Advances in Arabian stratigraphy: Allostratigraphic layering related to paleo-water table fluctuations in eolian sandstones of the Permian Unayzah A reservoir, South Haradh, Saudi Arabia

John Melvin, Brian P. Wallick and Christian J. Heine

ABSTRACT

In the early stages of development of the Permian Unayzah A gas reservoir at South Haradh, difficulties in intra-reservoir wireline log correlation, poor seismic character, and the recognition of multiple gas-water contacts, necessitated a detailed (core- and image log-based) geological study of the reservoir. This study revealed that the Unayzah A can be divided into two stratal units. The lower unit has poor reservoir quality. It consists of a thin, discontinuous basal eolian dune sandstone that is abruptly overlain by up to 70 ft (21 m) of very fine-grained and silty, irregularly laminated sandstones. These sediments were deposited in a very shallow ephemeral (playa) lake setting. They terminate upwards in a thin but widespread upward-finining interval that represents the Maximum Extent of the Lake (MEL horizon). In the upper unit several facies of varying reservoir quality are recognized, representing deposits that were laid down in a “mixed” eolian depositional system. Although these facies are generally common to all of the studied wells, they vary significantly in their proportions and associations from well to well. Thus a number of depositional settings are identified, which pass southwards across the study area from erg-center, eolian dune cross-bedded sandstones in the north (“dry” eolian system) through erg margin, interbedded dune and interdune deposits to very fine-grained sandstones representing ephemeral lake sediments in the south (“wet” eolian system). Depositional cycles in the upper Unayzah A interval are recognized among the facies in each well, and in every case these can be related to fluctuations in the paleo-water table. When the wells are displayed in a stratigraphic section using the MEL horizon as a datum, several of these cycles are seen to be correlatable across the study area. Significantly, these sub-regional correlations are maintained both within and between the various facies tracts. They are allostratigraphic in nature with facies distribution controlled by a number of extrinsic factors including position of the paleo-water table relative to the depositional surface, rates of fluctuation of the water table, sediment availability for eolian transportation, transporting capability of the wind and rates of subsidence. Proximity to local ephemeral stream sedimentation was probably also a factor. It may be that in the long term the pulsed nature of the rising water table in South Haradh reflects the onset of a distant, pulsed rise in sea level, possibly related to the creation of the Neo-Tethys Ocean in the southern and eastern part of the Arabian Plate. Recognition of this allostratigraphic reservoir layering clearly identifies significant stratigraphic compartmentalization within the reservoir. This permits a clearer understanding of the distribution of reservoir bodies within the Unayzah A, and explains the variable gas-water contacts in the area. This conceptual stratigraphic model has been incorporated in object-based geocellular modeling for reservoir simulation at South Haradh and also at other Unayzah A gas fields in the area. Integration with geophysical (impedance) data leads to significantly improved success rates in relation to the strategic location of wells, yielding enhanced results in reservoir development.

INTRODUCTION

During the last two decades of the twentieth century the Saudi Arabian Oil Company (Saudi Aramco) embarked upon a major initiative to explore the deep subsurface of eastern central Saudi Arabia (Figure 1a) for non-associated gas reserves. This venture proved to be a success, identifying a number of significant new gas accumulations. Many of these new gas fields are found within Upper Paleozoic (Permian) Unayzah siliciclastic reservoirs, particularly in the area at and in proximity to the southern end of the giant Ghawar structure (Figure 1b).
Figure 1: Location maps. (a) Map of the Arabian Peninsula showing the general location of the Ghawar structure. Box highlights position of Figure 1b. (b) Map of eastern-central Saudi Arabia showing the distribution of Upper Paleozoic gas fields (red) and Mesozoic oil fields (green) in relation to the Ghawar structure (note that the Permian Unayzah A gas reservoir underlies the southernmost part of the Mesozoic oilfields at Ghawar). Box highlights position of Figure 1c. (c) Map of the South Haradh area at the southern extremity of the Ghawar structure, showing the wells used in the current study.
In the southernmost part of the Ghawar structure, known as South Haradh (Figure 1b), a significant gas accumulation was discovered in sandstones of the uppermost Unayzah. This Unayzah reservoir at South Haradh is the subject of the present study. At an early stage of field development it became clear that the internal stratigraphy of the reservoir was highly complex. This was manifest in the general difficulties encountered when attempting lithostratigraphic correlations among wells using conventional wireline logs. Problems in correlation were compounded by the relatively low density of well spacing at the time. Furthermore, petrophysical analysis of wireline log data from a number of wells, as well as downhole Modular Formation Dynamics Tester (MDT) data from some wells suggested the presence of multiple gas-water contacts even though few faults were recognizable from seismic sections across the area. The combined effects of widely-spaced wells and the unsatisfactory stratigraphic results from the use of conventional wireline log correlation led to the need to develop a reproducible layering scheme (i.e. reservoir stratigraphy) at South Haradh. To achieve this end a selected number of cored wells were identified across the field (Figure 1c) wherein the core was described and integrated with wireline logs, especially gamma-ray and image logs. A depositional model was constructed for the reservoir that accounted for the reservoir architecture. This model was successfully tested for predictability with subsequent new penetrations of the Unayzah A reservoir.

