Sedimentology and play potential of the late Neoproterozoic Buah Carbonates of Oman

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ABSTRACT

The search for new exploration plays in Oman, and recent successes in the Ara Group, has rejuvenated the interest of Petroleum Development Oman (PDO) in the stratigraphy of the pre-Ara Group. Below the Ara Group, the late Neoproterozoic Nafun Group comprises five formations. The Buah is the youngest of these formations, and represents the most promising exploration target. Accordingly, an integrated outcrop and subsurface study was initiated to better understand the distribution of the Buah depositional facies. High-resolution chemostratigraphy and field gamma-ray surveys were used to correlate outcrop data with the PDO subsurface database. These studies resulted in the reconstruction, with an unprecedented accuracy, of the distribution of the depositional environments at Buah time throughout Oman.

This study indicates that the Buah was deposited on a distally-steepened carbonate ramp, during a highstand systems tract, as a shallowing and upward-coarsening cycle. Good reservoir facies (peloidal-ooidal grainstones) are ubiquitous in the shallow-water Buah sections, making up continuous sheets for tens of kilometers. Karst and fracture development at the top of the Buah may improve the reservoir quality, as in the case of the Makarem gas field in Oman. Buah reservoirs are generally capped by the Ara salt, except on structural highs where the top seal is provided by mudstones of the middle Haima Supergroup. The Buah off-ramp basinal facies represent potential source rocks with total organic carbon values ranging from 2.5–3.5%.

INTRODUCTION

In Oman, the late Neoproterozoic Buah Formation (Nafun Group, Huqf Supergroup) underlies the late Neoproterozoic-Cambrian Ara Group (Huqf Supergroup). The Ara Group contains important silicilyte and carbonate reservoirs sealed by thick salt, and constitutes a part of the exploration and production portfolio of Petroleum Development Oman (PDO). Below the Ara, the hydrocarbon potential of the older formations of the Huqf Supergroup, such as the Buah, was recognized in the 1990s by PDO (e.g. unpublished PDO reports by J.A. Rodd, 1990, and M. Vroon-ten Hove, 1997). With additional field studies (McCarron, 2000; Leather, 2001) and the discovery of commercial gas in the Buah Formation (Tiley et al., 2000), this older succession has become the target of renewed exploration studies. The Buah Formation, in particular, is now regarded as an emerging play and the focus of various exploration activities.

In this paper we present a study on the Buah Formation that integrates outcrop and subsurface data. It was initiated to better understand its reservoir properties in existing gas fields (Cozzi, 2000), and to assess its play potential. Particular importance is given to the petroleum implications, and the reader is referred to Cozzi et al. (2004; in press) for more detailed information on the sedimentary facies and chemostratigraphy.

LATE NEOPROTEROZOIC GEOLOGICAL SETTING

Stratigraphy

Neoproterozoic rocks crop out extensively in the north (Jabal Akhdar and Saih Hatat erosional windows), center (Huqf area) and south (Mirbat area) of Oman (Figure 1), and they have been
extensively drilled by PDO in the subsurface. They are comprised within the Huqf Supergroup (Loosveld et al., 1996), which is composed of the Abu Mahara, Nafun and Ara groups (Figure 2, Table 1). The Abu Mahara Group, which crops out mainly in the Jabal Akhdar and partly in the Huqf area, is made of glaciogenic sedimentary rocks alternating with shallow- and deep-marine clastics deposited in half-grabens (Leather, 2001; Leather et al., 2002). These are capped by the Hadash Formation cap carbonate (Leather, 2001, Leather et al., 2002), which transitionally passes upward into the overlying
Masirah Bay Formation in Jabal Akhdar. A carbonate succession that unconformably overlies the granodioritic basement and the volcaniclastic Halfayn Formation in the northern Huqf area (Al Jobah locality, Figure 1) is overlain by the Masirah Bay Formation. This carbonate succession shares the same stratigraphic position below the Masirah Bay Formation, as well as the transgressive nature and light δ13C signature of the Hadash Formation in Jabal Akhdar (Leather, 2001). Therefore, as suggested by Leather (2001), the carbonate succession in the Huqf area can be tentatively correlated with the Hadash cap carbonate. These carbonates mark the end of the Fiq glacial epoch and are incorporated in the Nafun Group (Table 1).

The Nafun Group, above the Hadash Formation, is made of two clastic-carbonate cycles that encroached over the whole of Oman, and crops out in the Jabal Akhdar and Huqf areas. The lower sequence (Masirah Bay and Khufai formations) is overlain by the Shuram Formation mixed carbonate-siliciclastic shelf deposits and by the Buah Formation carbonates. These pass upward into the Ara Group carbonate-evaporite cycles (Huqf and Oman Salt Basins), or into the time-equivalent Fara Formation carbonates-volcaniclastics in Jabal Akhdar (Figure 2).

