and southern margins of the South Oman Salt Basin. Periodic tectonic rejuvenation caused variation 
in sediment input and may have been the driving force which formed the 25-50 m thick fining-upward 
packages (Heward, 1989). In more distal areas to the north abundant wavy laminated sands with 
adhension ripples suggest a sabkha environment similar to that of the Miqrat in North Oman. Shale 
interbeds indicate the occurrence of ephemeral lakes. The absence of thick wedges of deltaic sediments 
suggests that these lakes were relatively shallow.

**Miqrat Formation**

New name, this unit equates to the “Andam Unit 1” and “Amin Unit 3” described by Hughes Clarke 
(1988).

**Type Area:** the Haima outcrops in the Huqf area (Millson et al., 1996; Buckley and Harbury, 1996; 
Buckley 1997). These include the sediments assigned to the Amin Formation by Millson et al. (1996) 
which are now considered to be the stratigraphical equivalent of the basal part of the Miqrat Formation 
in the subsurface (see Buckley and Harbury, 1996; Buckley, 1997).

**Definition:** Red-brown shales and siltstones intercalated with fine- to very fine-grained sandstones. In 
the western Ghaba Salt Basin an Upper and Lower Member can be recognised, the upper part of the 
Lower Member is characterised by a sand-rich interval.

**Distribution:** The Miqrat Formation is well developed in the Ghaba Salt Basin with maximum thickness 
in wells of over 350 m. On the Mabrouk Makarem High the formation is much thinner, possibly by 
erosion, and poorly developed while in the northern parts of the Fahud Salt Basin the Miqrat is absent, 
probably by erosion below the base Al Bashair unconformity. In the southwestern part of the Ghaba 
Salt Basin a transition into the Mahwis Formation of South Oman occurs with more sandy and 
conglomeratic sediments. The Lower Miqrat Member is well developed in the Ghaba Salt Basin but 
disappears towards its eastern flank, probably by onlap.

**Lithology:** Mottled red-brown shales and siltstones intercalated with light grey to grey-brown and very 
fine- to fine-grained sandstones. The sandstones are quartzose to feldspathic, micaceous and moderately 
hard to friable and in places silty or argillaceous. Very thin beds and laminae of coarser, medium 
sand- to granule-sized, grains are locally present.
A highly micaceous sandy siltstone marker bed present at the top of the Lower Miqrat Member can be recognised over most of the Ghaba Salt Basin and divides this formation into two overall fining upward units.

The main sandstone development occurs in the upper part of the Lower Miqrat Member in the middle of the formation. Due to onlap onto the eastern flank of the Ghaba Salt Basin, however, the sands rest directly on the Amin Formation in this area and were previously included into the Amin Formation (“Amin Unit 3” of Hughes Clarke, 1988).

Scattered outcrops of sediments of the Miqrat Formation in the Huqf area have been described by Millson et al. (1996) and Buckley (1997). The basal 50 m consists of an alternation of laminated to thin-beded poorly-sorted, red siltstones and grey sandstones. Low angle cross-bedded coarse sandstones are present locally near the base. Large (m-scale) polygonal mud-cracks were observed in red silt and claystones near the top of this unit. These are overlain by 20 m thick uniform package of clean, light grey to greyish brown coloured quartzose sandstones which are fine- to medium-grained, occasionally grading to coarse (conglomeratic) sand. The sandstones are very well-sorted, with rounded to subrounded, sometimes frosted, grains. The sandstones classify as sub-litharenite to quartz arenites, the lithics are mainly represented by cherts and metamorphic rock fragments. Only traces of white to reddish coloured shales are present. The sandstones show large-scale low and high angle cross-bedding with foresets up to several meters high of aeolian origin.

Outcrops of the upper part of the Miqrat show a less sandy interval dominated by laminated and thick-beded mudstones. The sandstones mainly occur as thin lenses up to 5 cm thick, occasionally thicker beds were observed (up to 1 m). They constitute about 40% of this formation. Mud chip conglomerates occur both in the sand and the mudstone intervals. Most of the sand grains are frosted, very well-rounded and spherical shaped suggesting aeolian reworking. The boundaries between the different lithologies is often disturbed by soft sediment deformation. A wide range of sedimentary structures occur in this unit with oscillation ripples, climbing ripples, trough-shaped cross-bedding, parallel lamination. Soft sediment deformation such as load casts, flame structures and chaotic bedding are common. Mudcracks, up to meter scale polygons (teepee structures) are common while some salt pseudomorphs have been observed.

No fossils have been observed in the Miqrat Formation.

**Wireline log response:** Spiky gamma-ray log with API’s higher than 100, with at the top of the Lower Miqrat Member, and occasionally at the top of the Upper Miqrat Member very high values up to 150 API. These are related to a very high mica/feldspar content of the sediments. The upper part of the formation typically shows a “shaling-upward” trend.

**Boundaries:** Seismic evidence suggest the presence of regional onlap surfaces both at the top and base of the Miqrat Formation indicating an unconformable relationship with the over and underlying units. The base of the formation is defined by the first appearance of red micaceous siltstones on top of the clean Amin sandstones. This break is clearly expressed by a change from a monotonous low (Amin) to a spiky high gamma log (Miqrat) response. The top of the formation shows a sudden shift and log break from an overall fining upward trend to the more sandy and calcareous Al Bashair Member of the Andam Formation. Truncation and complete removal of the Miqrat Formation below the Al Bashair Member has been observed in wells in the Fahud Salt Basin. The top of the Lower Miqrat Member is defined at the top of the micaceous mudstone marker bed with very high gamma-ray values.