**STRATIGRAPHIC SETTING**

Sharland et al. (2001) presented an evaluation of the sequence stratigraphy of the entire Arabian Plate. They recognized a number of “Tectonostratigraphic Megasequences” (TMS) that provided the foundations of that sequence stratigraphic framework. Specifically, their TMS AP5 megasequence comprises in its entirety the Unayzah Formation. It is bounded at its base by the “Hercynian” unconformity (pre-Unayzah unconformity of Al-Husseini, 2004), representing the middle Carboniferous “Hercynian” tectonic event. The upper boundary of TMS AP5 is the pre-Khuff unconformity of Senalp and Al-Duaiji (1995).

The subsurface Unayzah Formation was first described from central Saudi Arabia by Ferguson and Chambers (1991). They recognized a tripartite lithostratigraphic subdivision comprising an uppermost Unayzah A member that was underlain by the Unayzah B member and a basal unit that they referred to as the Unayzah C member (if it was present at all). This broad, informal subdivision of the Unayzah Formation in the subsurface found general acceptance among subsequent workers (e.g. McGillivary and Husseini, 1992; Senalp and Al-Duaiji, 1995; Aktas et al., 2000; Al-Qassab et al., 2001; Wender et al., 2004; Al-Husseini, 2004). Melvin and Sprague (2006) revisited the lower part of the Unayzah in an extensive core-based study. They confirmed and characterized the presence of the Unayzah C and Unayzah B members and also identified a new stratigraphic unit which they referred to as the “un-named middle Unayzah member”. This new member can be recognized throughout the subsurface of eastern central Saudi Arabia and occurs stratigraphically between the Unayzah B and A members (Melvin and Sprague, 2006). It occurs in a position that occupies a previously ill-defined interval in the lower part of the Unayzah A member as it was originally described by Ferguson and Chambers (1991). The Unayzah A member is the highest-occurring stratigraphic unit within the subsurface Unayzah Formation and is truncated at its upper boundary by the pre-Khuff unconformity of Senalp and Al-Duaiji (1995): it is this member that constitutes the reservoir at South Haradh. Melvin and Heine (2004) believe that the base of the Unayzah A member also is an unconformable surface. It appears to be generally true that all four of these component lithostratigraphic members of the Unayzah in the subsurface are separated from each other, as well as from overlying and underlying formations, by significant depositional hiatuses (Figure 2).

The biostratigraphy of the subsurface Unayzah Formation in Saudi Arabia is based on palynology and has been discussed by Stephenson and Filatoff (2000a, b) and Stephenson et al. (2003). Such studies have historically proved challenging as a result of a general paucity of preserved material, due to a predominantly terrestrial (i.e. oxidizing) depositional setting throughout the time of deposition of the Unayzah Formation, as well as a considerable degree of paleophytogeographical variation in the distribution of the palynomorphs at the time (Stephenson et al., 2003). It has been possible however to assign ages to the various members of this Formation, and also to make reasonably confident correlations with coeval deposits elsewhere on the Arabian Peninsula, specifically Oman (Stephenson et al., 2003). Thus the Unayzah C member is considered to be Late Carboniferous (Serpukhovian – Gzhelian) in age and the Unayzah B is Early Permian (Asselian – Early Sakmarian). Ongoing palynological studies are providing confirmation that the “un-named middle Unayzah member”
is latest Sakmarian in age (N.P. Hooker, personal communication, 2008), thus corroborating the view originally proposed by Melvin and Sprague (2006). The Unayzah A member is considered on extremely limited biostratigraphic data to be datable as Artinskian to Kungurian. The late Paleozoic Unayzah stratigraphy of Saudi Arabia is summarized in Figure 2.