Rocks of Neoproterozoic age also crop out in the Mirbat area, where the Mirbat Sandstone Formation overlies a metamorphic basement (Platel et al., 1992). The basement is intruded by the Mirbat Granodiorite (706 ± 40 Ma, Rb-Sr date, Gass et al., 1990) and the Leger Granite (723 ± 2 Ma, U-Pb date on single zircons, Kellerhals and Matter, 2003). The Lower Ayn Member of the Mirbat Sandstone is glaciogenic (Kellerhals and Matter, 2003), and is overlain by the clastic Middle Arkahawl and Upper Marsham members. To date, no direct correlation of the Mirbat Sandstone with the Huqf Supergroup, based on lithostratigraphy and/or geochronology, has been possible, and research-in-progress is trying to resolve this issue (Allen et al., 2002). One possible interpretation is to correlate the diamictites of the Lower Ayn Member to the glaciomarine deposits of the Fiq Member of the Ghadir Manqil Formation in Jabal Akhdar (Figure 2). In this interpretation the shales and two sandstone bodies of the Middle and Upper Mirbat members would be equivalent with the two transgressive-regressive cycles of the Masirah Bay Formation in the Huqf area (Leather, 2001; see Figure 14), while the rest of the Nafun Group would be truncated by the base Cretaceous unconformity in the Mirbat area.

An alternative interpretation would correlate the glaciogenic Ayn Member to the Ghubrah Formation glacial deposits in Jabal Akhdar, and the Middle and Upper Mirbat members would be older than the Fiq glacial rocks in North Oman.

**Geochronologic Data**

Geochronologic data from the Ara Group in both outcrops (544 ± 3.3 Ma, U-Pb on single zircons, Fara Formation in the Jabal Akhdar, Brasier et al., 2000) and subsurface (542.0 ± 0.6 Ma and 542.6 ± 0.3 Ma, U-Pb on single zircons, respectively in the A3 and A4 carbonates of the Ara Group in the South Oman Salt Basin, Amthor et al., 2003) (Figure 2, Table 1), constrain the top of the Nafun Group, and therefore the top of the Buah Formation, to about 550 Ma. This is in good agreement with chemostratigraphic correlations by means of δ13C (Burns and Matter, 1993; Brasier et al., 2000; Cozzi et al., 2004; Cozzi et al., in press), and 87Sr/86Sr (Burns et al., 1994) with other sections worldwide (Saylor et al., 1998; Pelechaty, 1998; Brasier et al., 2000; Brasier and Shields, 2000) (Figure 3).

While the age of the top of the Nafun is geochronologically and chemochronographically well constrained, the age of its base remains uncertain, due to the paucity of reliably datable material. An absolute age of 723 ±16/−10 Ma from a tuffaceous sandstone interbedded with rainout diamictites in the Ghubrah Formation (lower Abu Mahara Group, Brasier et al., 2000; recently refined to 711.8 ± 1.6 Ma by Leather, 2001) is the oldest possible age of the Nafun Group. The granodioritic basement cropping out in the northern Huqf area (Al Jobah, Figure 1) yielded U-Pb absolute age dates on single zircons of c. 822-825 Ma and the overlying Halfayn Formation welded tuffs have U-Pb ages of c. 802 Ma (Leather, 2001). This is in contrast with the previously published Rb-Sr age of 562 ± 42 from a rhyoliote in the same Halfayn Formation (Gorin et al., 1982) and with a K-Ar age of 654 ± 12 Ma on a correlatable trachyte cored in the center of the Khufai Dome in the Huqf area (PDO unpublished data in Gorin et al., 1982). The younger age (562 Ma) is considered to be reset, as commonly occurs within the Rb-Sr and K-Ar isotope system (Evans, 2000), because it implies a very
short time span for Nafun Group deposition (only 10 my). This span seems geologically unjustified, given the generally slow subsidence that allowed Nafun facies to encroach over the whole of Oman (see section on basin evolution).

As previously noted, a tentative correlation between the Hadash Formation cap carbonate in Jabal Akhdar, and the carbonate succession overlying the Hafayn Formation in the Huqf area, is reasonable (Leather, 2001). This implies nearly continuous sedimentation during Nafun Group deposition, interrupted only by minor sequence boundaries (see Figure 14), in agreement with field data (McCarron, 2000; Cozzi et al., in press) and Arabian Plate sequence stratigraphic interpretations (Sharland et al., 2001). At the base of the Nafun Group, the Hadash Formation is interpreted as the initial flooding after the first Marinoan snowball Earth-type glaciation (N3 negative isotopic shift, Figure 3), and the start of the Nafun depositional megasequence. Soon-to-be-released data from other sections worldwide (Halverson et al., in review), confirm this correlation and constrain the duration of Nafun Group deposition to approximately 80-90 my.

**Basin Evolution**

The tectonic setting during the deposition of the Huqf Supergroup was addressed by Gorin et al. (1982), Loosveld et al. (1996), Immerz et al. (2000), Sharland et al. (2001) and Grotzinger et al. (2002), but remains highly debated. One model interprets the Abu Mahara Group as a syn-rift basin fill,
and attributes the ensuing thermal relaxation phase to the deposition of the Nafun Group. This interpretation is consistent with the estimated duration of Nafun deposition, of about 80-90 my, based on current stratigraphic, sedimentologic and geochronologic data. The genetic link between the Abu Mahara glaciogenic deposits and the overlying transgressive cap carbonate of the Hadash Formation (possibly corresponding to ca. 660-630 Ma Marinoan snowball Earth epoch, Sohl et al., 1999; Halverson et al., in review) correctly fits this time frame, excluding the existence of major unconformities within the Nafun Group. The weaknesses of the post-rift model are the absence, so far, of terminal Neoproterozoic ages from the underlying syn-rift deposits of the Fiq Member of the Ghadir Manqil Formation, and the low thermal maturity of both the Abu Mahara and Nafun groups (Terken et al., 2001).