**Age:** No biostratigraphic data are available. An Early to Middle Cambrian age has been inferred from the assumed Early Cambrian age of the underlying Amin Formation and the Middle to Late Cambrian datings of the Al Bashair Member of the Andam Formation.

**Depositional Setting:** There are no marine indications in this formation. The mainly fine-grained nature of the sediments, good sorting, rounding, occurrence of frosted grains, the numerous sedimentary
structures indicative of current, wave and aeolian action and the evidence for frequent exposure suggest a playa (inland sabkha) setting in a low relief continental environment. The conglomeratic sands observed at the base of the formation in the outcrops are fluvial in origin. Well logs suggest that the thick sandstone beds, which probably are of aeolian origin as shown by the large-scale cross-bedding in the Huqf outcrops, only occur along the eastern edge of the Ghaba Salt Basin. Cores from the central parts of the Ghaba Salt Basin still show thin beds of aeolian origin but most of the sands seem to have been deposited following flash floods. These partly eroded and reworked the underlying sediment into mud flake conglomerates and deposited widespread, thin sheets of sands. The finer-grained intervals represent wet interdune/sabkha deposits. The soft sediment deformation is caused by the sudden emplacement of the sand load onto the water saturated mudstones. Some of the deformation may be related to displaceic growth of evaporite minerals, haloturbation, in the sediment.

**Andam Formation**

*Author:* Oprinsen (unpublished report, PDO, 1986), see also Hughes Clarke (1988) based on subsurface data. The definition has been revised in this paper and the formation comprises only Unit 2 ("Limestone Member") and Unit 3 of the original three informal members shown in Hughes Clarke (1988). Unit 1 is now included in the underlying Miqrat Formation.

*Type Area:* The Haima outcrops in the Huqf area (Millson et al., 1996; Buckley and Harbury, 1996; Buckley 1997) and the subsurface of the Ghaba Salt Basin.

*Definition:* Predominantly fine clastic unit in which four members can be recognised: (1) the Al Bashair Member, a basal interval of very fine-grained quartz sandstones and clayey silts with intercalations of thin carbonate beds overlain by mudstones; (2) the Barik Sandstone Member, a fine-grained sandstone interval; (3) the Mabrouk Member, a mudstone unit; and (4) the Barakat Member, fine-grained sandstones and mudstones. The Andam Formation is the only unit of the Mahatta Humaid Group with clear marine indicators such as glauconite and bioclasts in cuttings.

*Distribution:* The Andam Formation occurs all over North Oman, the thickest development is in the Central Ghaba Salt Basin. The formation reaches 1,700 m in wells on structural highs and thicker intervals are expected in intervening lows. Towards the south and west a decrease in thickness occurs due to stratigraphic thinning, internal truncation(s), probably at the base of the Barakat Member, and onlap at the base. Along the eastern edge towards the Huqf outcrop area the Andam Formation is truncated below the base Al Khlata unconformity.

*Boundaries:* The base of the Andam Formation is characterised by a sharp gamma-ray log break to much lower values at the top of the general increasing gamma-ray trend of the upper Miqrat Formation. In many wells it corresponds to a thin calcareous sandstone bed overlying the shales of the Miqrat Formation. This boundary marks the onset of series of cleaning upward cycles on the logs with more sandy lithologies characteristic for the basal Al Bashair Member. If this thin basal sandstone layer cannot be distinguished, the boundary should be put at the base of the first sandy interval (gamma-ray log break to lower values) above the mudstones of the Miqrat Formation. The transition of the Andam Formation with the overlying Ghudun Formation is often gradual and occurs within a coarsening upward trend. The boundary should be picked at the top of the uppermost fine clastics with marine indications (bioclasts) of the Andam Formation.

*Age:* Palynological data (PDO palynozone 1108) and paleontological data (trilobites, Fortey, 1995) suggest a Middle Cambrian to Early Ordovician age.

*Depositional Setting:* The Andam Formation consists of sediments deposited in a shallow marine to braid delta setting which are stacked into three major transgressive-regressive cycles with major marine maximum flooding surfaces in the middle of the Al Bashair Member, at the base of the Mabrouk Member and in the middle of the Barakat Member.
**Al Bashair Member**

New name, this member corresponds to the “Andam Unit 2” (“Limestone Member”) and basal part of the “Andam Unit 3” described by Hughes Clarke (1988).

**Type Area:** The Haima outcrops in the northern Huqf area (Millson et al., 1996; Buckley and Harbury 1996; Buckley 1997).

**Definition:** Fine-grained siliciclastic unit, commonly intercalated with thin carbonate beds and at the top dominated by mudstones. Bioclasts and glauconite are common.

**Distribution:** The Al Bashair Member is widespread in North Oman. The maximum recorded thickness in a well is 700 m in the center of the Ghaba Salt Basin. The thickness decreases towards the margins by stratigraphic thinning and possible onlap. The decrease in thickness is most pronounced towards the south as a result of lateral facies change into sandstones of the Barik Sandstone Member.

**Lithology:** Heterolithic unit dominated by very fine-grained quartz sandstones and clayey silts with intercalations of coarser-grained lithoclastic and thin carbonate beds. The upper part of the member is dominated by mudstones. Small-scale coarsening upward cycles, several meters in thickness, often capped by thin carbonate beds are common in the basal part of the member.