An alternative scenario is that the Nafun may represent dynamic subsidence in a retro-arc setting related to the westward subduction of an oceanic slab beneath the Arabian Plate (Grotzinger et al., 2002). This model would explain the occurrence of volcanics and volcanioclastic of the overlying Ara Group as subduction-related melting, and the carbonate-evaporite cycles as the result of retro-arc desiccation. A third scenario is that the Nafun Group may have accumulated in a wide basin flexed down between a magmatic arc at the eastern margin of Gondwana, and a transpressive magemargin to the west (Cozzi et al., in press). Alternative tectonic models for explaining the Ara Group deposition, i.e. compression (Immerz et al., 2000) versus renewed rifting (Gorin et al., 1982; Loosveld et al., 1996; Sharland et al., 2001), are still open to debate.

THE BUAH FORMATION, NAFUN GROUP, HUQF SUPERGROUP

The Buaht Formation is mainly a dolomitic unit, with commonly a calcareous basal part, and terminates the second clastic-carbonate cycle of the Nafun Group. Its type locality is in the Mukhaibah Dome (southern Huqf area, Gorin et al., 1982; Hughes Clarke, 1988; Figures 1 and 9). Additionally, extensive outcrops are found throughout the Huqf area and in Jabal Akhdar (Rabu, 1988), where it is equivalent, as suggested by Tschopp (1967) and Gorin et al. (1982), to the Kharus Formation. A possible Buah equivalent is also found in the Saih Hatat, to the east of the Jabal Akhdar. Here a dolomitic unit called the Hiymol Dolomite (Glennie et al., 1974), later renamed by Le Métour (1988) the Hiyam Formation, overlies the Hatat metamorphic series and is unconformably over lain by the Ordovician Amdeh quartzites (Le Métour, 1988; Rabu et al., 1993). Stable isotopic data (δ13C), reported by Miller et al. (2002), seem to confirm the correlation of the Hiymol with the Buaht Formation as also proposed by Mattes and Conway-Morris (1990). However, the severe metamorphism and intense folding of the units outcropping in the Saih Hatat has discouraged further attempts to study these sections.

The age of the Buaht Formation cannot be determined with biostratigraphy due to the absence of skeletal fossils. Recent geochronologic data from both outcrops (Fara Formation, Jabal Akhdar; Brasier
Figure 3: Summary of $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ data from Nafun Group and Abu Mahara Group rocks in outcrops and wells of Oman. Tentative correlation with existing Neoproterozoic chemostratigraphic reference scale (Brasier and Shields, 2000). Isotopic data from Burns and Matter (1993), Burns et al. (1994), McCarron (2000), Leather (2001) and Cozzi et al. (2004; in press). See Figures 1 and 16 for locations.
et al., 2000), and subsurface (Ara cycles, South Oman Salt Basin; Amthor et al., 2003), constrain the top of the Buah at about 550 Ma. The age of the base of the Buah is speculatively assigned to be ca. 555 Ma, based on typical sedimentation rates for carbonate ramps in slowly subsiding tectonic settings (Burchette and Wright, 1992). This assumption fits with the age-dated Zaris Formation carbonate ramp deposits of Namibia (Saylor et al., 1998), and the Krol Group of India (Jiang et al., 2002, 2003). This tentative correlation is further confirmed by combining $\delta^{13}$C and $^{87}Sr/^{86}Sr$ curves from the Nafun Group and other sections worldwide (Figure 3), which correctly place the Buah Formation in the proximity of the Precambrian-Cambrian boundary (Burns and Matter, 1993; Burns et al., 1994; Saylor et al., 1998; Pelechaty, 1998; Brasier et al., 2000, Cozzi et al., 2004; Cozzi et al., in press).

The initial field studies on the Buah Formation by Gorin et al. (1982), Beurrier et al. (1986), Wright et al. (1990) and Dubreuilh et al. (1992) were followed by more recent ones summarized in internal PDO reports (C. Kapellos et al., 1992; R. Pilcher and R. Buckley, 1995; C. Gendrot and J.L. Rubino, 1996). Most recently McCarron (2000) first attempted a comparison between the Jabal Akhdar and Huqf sections of the Buah Formation.

**BUAH FORMATION IN OUTCROPS**

**Sedimentary facies in Jabal Akhdar**

Buah sections in the Jabal Akhdar (Figure 4) display shallow- and deep-water facies. Shallow-water facies occur in the eastern and southern parts of Jabal Akhdar (Wadi Hajir, Wadi Bani Kharus, Jabal al Jaru and Wadi Mu’aydin, Figure 4), while deep-water facies are found in the west (Wadi Bani Awf). The lower boundary of the Buah with the red siltstones and shales of the Shuram Formation, is always gradational (Figure 8a). It is represented by a 20-30 m-thick transition zone where storm-generated carbonate beds and red siltstone lithologies alternate, with the former becoming more abundant towards the base of the Buah. The top of the Buah is generally truncated via an angular unconformity by the Permian Saiq Formation (Figure 5a). Only the deep-water section in Wadi Bani Awf shows an apparently conformable boundary with the overlying Fara Formation.