In the lower part of this member greenish-grey siltstones and grey very fine-grained sandstones are interbedded on a cm-scale and show a wide range of sedimentary structures including low angle cross-lamination and wave ripples. The sandstone beds have an erosive base and are fining upwards. Coarser-grained intervals of fine to medium-grained sandstone occur as cm to decimeter scale beds.

The carbonate beds consist of oolitic grainstones, stromatolitic/oncolithic beds or lime-wackestones. The oolitic grainstone beds show cross-bedding and are erosional at the base. The contact with overlying finer-grained sediments is gradual. Ooids can also occur in some sandstone beds. The ooids are calcitic with a radial internal structure and can be very large with diameters of 1.5 mm. The nucleus of the ooids seems to be calcitic. The stromatolites occur in beds of about 35 cm thick with domes that can reach a diameter of more than 1 meter.

Accessory components include bioclastic fragments among which primitive corals, shell fragments, *Lingula* type of shells (both in situ and reworked into thin lags), and trilobite debris, glauconitic grains and pyrite. Different types of burrows, among which *Cruziana*, have been observed. Several levels with synaeresis cracks (very irregular shaped cracks infilled by overlying sands) occur. Moulds of halite crystals are common in the basal part of this member.

In the upper part of the Al Bashair Member the sediments consist of red-brown mudstones with some intercalations of sandstone beds. The mudrocks are sandy and contain mm to several cm thick sandstone layers. The sandstones are laminated or rippled, the mudstones are usually mottled. Intercalated in this mudstone dominated facies are infrequent thicker bedded (typically < 100 cm) fine- to medium-grained sandstones. These are sharp based, parallel laminated to hummocky cross stratified. Bed bases show tool marks, or, more rarely, *Cruziana* sp. trace fossil moulds. The sandstones may contain coarse quartz grains, bioclasts such as disarticulated trilobites and *Lingula* and ooids. The bioclasts are often rounded and concentrated in thin coarse-grained lags at the top of the beds.

**Wireline log response:** The gamma-ray is serrated with average values of about 100 API. Cleaning upward (funnel shaped) trends are common in the basal part of the Member. The interval is prone to washouts.

**Boundaries:** The base of the Al Bashair Member is defined at a log break which forms the top of the general increasing gamma-ray trend of the underlying Miqrat Formation. In many wells it corresponds to the base of a thin calcareous sandstone bed overlying the shales of the Miqrat Formation. This boundary marks the onset of a series of cleaning upward cycles on the logs with more sandy lithologies characteristic for the basal Al Bashair Member. If this thin basal sandstone layer cannot be distinguished, the boundary should be put at the base of the first sandy interval (gamma-ray log break to lower values) above the mudstones of the Miqrat Formation.
The top of the Al Bashair Member is formed by the base of the clean non-micaceous sandstones of the Barik Sandstone Member. On logs this boundary can be picked at the change of the cut-off value of the minimum gamma-ray peaks which are significantly lower in the Barik Sandstone Member from an average 100 API for the Al Bashair to about 50 API for the Barik Sandstone Member).

Age: Trilobites suggest a Late Cambrian age for the Al Bashair Member (Fortey, 1994). Palynoflora indicate PDO palynozone 1108.

Depositional Setting: The presence of glauconite and the scattered bioclasts throughout the member suggests a marine-influenced environment of deposition. The trilobite fauna consist of an assembly of shallow subtidal features (Fortey, 1995). The coarsening upward trends in the basal part suggest shallowing upward cycles from very shallow marine to inter- and supratidal, indicated by the halite pseudomorphs, sediments. The stromatolites and oolitic grainstones at the top of some cycles reflect a reduction in clastic input and may be associated with a relative rise in sea-level. The concentration of coarse-grains and bioclastic debris at the top of the cycles are the result of winnowing and represent transgressive lags. The shallowing-upward cycles are stacked in an overall transgressive trend. The sedimentary features of the sandstones in the upper part of the Al Bashair Member suggest the periodic occurrence of intense currents and the presence of hummocky cross-stratification indicates that these are associated with storm to storm-surge ebbs currents. The upper part of this member is interpreted as a prograding unit of shallow marine sediments in front of the braided delta system of the Barik Member. A major (second order?) maximum marine flooding surface (MFS-1) separates the lower and upper part of the Al Bashair Member. The relative poor, monospecific fauna’s and relative limited burrowing in the Al Bashair Member may indicate restricted conditions, possibly high salinity in the basal part and low salinity (approach braid delta system) in the upper part. An open marine, deep water fauna (graptolites) has not been encountered in this member.

Barik Sandstone Member
New name, this member comprises the sandy middle part of the “Andam Unit 3” described by Hughes Clarke (1988).

Type Area: the Haima outcrops in the northern Huqf area (Millson et al., 1996; Buckley and Harbury, 1996; Buckley, 1997).

Definition: Interval dominated by fine-grained sandstones with some intercalated reddish mudstones.

Distribution: The Barik Sandstone Member is widespread in Central Oman and shows a gradual increase in thickness towards the center of the Ghaba Salt Basin where a thickness of some 550 m has been penetrated in wells. Net to gross ratio decreases towards the north. The Barik Sandstone Member is absent on the Central Oman High and on the western edge of the Mabrouk - Makarem High due to onlap and/or truncation below the base Barakat Member. Towards the east and in the Huqf outcrop area this member is progressively truncated below the base Al Khlata unconformity.

Lithology: Thick bedded, white coloured, cross-bedded sandstones with local intercalations of reddish mudstones. The sandstone beds are erosionally based and stacked into packages of several meters in thickness. Outcrops in the Huqf area show that the erosional relief at the base can be more than one meter. The sandstones are fine-grained and may contain some pebbles of reworked mudstones at the base. Sedimentary structures in the sandstones are dominated by large-scale trough cross-lamination and parallel lamination. The main current direction is towards the north, and no clear evidence for bimodal currents was found. The sandstones may form large-scale channels with widths of several hundred meters within the mudstones units. Fragments of trilobites and lingulids shells occur infrequently in lags at the top of the sand units. Also along the upper surface of the sandstone intervals some small Cruziana type trace fossils have been found. The mudstones are red coloured and occur in intervals up to 5 meters in thickness. They contain thin sandstone to silt lenses and beds which are parallel or wave-ripple laminated and may contain synaeresis cracks/sand injection structures. Loading at the base of these beds is common often leading to ball and pillow structures.
**Droste**

**Wireline log response:** Typical blocky, occasionally funnel and barrel-shaped log response with low gamma-ray values for the sandstones (30-60 API) and much higher values for the mudstones (60-150 API). Mudstone interbeds are prone to washouts. Dipmeter logs typically show high angle sedimentary dips.

**Boundaries:** The boundary with the underlying Al Bashair Member is defined at the base of the clean non micaceous sandstones. On logs this boundary can be picked at the change of the cut-off value of the minimum gamma-ray peaks which are significantly lower in the Barik Sandstone Member. The boundary with the mudstones of the overlying Mabrouk Member is placed at the top of the last clear sandstone layer. This boundary is well expressed on logs by a sharp shift to higher gamma-ray values. Both the upper and lower boundaries are conformable, but diachronous surfaces.

**Age:** Trilobites suggest a Late Cambrian age for the Barik Sandstone Member in the outcrops of the Huqf area (Fortey, 1995). Conodont samples of the stratigraphic higher Barakat Member suggest an Early Ordovician age for this unit. Therefore a Late Cambrian to possibly Early Ordovician age can be assumed for the Barik Sandstone Member. The palynoflora indicates PDO palynozone 1108.

**Depositional setting:** The large-scale cross-bedding with an unidirectional current direction are thought to reflect fluvial influence. The trace fossil content suggest a marine influence for the muddy intervals and the fossil lags at the top of the sandstones represent marine ravinement surfaces. The sequence is interpreted to represent a series of stacked braid delta lobes separated by marine flooding. The sand packages in the central Ghaba Salt Basin represent distributary channels and distributary mouth shoals in a braid delta platform to front setting. The mudstone intervals may represent inter- to subtidal flats and shallow marine deposits. Marine influence decreases towards the Central Oman High in the south and a braid delta plain setting predominates. Towards the northern part of the Ghaba Salt Basin the marine mudstones become more abundant reflecting a more distal braid delta front to shelf setting. The Barik Sandstone on the Mabrouk-Makarem High and in the Fahud Salt Basin seems to have been deposited in a shallow marine to shoreface facies adjacent to the main delta system.

**Mabrouk Member**

New name, this member was previously included within the “Andam Unit 3” by Hughes Clarke (1988).

**Type Area:** Central Ghaba Salt Basin.

**Definition:** Unit dominated by red-brown mudstones, which is overlying the sandstones of the Barik Sandstone Member.

**Distribution:** The Mabrouk Member is widespread in Ghaba Salt Basin with a maximum thickness of some 600 m in wells in the centre of the basin. Towards the south and west of the Ghaba Salt Basin the top of this member is being progressively truncated below the Barakat Member.

**Lithology:** Micaceous, red-brown mudstones with occasionally some sandstones occurring as thin interbeds or lenses. The mudstones are irregularly horizontally laminated, with laminae and ripple forming sets of coarse sand and silt. Bioturbation is common to abundant, mainly represented by simple cylindrical burrows, and locally as dm long vertical burrows (Skolithos). Laminae and lenses are commonly deformed, with injection structures and possible shrinkage cracks. The sandstones are very fine- to fine- (rarely medium-) grained and occur in beds of up to 50 cm thick. The beds are generally sharp based, burrowed and may show some loading. Structures are generally obscured by burrowing but cross lamination is locally visible. The sand content rapidly decreases upward in the basal few meters of the Mabrouk Member. Bioclasts (shelly fragments), pelletoidal carbonate grains and glauconite have been observed. In cuttings bioclasts are only encountered in the lowermost part of the member. The are only few data available of the muddy upper part of the Mabrouk Member. At the top of the member just below the Barakat Member cuttings and well logs sometimes demonstrate the presence of dolomite occurring as thin interbeds. Cores from a well in the eastern Ghaba Salt Basin show the presence of anhydrite lenses and nodules, chickenwire anhydrite and mud cracks.
**Wireline log response:** The Mabrouk Member is characterised by a monotonous, slightly serrated log response. The gamma-ray values are typically around 100 API. Severe washouts occur in these mudstones.

**Boundaries:** The base of the Mabrouk Member is picked at the change from red brown mudstone above to the underlying clean sandstone of the Barik Sandstone Member. This boundary is well expressed on the gamma log by a sharp shift from high values of the Mabrouk Member to low values of the Barik Sandstone Member. This boundary is a conformable, diachronous surface.