![Figure 4: Schematic geologic map of the central part of Jabal Akhdar window, highlighting the late Neoproterozoic units.](http://pubs.geoscienceworld.org/geoarabia/article-pdf/9/4/11/5441895/cozzi.pdf)
Figure 5: (a) Angular unconformity between the steeply inclined Buah Formation and the overlying upper Permian Saiq Formation; Wadi Bani Kharus. (b) Edgewise conglomerate mound overlain by swaley and planar laminated wackestone-packstone, Wadi Hajir (lens cap is 5 cm across). (c) Meter-scale stromatolite dome flanked by flat pebble breccias. Note the flat top of the mound and the steep side showing rapid lateral growth; Wadi Bani Kharus, Jacob stick is 1.5 m long. (d) Silicified columnar stromatolites, Wadi Hajir (lens cap is 5 cm across); compare with Figure 8d.
The most complete shallow-water Buah section occurs in Wadi Hajir, where the Buah is 350 m thick (Figure 6). The lower 50 m of the section consists of thinly-laminated, dark-gray limestones interbedded with edgewise conglomerates and swaley and hummocky, cross-stratified wackestones-packstones (Figure 5b). This facies association passes upward into a 75 m-thick dolomitic interval consisting of elongated m-scale stromatolite mounds (Figure 5c). The mounds are overlain by a 100 m-thick unit of large-scale, cross-stratified ooidal-peloidal packstones-grainstones. These are interbedded with flat pebble breccias and dm-thick partially silicified columnar stromatolites (Figure 5d) with abundant white silica nodules. The uppermost part of the Buah consists of few columnar stromatolite beds, meter-thick mud-supported breccias, flat pebble breccias with mudstones and gypsum/anhydrite rosettes occurring towards the top.

Buah deep-water facies occur in Wadi Bani Awf (Figures 4 and 7), only a few kilometers to the west of Wadi Hajir, where the Buah is conformably overlain by the mixed carbonate-volcaniclastic deposits of the Fara Formation. The lower part of this 260 m-thick section consists of limestones with alternating planar laminated mudstones-wackestones and cm-thick graded beds (Figure 8a), which pass upwards into a few stromatolite mound horizons, edgewise conglomerates and flat pebble breccias. This interval, in turn, is overlain by 30 m of alternating black shales, siltstones and mudstones that exhibit planar lamination and normal grading (Figure 8c). The upper part of this section is entirely dolomitic and consists of a 20 m-thick matrix- to clast-supported megabreccia deposit with incorporated m-size clasts consisting of peloidal packstones-grainstones (Figure 8b). This unit passes upwards into slumped, graded and laminated dolarenites as well as massive flat pebble breccias. The uppermost part of the Buah in Wadi Bani Awf consists of platform-derived breccias (Figure 8d) and re-sedimented ooidal grainstones that are overlain by the first m-thick volcaniclastic sediments of the Fara Formation.

Interpretation in Jabal Akhdar

The lateral facies change that occurs in Jabal Akhdar is interpreted as due to ramp differentiation into a starved outer ramp in the west (Wadi Bani Awf section), and mid ramp-inner ramp depositional environments in the east and south (Cozzi et al., 2001; Cozzi et al., in press), originating a distally-steepened ramp paleotopography. Combining facies and chemostratigraphic correlations, Cozzi et al. (2004; in press) reconstructed paleowater depths in the Wadi Bani Awf area of ~150 m, and slope angles connecting inner-ramp to outer-ramp environments of 1-2 degrees. The presence of megabreccias in Wadi Bani Awf and of m-thick breccias in Wadi Hajir suggests sudden collapses of the Buah ramp, possibly due to synsedimentary tectonics, which would also have controlled the initial ramp differentiation (Cozzi et al., in press). No conclusive evidence for a karst origin of these breccias has been found.

Mapping of the direction of the slump folds in the surroundings of Wadi Bani Awf indicates that this area had a ‘cul de sac’ paleogeography, with a very articulated ramp-margin geometry and basin orientation, approximately towards the NNE (Cozzi et al., in press).