The Mabrouk Member is unconformably overlain by the Barakat Member. Correlation of markers within the upper part of this member indicate truncation of Mabrouk mudstones below a regional erosional surface which is placed at the first clear gamma-ray log break to lower values of the, often fossiliferous, sandstones at the base of the Barakat Member. In the absence of the basal sand this boundary is difficult to pick. Criteria that may be used are: (1) evidence for truncation of the Mabrouk Member; (2) a log break in the gamma-ray from monotonous, more or less constant, to a cleaning-upward trend; and (3) occurrence of bioclasts at the base of the Barakat Member. More truncation/onlap surfaces may be present within the Mabrouk mudstones.

**Age:** A Late Cambrian to Early Ordovician age is assumed for the Mabrouk Member. This is based on the Late Cambrian age established for the basal part of the underlying Barik Sandstone Member in the outcrops of the Huqf area (Fortey, 1995) and the Early Ordovician age suggested by conodonts from the overlying Barakat Member. Palynoflora are indicative for PDO palynozone 1108.

**Depositional Setting:** The presence of bioturbation, shell fragments and glauconite suggest a shallow marine depositional environment. The rapid upward decrease in sand content at the base is interpreted as an overall deepening trend towards a major maximum flooding surface within this Member (MFS-2). The transgressive part represents the distal parts of the retreating braid delta of the Barik Sandstone Member. Above the major flooding surface there is no major change in lithology, although a slightly cleaning upward trend in the gamma-ray occurs which may be interpreted to indicate some progradation. However, intertidal sabkha conditions are suggested for the upper Mabrouk Member in cores from the eastern Ghaba Salt Basin while the transition to the underlying open marine unit is not clear (e.g. intermediate shoreface sands are missing). It may be possible that the major unconformity now placed at the base of the Barakat Member occurs within the upper Mabrouk Member or that more erosional/onlap surfaces are present within the Mabrouk Member. With the current data, however, this cannot be proved. The presence of dolomite at the top may be related to soil (calcrete) formation or to the sabkhas conditions.

**Barakat Member**

**Author:** New name, this member comprises the uppermost part of the “Andam Unit 3” described by Hughes Clarke (1988).

**Type Area:** Central Ghaba Salt Basin.

**Definition:** Unit consisting of fossiliferous mudstones with some sandstone interbeds which predominate at the base. The unit is sandwiched between the underlying mudstone dominated Mabrouk Member and overlying sandstones of the Ghudun Formation.

**Distribution:** The Barakat Member is widespread over Central and North Oman. The thickest development is in the centre of the Ghaba Salt Basin where wells penetrated some 220 m section.

**Lithology:** The Barakat Member shows a sandy base and top and is mudstone dominated in the central part. The sandstones are light grey to brown-grey in colour and very fine- to fine-grained. The mudstones have either a red-brown or green colour and contain streaks of sand. Common bioclasts and occasional glauconite grains have been reported. Cores in a well from the eastern Ghaba Salt Basin show an overall fining-upward trend into the mudstone interval. The sandstones occur as thin beds or streaks and occasionally show cross-bedding and lamination. Bed bases can be erosional and
mudstone pebbles and flakes are common. The mudstones contain sand and silt streaks with ripples. Burrowing is abundant among which frequent vertical burrows (Skolithos). Bioclasts occur throughout the interval and consist of shell fragments. Well logs in the upper part show a cleaning upward trend and a gradual lithologic change from mudstones into sandstones of the overlying Ghudun Formation.

Wireline log response: The gamma-ray shows an overall shaling upward trend or bell shape at the base overlain by a more serrated cleaning upward trend towards the top of the unit. The sandstone interval at the base often has a blocky appearance. Severe washouts occur in the mudstones.

Boundaries: The Barakat Member unconformably overlies the Mabrouk Member. The lower boundary is placed at the base of the, often fossiliferous, sandstones marked by a clear gamma-ray log break to higher values of the mudstones of the Mabrouk Member. In the absence of the basal sand this boundary is difficult to pick; criteria that may be used are: 1) evidence for truncation of the Mabrouk Member, 2) a gamma-ray log break from monotonous, more or less constant, to a cleaning upward trend, and 3) occurrence of bioclasts at the base of the Barakat Member.

The boundary of the Barakat Member with the overlying more sandy Ghudun Formation is transitional and appears as a diachronous conformable surface. The boundary should be picked at the change from fossiliferous interbedded mud- and sandstones below to clearly sand-dominated, low gamma-ray sediments of the Ghudun Formation above.

Age: An Early Ordovician age is suggested by conodonts from cores of the Barakat Member. The palynoflora is indicative for PDO palynozone 1108.

Depositional setting: The burrowing, bioclasts, glauconite and the presence of cross bedding suggest a shallow marine setting. A major transgressive-regressive trend can be recognised. The sandstones at the base are interpreted as transgressive coastal sands. Infill of erosional topography created during exposure of the underlying Mabrouk Member and wave erosion during shoreface retreat may result in a very irregular distribution of this unit. The overlying interbedded sand and mudstone unit was deposited in more open marine setting dominated by fair-weather mudstones with occasional influx of sands by storms. This is followed by a shallowing upward into more sandy sediments deposited in front of the braid delta complex of the Ghudun Formation.

Ghudun Formation

Authors: Winkler and Rácz (unpublished report, PDO, 1978), see also Hughes Clarke, 1988.

Type Area: Ghaba Salt Basin.

Definition: Generally very thick package of micaceous quartz sandstones with intercalated micaceous siltstones and shales.