Sedimentary facies in the Huqf

The Buah Formation in the Huqf area extends over more than 3,000 sq km, with an outcrop belt that generally is elongated in a NNE direction (Figure 9). The lower boundary is gradational with the underlying Shuram Formation mixed carbonates and clastics (Figure 10a), while the top is sharply overlain by the ~600 m-thick carbonates of the possible Ara Group surface equivalents (Nicholas and Brasier, 2000) (Figure 10b). Previous studies (Gorin et al., 1982; Wright et al., 1990; McCarron, 2000; Sharland et al., 2001) incorporated the equivalents of the Ara cycles into the Buah Formation, distinguishing a lower and upper Buah. In this study, instead, the Buah Formation proper terminates at the base of the thick peritidal cycles of the Ara equivalents Figure 10b, where the boundary is marked by the sharp appearance of lithic arenites and sabkha facies (McCarron, 2000; Nicholas and Brasier, 2000). In this manner, the Buah Formation in this study only corresponds to the lower member of the Buah as defined in the previous studies (Gorin et al., 1982; Wright et al., 1990; McCarron, 2000; Sharland et al., 2001).
Figure 6: Sedimentological log of the Wadi Hajir measured section. Outcrop-subsurface correlation of shallow water Buah facies via gamma-ray and $\delta^{13}$C profiles. Key to lithology applies also to Figures 7, 11 and 19. See Figures 1 and 16 for locations.
Figure 7: Sedimentological log of the Wadi Bani Awf measured section. Outcrop-subsurface correlation of deep-water Buah facies via gamma-ray and δ13C profiles. See Figures 1 and 16 for locations.
Figure 8: (a) Field photograph of the lithological boundary between the Shuram and Buah formations in the Wadi Bani Awf measured section. Note the gradual increase of carbonate lithologies as approaching the base of the Buah. (b) Field photograph of megabreccia bed in the Wadi Bani Awf section. Note the vacuolar aspect of the megabreccia bed. (c) Cm-thick bituminous mudstones and red-black shales alternation; Wadi Bani Awf, rock hammer for scale. (d) Decimeter-sized shallow-water-derived clasts of columnar stromatolites found in redeposited breccias in the Buah outer ramp facies of Wadi Bani Awf; compare with Figure 5d (lens cap is 5 cm across).
The Buah Formation in the Huqf region attains a thickness of 130–190 m, and generally increases from north to south and from east to west (Figure 9). It can be informally divided into a lower and upper part (Figure 11). The lower part is 20–75 m thick and characterized by planar laminated limestones with frequent edgewise conglomerates and swaley cross-stratified wackestones-packstones, rare silty interbeds (more frequent in the southern sections), and isolated m-scale stromatolite mounds. The upper part of the Buah is made of m-scale elongated stromatolite mounds, making 20 m-thick bioherms, associated with large scale cross-stratified peloidal-ooloidal grainstones with bidirectional foresets (Figure 12a). These are capped by micritic dolostones and columnar stromatolites (Figure 12b) with increasingly abundant evaporites (gypsum/anhydrite) to the top. No evidence for prolonged exposure at the top of the Buah Formation has been so far found in the Huqf area, which implies continuous deposition into the overlying Ara-equivalent peritidal cycles (Nicholas and Brasier, 2000).

**Interpretation in the Huqf**

The vertical stacking of the sedimentary facies in the Huqf area is interpreted as a shallowing-upward cycle of a prograding, gently-deepening carbonate ramp. Mid-ramp storm-dominated environments passed upslope into a mid-inner ramp transition zone setting. The transition zone was made of an ooidal-peloidal tide-dominated shoal complex and associated m-scale stromatolite bioherms. Inner-ramp environments were characterized by shallow subtidal mudstones and evaporites deposition. Outer-ramp facies with bituminous mudstones and black shales, found in the western part of the Jabal Akhdar, is absent in the Huqf area. This attests to the slow overall subsidence and small depositional slope angles of the Buah ramp. Correlation of key sections confirmed that deposition took place on a gently inclined slope with angles of ~0.1 degree (Cozzi et al., 2004; in press), and that lateral progradation of sedimentary facies took place throughout Buah deposition. The progradation was controlled by subsidence rates that were low in the north (close to the Al Jobah basement outcrop) and greater in the south and west (Figure 17). Based on paleocurrent measurements of bi-directional foresets in herringbone cross-stratification in the ooid grainstones and measurement of m-scale stromatolites major axis elongation, Cozzi et al. (in press) concluded that tidal currents shaped both ooid sand waves and stromatolite buildups located at the mid-inner ramp transition. Paleoflow direction was NE-oriented, roughly orthogonal to the Buah prograding ramp in the Huqf area.

**BUAH DEPOSITIONAL MODEL ACROSS OMAN**

Integrating the data from Jabal Akhdar and the Huqf outcrops, it is proposed that the Buah carbonates accumulated on a distally-steepened carbonate ramp (Read, 1985) (Figure 13). In the case of Jabal Akhdar, the different subsidence rates between Wadi Bani Awf and Wadi Hajir controlled the ramp differentiation, with a starved slope where oil-prone facies were deposited. A laterally-equivalent carbonate ramp persisted in the shallow-water realm and shoaled up into peritidal facies. The slowly subsiding Huqf area allowed for the ubiquitous development of a gently-deepening carbonate ramp. Thickening away from low subsiding areas in the north (i.e. the Al Jobah basement high, Figure 17) and in the east (Figure 9) took place, together with lateral progradation over 10s of kilometers. This subsidence control and Buah facies development is implied by the doubling of the Buah thickness from the two Huqf outcrop areas, and towards the Jabal Akhdar sections. This interpretation is also consistent with data from wells located to the south of the Huqf area. There, shallow-water Buah facies thicken dramatically, before passing laterally into a sediment-starved organic-rich condensed outer-ramp sequence. The development of a ramp edge, before the facies change into oil-prone deep-water Buah, has also been observed in seismic lines to the south and west of the Huqf (Figure 18), in south (Figure 17) and in north Oman (Makarem High).

**SEQUENCE STRATIGRAPHIC INTERPRETATION**

**Buah Formation**

The outcrop data suggest that the Buah Formation was deposited during a highstand systems tract (HST), reflected in the general shallowing-upward character of the sedimentary facies and lateral ramp progradation (Figure 14). This interpretation is in agreement with the one of Gorin et al. (1982),...
Figure 9: Geologic map of the Huqf area of central Oman showing the Buah Formation outcrops (green) and measured sections. Black arrows indicate the accommodation space trends as inferred from the Buah outcrops (see text for explanation).
Wright et al. (1990), McCarron (2000) and Sharland et al. (2001). A maximum flooding surface (MFS) is interpreted within the top part of the Shuram Formation (Figure 14), below the gradual transition with the basal part of the Buah (characterized by a decrease in the clastic silty fraction and a strong increase in the carbonate content). No evidence for further subdivision of the Buah into other depositional sequences has been found; MFSs or sequence boundaries being absent.

In the present interpretation, an MFS surface is interpreted at the top of the Shuram prograding siltstone-ooid grainstone, decameter-scale, parasequence stack observed in the northern Huqf area (Figure 10a). The parasequences represent the highstand deposits of the underlying sequence (Figure 14). The maximum flooding at top Shuram is not sedimentologically expressed in the Jabal Akhdar sections. This is probably due to the deeper-water environment of this area with respect to the Huqf area. This interpretation differs from the one of Sharland et al. (2001) in two aspects. First, their MFS Pc20 at the base of the Shuram Formation implies the upper Shuram together with the Buah represent a long lived single HST. Second, these authors (their Figure 4.2, page 130) place their ‘base Shuram’ Pc20 in the lower part of the Buah, as logged by Cozzi at the same Wadi Shuram locality (Figure 15).

**Nafun Group**

The sequence stratigraphic interpretation of the Nafun Group is sketched in Figure 14 in terms of five Nafun third-order depositional sequences. The two second-order maximum flooding surfaces are located at the base of the Nafun Group (above the Hadash Formation cap carbonate): (1) MFS Pc10 of Sharland et al. (2001); and (2) MFS Pc20 at the base of the Shuram Formation of Sharland et al. (2001). The lower part of the Masirah Bay Formation is composed of two 3rd-order depositional sequences (Nafun 1 and 2), as proposed by Leather (2001), with their HSTs corresponding to two shallow-water prograding sand bodies. The overlying Nafun 3 sequence is marked by upper Masirah Bay transgression that culminates with an MFS in the green shales at the top of the formation (Leather, 2001). The overlying Khufai carbonates were deposited during the HST part of Nafun sequence 3.

![Figure 10](http://pubs.geoscienceworld.org/geoarabia/article-pdf/9/4/11/5441895/cozzi.pdf)
and are capped by SB4 as marked by a possible exposure surface (Huqf area), and incised valleys in seismic lines (to the NW of the Huqf outcrops; M. Vroon-ten Hove, 1997, PDO Report). The shelf margin systems tract (SMST) deposits are found in the Jabal Akhdar sections where resedimented, poorly to well-sorted quartz sandstones are found (McCarron, 2000; Cozzi et al., 2002). The following Nafun 4 TST and MFS are represented by the base of the Shuram Formation, which correlates with MFS Pc20 (Sharland et al., 2001).

The MFS Pc10 and Pc20 correspond to two major glacio-eustatic sea-level rises. MFS Pc10 may coincide with the end of the Marinoan snowball glacial epoch (Brasier and Sukhov, 1998; Brasier et al., 2000; Hoffman and Schrag, 2002; Halverson et al., in review). MFS Pc20, because of its associated major negative shift in δ¹³C (Burns and Matter, 1993; McCarron, 2000; Cozzi et al., 2002), has been correlated by Saylor et al. (1998) and Pelechaty (1998) with the Blasskranz glacial diamictites-cap carbonate sequence of Namibia. Alternatively, Halverson et al. (in review) correlate the Khufai-Shuram negative isotopic anomaly with the one found in the Johnnie Formation of California, with the one of the Wonoka Formation in Australia, and with the negative anomaly just below the Mortenstens glacial diamictites of northern Norway. Despite this, evidence for either glacial diamictites and/or cap carbonates is absent in the Omani sections. Current research for other possible mechanisms for the negative δ¹³C shift, besides a snowball glaciation, is in progress (Cozzi et al., 2002; Le Guerroué et al., 2003).

Figure 12: (a) Large scale cross-stratified ooidal grainstones at top Buah in the Huqf region. Note the bimodal component of the paleoflow direction, indicating deposition under tidal currents (lens cap is 5 cm across). (b) Cm-wide columnar stromatolites capping a m-scale stromatolite mound within the cross-stratified ooidal grainstones (lens cap is 5 cm across).
OUTCROP TO SUBSURFACE INTEGRATION

A study of cores, cuttings and side-wall samples in all Buah penetrations available in PDO was conducted for all of Oman. Gamma-ray profiles of the Buah outcrops and $\delta^{13}C$ curves from key measured sections, were used to transpose the high-resolution outcrop stratigraphy to the unsampled areas of the subsurface (Figures 6 and 7).