Distribution: The Ghudun Formation is the most widespread and the thickest unit of the Haima Supergroup in northern Oman. Maximum drilled thickness of some 1,400 m is in the center of the Ghaba Salt Basin. The formation thins towards the (south) east and is missing on the Eastern Flank and the Central Oman High as a result of truncation below the base Al Khlata or younger unconformities.

Lithology: The formation is dominated by sand- and siltstones with a very low clay content. The yellowish-brown, grey or reddish-grey (sub-) feldspatic quartz sandstones (arkosic arenites) are fine-to medium, occasionally coarse-grained and can contain greenish-grey mudstone intraclasts. The coarser grain sizes occur in the south and in the upper part of the formation. The sandstones are meter-scale bedded and can be stacked into packages of more than 10 m thick. Sedimentary structures include high to low angle dm-scale cross-bedding, parallel lamination and current ripples, some intervals are bioturbated and contain sand injection features. The mudstones are variably mottled,
disrupted or laminated. Phosphatic shell fragments and pellets were recorded in thin sections but have never been reported in cutting descriptions and are considered to be very rare. Several large-scale fining and coarsening upward trends are present which are correlatable on a regional scale.

Wireline log response: Highly serrated gamma-ray log response with typical barrel to funnel shaped cycles of 10 to > 100 m thickness which can be correlated regionally. Gamma-ray values range from 50 to 100 API or 100 to 150 for the different cycles. Mudrocks are prone to washouts which seem to be correlatable regionally.

Boundaries: The basal boundary is at the top of the cleaning/coarsening upward trend of the Barakat Member and may be difficult to pick. The boundary should be picked at the base of the sand-dominated package with low gamma values, above the very fossiliferous interbedded mud- and sandstones of the Andam Formation. This boundary is conformable and diachronous.

The contact of the Ghudun Formation with the overlying Safiq Group is formed by a major unconformity. This unconformity can clearly be shown by the truncation of regional correlatable intra-Ghudun flooding surfaces. The top has been defined at the base of the clay-rich beds of the Safiq Group which are usually rich in micro-flora typically indicating a Middle Ordovician or Early Silurian age. Lithologically the boundary may be difficult to pick where the basal part of the Safiq is sandy. The Safiq Group sands can be distinguished by their more ‘blocky’ log response from the more ‘spiky’ response of the Ghudun sands and the boundary should be picked at the base of the ‘blocky’ sands.

Age: No biostratigraphic data are available for the Ghudun Group. The age is constrained by the Early Ordovician conodont dating of the underlying Barakat Member and the Middle Ordovician age based on palynomorphs and graptolites occurring at the base of the overlying Safiq Group. Close resemblance of the Ghudun facies with those of the underlying Andam Formation, the transitional contact with the Barakat Member, and the presence of a major unconformity at base Safiq suggest an Early Ordovician age for the Ghudun Formation.

Depositional Setting: The large-scale cross-bedded and laminated sandstones represent fluvial channel and sheet flood deposits. Argillaceous sandstones and mudstones may have accumulated in interchannel areas. The occurrence of bioturbation and rare bioclasts suggests occasional marine incursions. This sequence is interpreted to represent a series of stacked braid delta lobes separated by marine floodings. The sand packages represent channels of sheet flood deposits on the braid delta plain to distributary channels and distributary mouth shoals on the braid delta platform. The top of the underlying Barakat Member represents the prograding braid delta front of the Ghudun Formation. A more distal setting is suggested in the northern part of the study area by the overall finer grains size and clear evidence of marine conditions. Deepening events within the Ghudun seem to have been minor and depositional cycles are stacked in an overall aggrading pattern.

SAFIQ GROUP

Authors: Winkler and Rácz (unpublished report, PDO, 1978), see also Hughes Clarke, 1988, now upgraded to Group status.

Type Area: Ghaba Salt Basin.

Definition: Unit with alternation of major, clearly distinguishable sandy and shaly packages of Middle Ordovician to Early Silurian in age. Three major transgressive-regressive cycles of open marine to restricted marine/deltaic sediments can be recognised (Figures 22 and 23). The Safiq Group overlies a major unconformity and onlaps the underlying Ghudun Formation. The top of the Safiq Group is truncated by the base Al Khlata or younger unconformities which completely removed the Safiq sediments along the eastern flanks of the Ghaba Salt and South Oman Salt Basins. The Safiq Group has been subdivided into three formations based on distinctive palynological assemblages and each formation forms a transgressive-regressive cycle. The formations are from bottom to top: Saih Nihayda, Hasirah and Sahmah.
Saih Nihayda Formation

Author: Defined as Member by Oprinsen (unpublished report, PDO, 1986) see also Hughes Clarke (1988), in this paper upgraded to Formation status.

Type Area: Central Ghaba Salt Basin.

Definition: This Formation comprises all Middle Ordovician (Llanvirn to Llandeilo, PDO palynozone 1098). The lithologies are stacked in a major fining and coarsening upward trend.

Distribution: The Saih Nihayda Formation is only present in northern Oman and disappears by onlap onto the Ghudun towards the south. Along the eastern flank of the Ghaba Salt Basin the formation is truncated below the base Al Khlat and younger unconformities. The maximum drilled thickness is in the center of the Ghaba Salt Basin is 650 m.

Lithology: A fining and subsequently coarsening upward trend with a sandy base and top separated by a shale interval. A core from the base of the Saih Nihayda showed the presence of a conglomerate with red-brown and grey-green pebbles and boulders of sand and siltstones up to 70 cm thick in a matrix of coarse-grained, rather incoherent sandstone. These sediments are possibly derived from the underlying Ghudun Formation. The basal sands are sharply overlain by an overall fining upward unit of dark grey to black shales with thin beds of silt to fine-grained sandstone. These beds are fining upward, sharp-based with possible flute casts and loading. Sedimentary structures include frequent parallel lamination and small-scale cross-lamination, dewatering pipes, burrowing and occasional convolute bedding. Mudstone pebbles occur in thicker dm-scale bedded sands. Towards the top the sediments gradually coarsen upward to fine- to medium-grained sandstones.

Wireline log response: The sandstones at the base often have a ‘blocky’ character base. The overlying shales are monotonous serrated, reflecting the interbedded sand and shale lithologies, with occasional some funnel-shaped trends. The sandstones at the top are serrated and show an overall funnel-shaped response. Gamma-ray values for the shales approximates 150 API.

Boundaries: The contact of the Saih Nihayda Formation with the underlying Ghudun Formation is formed by a major unconformity. This unconformity can be clearly shown by the truncation of intra-Ghudun markers. It has been defined at the base of the more shale-rich beds of the Saih Nihayda Formation. These are usually rich in micro-flora typically indicating a Middle Ordovician (PDO palynozone 1098) age. Lithologically the boundary may be difficult to pick where the basal part of the Saih Nihayda is sandy. The sandstones can be distinguished by their more ‘blocky’ log response from the more ‘spiky’ Ghudun sandstones and the boundary should be picked at the base of the ‘blocky’ sands. The contact of the Saih Nihayda Formation with the overlying Hasirah Formation is an
unconformable surface. The boundary is picked at the base of the sharp-based “blocky” sandstone of the Hasirah Formation which occurs in the PDO palynozone 1012/1005 (Late Ordovician, Caradoc to Ashgill). If this contact cannot be recognised because this sandstone is overlying sandstones of the Saih Nihayda and no biostratigraphy is available, the boundary should be picked at the base of the lowest Upper Ordovician (PDO zone 1005) shale.

Age: The Saih Nihayda is Middle Ordovician in age (Llanvirn to Llandeilo, palynozone 1098). This age has been confirmed by graptolites and conodonts.

Depositional Setting: This member consists of a major transgressive-regressive cycle. The blocky fining upward sands at the base with the large sand and silt boulders may represent fluvial sediments deposited in channels that eroded into the underlying Ghudun Formation. The graptolitic shale intervals with sandstone and siltstone beds were deposited in an open marine setting, the sand and silt beds representing proximal to distal storm deposits or turbidites. The sharp contact with the basal sand suggest a rapid, erosive transgression. The coarsening upward trend towards the top suggest a progradation into a shallower marine shelf-face setting.

Hasirah Formation

Author: Defined as member by Oprinsen (unpublished report, PDO, 1986), see also Hughes Clarke, 1988), in this paper upgraded to Formation status.

Type Area: Southwestern flank of Ghaba Salt Basin.

Definition: All Upper Ordovician sandstones and shales (PDO palynozone 1012/1005, Caradoc to Ashgill). The lithologies are stacked in a major fining and coarsening upward sequence.

Distribution: The Hasirah Formation is the most widespread formation of the Safiq Group. Along the eastern flank of the Ghaba and South Oman Salt Basin the formation has been truncated below the base Al Khlata and younger unconformities. The formation onlaps onto Ghudun Formation in central and south Oman. The maximum drilled thickness is on the (south)western margin of the Ghaba Salt Basin at the border with Saudi Arabia is about 550 m.

Lithology: The Hasirah Formation comprises three lithological units which may in the future be used to define members: a basal clean sandstone overlain by a shale to argillaceous sandstone package which is capped by a thick sandstone unit. The basal sandstone is medium to coarse-grained with traces of glauconite and very well-developed where overlying the Ghudun Formation. This is overlain by a package of dark grey, organic-rich, micaceous shales which are interbedded with centimeter beds of silt and fine-grained sandstones with current ripples. Contorted bedding and slumps have been
observed in cores. Within the shales thicker packages of fine to medium, occasionally very coarse grained to conglomeratic sandstones occur which form coarsening upward units of several tens to hundred meters in thickness. These are made up of meter-scale, stacked sandstone beds which are sharp-based and appear to have a fining-upward trend. Internally the sands are structureless with only some convolute bedding and dish (dewatering) structures. At the top of the beds some ripples, lamination and burrowing is visible. Intra-formational clasts of silt and shale are common. The upper part of the Hasirah Formation consists of a sharp-based interval of very fine- to medium-, occasionally coarse-grained sandstones interbedded with some silt and shales. This interval can reach a considerable thickness of up to 300 m and is for most part undifferentiated, although some trough-crossed sandstone beds have been observed. In places, the upper part contains thicker silt and shale intervals and coarsening-upward cycles.

**Wireline log response:** The basal sandstone shows a blocky clean log character with gamma-ray values of 20 API. The shales are monotonous, slightly serrated with gamma values of 150 to 200 API. These get more serrated and show funnel-shaped (cleaning-upward trends) in the more sandy intervals. The massive sand interval has a variable log response; moderately to strongly serrated, cylindrical-shaped units of several tens of meters thick and funnel-shaped trends near the top with gamma-ray values averaging around 50 API.