Field gamma-ray profiles on the shallow-water (Wadi Hajir) Buah outcrops in Jabal Akhdar have a blocky but generally flat gamma ray signature (Figure 6), reflecting the lack of siliciclastics. This upward trend towards a more clastic-free signal is also seen on gamma-ray signatures in Buah penetrations located to the west of the Huqf area, and to the southern edge of the South Oman Salt Basin (Figure 16). In contrast, the Buah outer-ramp facies of Wadi Bani Awf display serrated gamma ray signatures with spikes of high Th, U and K concentrations that correlate with clastic-rich parts of the sections (Figure 7). Similar log signatures are found in deep-water facies of the Buah in wells drilled along the Eastern Flank of the South Oman Salt Basin (Figure 16).
The δ¹³C profile in the Buah is characterized by a lower part with negative values hovering around −6‰ vs. Peedee Belemnite (PDB), that increase up-section to 0‰ and positive values of +2-3‰ at the top (Figures 6 and 7) (Cozzi et al., 2004; in press). This distinctive δ¹³C curve has been reproduced in all the outcrop sections within the present study, and in several Buah penetrations in Oman, pointing to the good preservation of the original isotopic signal in the Buah (Burns and Matter, 1993).

Correlation between the Buah outcrops and well penetrations via δ¹³C profiles, provides a correlation tool that is independent from sedimentary facies and gamma-ray logs.

Seismic interpretation of the Buah reflectors in all of Oman was carried out, starting with the best seismic-to-well ties available. The Buah reflectors are represented by bright loops varying from one to four reflection groups (Figure 17 bottom), depending on the Buah thickness. The reflections are sandwiched between an almost transparent package, attributed to the Ara salt-basal Ara carbonate above, and to the Shuram below. Clear downlapping reflectors at Buah level are recognized south and west of the Huqf area (Figure 17 top), in northern Oman around the Makarem High and in the South Oman Salt Basin (Figure 18 top). These are interpreted as prograding carbonate slope deposits connecting the edge of the Buah ramp with the adjacent sediment-starved basin. Thinning of the Buah reflectors to the south of the PDO concession area, is interpreted as due to the reduction of accommodation space. The reduction is due to slowly subsiding basement highs, as in the outcrop analog of the Huqf area and Al Jobah basement high (Figure 18 bottom).

The synthesis of the outcrops and subsurface data (Figure 16) shows a remarkably uniform depositional scenario in Oman. Sedimentation patterns at Buah time were controlled by areas of
Figure 16: Map showing the distribution of Buah sedimentary facies across Oman. Note the location of basement highs and their correspondence with inner ramp shallow-water Buah facies. The lettering refers to the traces of seismic lines and outcrop analog model shown in Figures 17 and 18.

slow subsidence, corresponding to the Al Jobah (Huqf outcrops), Makarem and Salalah basement highs (subsurface) (Cozzi et al., in press). These basement highs acted as nucleation points for the shallow-water Buah carbonate ramps to prograde laterally onto faster subsiding areas. The equilibrium points between sediment production and accommodation space creation halted the Buah ramp progradation, causing a downslope evolution from a homoclinal ramp into a distally-steepened carbonate ramp. With the exception of the Buah in Jabal Akhdar, shallow- and deep-water conditions
persisted roughly in the same areas throughout the deposition of the Nafun Group, as attested by the shallow- and deep-water stratigraphy in the Huqf and Jabal Akhdar areas, respectively (see also M. Vroon-ten Hove, 1997, PDO Report). This suggests that the depositional role of these basement highs was long lived in an overall context of moderate subsidence. The latter was conducive for the development of relatively deep-water starved basins where source rock facies accumulated, flanked by shallow-water areas where reservoir-prone facies deposited.

THE BUAH PLAY POTENTIAL

The discovery of commercial gas in the Buah (Tilesy et al., 2000) establishes it as the only proven play in the pre-Ara Group section of Oman. The distribution of Buah reservoir facies is restricted to areas where shallow-water ramp carbonates occur (Figure 16). These facies are in the form of cross-stratified peloid-ooid packstones-grainstones that, in the proximity of the Buah ramp edge, can attain a thickness of at least 70 m (e.g. Wadi Hajir). In the more interior areas of the ramp, where creation of

Figure 17: (top) Seismic line showing the transition from mid-inner ramp to outer ramp facies in the Buah Formation. See figure 16 for location. (bottom) Seismic character of thick inner ramp Buah facies that are represented by 3-4 bright loops. See Figure 16 for location.
accommodation space was reduced, this facies is limited to 15-30 m on average. The lateral continuity of the reservoir-prone facies is remarkably good, due to the pronounced HST ramp progradation, the grainstones making up laterally continuous sheets for tens of kilometers (e.g. Huqf area).

Other possible reservoir facies occur as calciturbidites and breccias of the outer ramp, which extend for several kilometers in the Jabal Akhdar outcrops and in the subsurface seismic sections, with degrading reservoir properties moving downslope towards the basin. The Buah ramp edge, apart from accumulating thick reservoir-prone facies (oid grainstones), was characterized by stacked m-scale stromatolite buildups. These microbial mounds hold the potential of being reasonably good reservoir facies if, upon organic matter decay, a new porous network developed. Such extensive buildups have been noted in the outcrops (e.g. the Wadi Hajir section), and possibly in seismic lines as chaotic reflections at the Buah ramp edge, as also noted in younger examples by Burchette and Wright (1992).