**Boundaries:** The most distinctive criterion for the Hasirah Formation is the Late Ordovician age indicated by the presence of in-situ palynomorphs characteristic for PDO palynozone 1012/1005. As the sands at the top and bottom of the formation often do not contain any palynomorphs and the over and underlying units are also sandy the boundaries are often difficult to define. Where it directly overlies the Ghudun Formation the lower boundary of the Hasirah can be picked at the base of the clean ‘blocky’ sand above the more ‘serrated’ sandstones of the Ghudun. This boundary is an unconformity often associated with a clear dipmeter break. Where overlying sandstones of the Saih Nihayda Formation the base is much less clear and is put at the base of the fining-upward sand bed just below the lowermost Upper Ordovician shale. The top of the Hasirah Formation is picked at the base of the (fining-upward) Sahmah sand underlying a very high gamma-ray shale peak.

**Age:** The Hasirah Formation is Late Ordovician in age (Caradoc to Ashgill, PDO palynozone 1005/1012).

**Depositional Setting:** The Hasirah Formation forms a major transgressive-regressive cycle containing offshore, shallow marine and fluvial deposits. The basal sandstone has been interpreted as a shallow marine transgressive deposit. The overlying shales and interbedded sands with slumps are open marine deposits, the sandy coarsening-upward intervals representing proximal to distal turbidites in a prograding fan complex in front of a delta. Conglomeratic units at the top of these coarsening-upward cycles may even represent fluvial deposition on the delta plain. The sharp base of the upper sand unit is probably an erosional surface and a fluvial setting is suggested for the upper part of this sequence. This suggests that the whole unit represents a prograding delta complex with mass flow sands at the base overlain by prograding delta lobes and capped by delta plain fluvial deposits. The sudden influx of significant amounts of sands in a deeper-marine setting suggests a major drop in relative sea-level. This can be correlated with major glaciations that have been reported from the Ashgill to ?Lower Llandovery of Saudi Arabia (Vaslet, 1989; 1990).

**Sahmah Formation**

**Authors:** Defined as member by Wiemer (unpublished report, PDO, 1981) and Oprinsen (unpublished report, PDO, 1986), see also Hughes Clarke (1988), in this paper upgraded to formation status.

**Type Area:** Western flanks of the Ghaba Salt Basin.

**Definition:** The Sahmah Formation comprises all Lower Silurian sediments and is based on the presence of PDO palynozone 1003 (Llandovery). These consist of organic-rich shales interbedded with thin sandstones stacked in an overall coarsening-upward trend. Typically a very high (>200 API) gamma-ray peak occurs at the base of this formation.

**Distribution:** The Sahmah Formation is only present along the western margin area. Widespread post-Haima erosion has removed this formation from nearly all Central and North Oman. This erosion
also resulted in a very irregular thickness distribution of the Sahmah Formation. The thickest Sahmah (220 m) has been encountered on the Western Margin near the Saudi Arabian border.

Lithology: The Sahmah Formation comprises organic-rich, grey shales and sandstones which form a fining- and coarsening-upward package separated by relatively more organic-rich (gamma >200 API) shale interval.

At the base of the formation a fining-upward sandy unit may be present. This unit consists of predominantly medium- to coarse-grained, large-scale cross-bedded, parallel-laminated and structureless sandstones grading into fine- to coarse-grained sand dominated heterolithic facies with flaser to wavy bedding and some burrowing. These sandstones are over lain by a very organic-rich shale bed which can be recognised on logs by the very high gamma peak and which is a very useful marker for correlations. Above this bed an overall coarsening-upward trend occurs from laminated micaceous shales with siltstone to fine-grained sandstone streaks grading upwards into medium-grained, in places medium to coarse-grained, thick-bedded sandstones with some shaly interbeds. The sandstones show ripples, fining upwards waning flow sequences and mudstone clasts.

Wireline log response: Typically an overall cleaning upward trend from a very high gamma-ray peak (> 200 API). The lower shale-dominated interval is slightly serrated, the upper interbedded shales and sandstones are highly serrated.

Boundaries: The most distinctive criterion for the Sahmah Formation is the Early Silurian age shown by the presence of in-situ palynomorphs characteristic for PDO palynozone 1003. The base of the Sahmah Formation is picked at the base of the (fining-upward) sand underlying a high gamma-ray shale peak at the base of the Lower Silurian Shales. The top of the Sahmah Formation has been eroded by the base Haushi Group unconformity.

Age: The Sahmah Formation is Early Silurian in age (Llandovery, PDO palynozone 1003).

Depositional Setting: The Sahmah consists of a major transgressive-regressive cycle. The base of the Sahmah consists of a rapidly deepening upward unit from very shallow marine, above wave base (basal sandstone) to open marine below storm wave base conditions. Anoxic bottom waters, probably related to a worldwide anoxic event, resulted in the accumulation and preservation of organic shales. The overlying sediments show an overall shallowing-upward trend with increasing influx of sands by turbidites and/or storms. The major flooding at the base of the Sahmah Formation may be caused by the rising sea-level resulting from the melting of the ice cap at the end of the Late Ordovician glaciation (Vaslet, 1989; 1990).

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**ABOUT THE AUTHOR**

**Henk H.J. Droste** joined Shell in 1984 after receiving his MSc in Geology from the University of Amsterdam. He worked as a Carbonate Geologist with Shell Research in The Netherlands and as a Sedimentologist in the Regional Studies Team of Shell Expro in London. He was posted to Petroleum Development Oman in 1992 where he joined the Exploration Department as a Geologist/Seismic Interpreter. He is currently working as a Production Geologist in the North Oman Development and Production Unit.

**Manuscript Received 5 August, 1997**

Revised 18 October, 1997

Accepted 30 October, 1997

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