Figure 18: (top) Seismic line showing downlapping geometries to the right, interpreted as prograding clinoforms of the Buah distally-steepened carbonate ramp. Horizontal scale and clinoform dipping angles obtained from seismic line. See Figure 16 for location. (bottom) Sketch representing the development of a gently steepening Buah carbonate ramp in the Huqf area, constituting an outcrop analog for the general trends observed in the seismic (see above).
Overall, the vertical stacking of Buah shallow-water facies can be modeled as a layer-cake, tight-porous-tight, system (Figure 19). The lower and uppermost parts being low-porosity zones, while the middle part (grainstones and m-scale stromatolite domes) being the high-porosity and high-permeability zone. The top of the Buah, at least in the subsurface over structural highs, is heavily fractured and karstified, complicating the distribution of porous and tight zones, as in the case of the Makarem gas field.

The reservoir quality of the shallow-water facies is variable. Porosity values from subsurface penetrations range form 0.1–5%, and permeability from 0.1–1 mD. These low values are attributed to burial diagenesis in the form of dolomitization, calcite and silica precipitation, as well as bitumen plugging. Early hydrocarbon migration and retention into Buah traps could reduce burial diagenetic effects, thereby preserving primary reservoir properties (J.A. Rodd, 1990, PDO Report). Reservoir quality can also be enhanced by the development of fractures. Buah gas accumulations in the Makarem field are associated with a fracture and fault network that connects permeable vuggy layers (Tiley et al., 2000), locally enhanced by karst development.

Within most of the study area, the primary seal for the Buah reservoirs is the overlying Ara salt. In areas where the Ara salt has been completely removed due to dissolution (Heward, 1990), locally developed middle and lower Haima mudstones can provide intra-formational seals. An example of such a case occurs in the Makarem gas field (Tiley et al., 2000).
The aerially extensive Buah basinal facies consists of bituminous mudstones and black shales (Figure 20), similar to the bituminous interval found in the Wadi Bani Awf section of the Jabal Akhdar (Figure 8b). The relatively deep-water starved basins (~150–200 m deep, based on the outcrop analogs in the Jabal Akhdar) located in between the areas of shallow-water, mid-inner ramp sedimentation, must have experienced water stratification and disoxic-anoxic conditions, allowing the preservation of organic matter. Analysis from cored intervals of this facies (well Saba-1, Figures 1 and 20) document the occurrence of organic matter of bacterial origin that constitute fair to good type I/II source rocks. Measured TOC values from these intervals range from 2.5–3.5% (J.M.A. Buiskoll Toxopeus and F.A.M. de Gier, 1994, PDO Report).

The prolonged persistence, in some cases for the entire Nafun Group deposition, of basin depocenters with similar oil-prone facies (deep water Shuram and Buah formations) could constitute a large source rock accumulation capable of expelling large quantities of hydrocarbons. In fact, Huqf source rocks are believed to be the source of most of the hydrocarbons found in Oman (Terken et al., 2001). According to Terken et al. (2001) the generation of hydrocarbons from the Nafun source rocks occurred during early to middle Paleozoic. It is also possible that some of the Buah and Shuram source rocks generated hydrocarbons at a much later time. Later thermal cracking of oil into gas is supposed to have occurred in the deepest and hottest parts of Oman’s subsurface, i.e. in the Fahud and Ghaba Salt basins of north Oman (Terken et al., 2001). Hydrocarbons are inferred to have migrated from the deepest parts of the basins into the early-formed intrabasinal highs and the Eastern flank.

A number of basement-related highs are recognised in the study area, all of which formed during Ara times (Loosveld et al., 1996; Immerz et al., 2000; Grotzinger et al., 2002). In the few penetrations that targeted some of the highs, Nafun sediments were encountered. The commercial discovery of gas in the Makarem field has rejuvenated interest in the remaining Huqf highs. Trap styles for the Buah play are four-way dip or fault-bounded closures that are sealed by the overlying Ara salt or Haima intra-formational seals. Provided that the structural configuration is favorable, the occurrence of stratigraphic traps is also possible, especially in areas where the Buah changes from inner-ramp to outer-ramp facies.

CONCLUSIONS

The late Neoproterozoic Buah Formation is mainly a dolomitic unit that terminates the second clastic-carbonate cycle of the Nafun Group in Oman. It is proposed, on the basis of close integration of outcrop (Jabal Akhdar and Huqf areas) and subsurface data, that the Buah carbonates accumulated on a distally-steepened carbonate ramp during a HST. Abrupt lateral facies changes displayed by Buah sections in Jabal Akhdar are interpreted to be the result of ramp differentiation into a starved slope and ramp margin-inner ramp depositional environments. The slowly subsiding Huqf area, on the other hand, allowed for the ubiquitous development of a gently-deepening carbonate ramp with laterally continuous facies belts.

Assessment of the Buah play elements indicates the occurrence of favorable reservoir facies in the form of shallow-water peloidal-oidal grainstones that form continuous sheets for tens of kilometers. The off-ramp basinal facies, with TOCs ranging from 2.5–3.5%, represent potential source rocks. Top seal for any potential Buah reservoir will most likely be provided by the overlying Ara salt, or mudstones of the middle Haima Group. Four-way dip or fault-bounded closures are the most common trap types, but stratigraphic opportunities are also possible.

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