SEDIMENTOLOGY OF THE UNAYZAH A RESERVOIR AT SOUTH HARADH

Early studies of the subsurface Unayzah interpreted the Unayzah A sandstones as having been deposited in a fluvial to marginal marine setting (Ferguson and Chambers, 1991; McGillivray and Husseini, 1992). Senalp and Al-Duaiji (1995) described the Unayzah A member from a well at Hawtah field in central Saudi Arabia and attributed the sediments to deposition in a braided fluvial to flood plain setting, Evans et al. (1997) identified an eolian facies at the top of the Unayzah A member in a well in central Saudi Arabia and subsequently Heine et al. (1998) identified eolian facies more generally within the Unayzah A, based on interpretation of borehole image logs. Aktas et al. (2000) and Al-Qassab et al. (2001) recognized two sequences in the Unayzah A member at Hawtah field, which they correlated to the Chawar area and interpreted as comprising varying proportions of lacustrine, ephemeral fluvial and eolian sediments. Melvin and Heine (2004) described how the Unayzah A member in many places is characterized by sediments of an arid to semi-arid depositional setting and Melvin et al. (2005), in notes for a core-based workshop, elaborated by demonstrating how in the subsurface across the entire eastern-central part of Saudi Arabia the Unayzah A member comprises a complex mix of facies representing eolian ergs, ephemeral streams and ephemeral (playa) lakes.

In the current study at South Haradh a total of nine wells were selected for detailed study (Figure 1c): selection criteria required the Unayzah A member in the wells either to have been extensively cored and/or to have been logged by image logs as well as the normal suite of “conventional” wireline logs. A total of 1,060 ft (318 m) of core were described in the exercise. These core studies revealed that the Unayzah A member could be readily subdivided into a lower stratal unit and an upper one. The lower unit comprised a limited number of depositional facies, whereas the upper unit displayed a more varied suite of facies. These facies are described below.

| Stratigraphic Units | Kingdom of Saudi Arabia Subsurface Stratigraphy |
|---------------------|-----------------------------------------------|
|                      | TMS* (Sharland et al., 2001)                  |
| Late                | This paper                                    |
| Changhsingian           | TMS AP6                                      |
| Wuchiapingian           | Khuff                                        |
| Capitanian            | Basal                                        |
| Wordian              | Hiatus                                        |
| Roadian              | Hiatus                                        |
| Middle              |                                               |
| Kungurian            | Unnamed middle Unayzah member                |
| Early               | Unayzah A member                             |
| Artinskian          | H hiatus                                     |
| Sakmarian            |eresa of Sharland et al. (2001).              |
| Asselian             |                                             |
| Carboniferous       |                                               |
| Late                | Hercynian                                    |
| Serpukhovian - Gzhelian | Hiatus                                      |
| Permian             | Unayzah C member                             |
| (multiple hiatuses)  |                                              |
| Carboniferous       |                                               |
| Early               | Unconformity                                 |
| Hercynian           | Hiatus                                        |

Figure 2: Diagram illustrating the Late Carboniferous to Late Permian stratigraphy of Saudi Arabia. The Unayzah A member (the subject of this study) is highlighted in yellow. Note: TMS = Tectonostratigraphic Megasequences of Sharland et al. (2001).
Depositional Facies of the Lower Unit of the Unayzah A Member

High-angle Cross-bedded Sandstones

Description: In several (but not all) of the studied wells the basal contact of the Unayzah A member is overlain by an interval of fine- to medium-grained, well sorted sandstone that ranges in thickness from about 2 ft (0.6 m) to 6 ft (1.8 m) (Figure 3a, b, c). The sand grains are well rounded, with high sphericity and are very commonly frosted. This sandstone commonly displays high-angle, grain size-segregated cross laminations that in some places are quite highly contorted (e.g. well H: Figure 3a, 3 ft). In well E these cross laminations are abruptly truncated by a horizontal surface that is overlain by flat-laminated sandstone that contains a thin interval of siltstone (Figure 3c, 6 ft; Figure 4).

Interpretation: The high-angle cross-bedding and the textural characteristics of these sandstones at the base of the Unayzah A member at South Haradh suggest that they are the residual deposits of eolian dunes. The abrupt horizontal truncation of these cross laminations in well E (Figure 3c, 6 ft; Figure 4) is very significant. Stokes (1968) identified many extensive, smooth, parallel surfaces that sharply truncate eolian cross-bedding within many of the sandstone formations of the Colorado Plateau in the United States. He attributed these surfaces to rising paleo-water table through the eolian dunes, with concomitant deflation of the dunes down to the water table prior to subsequent migration of new dune fields across the water table surface. Such surfaces are commonly referred to as “Stokes’ surfaces”. Fryberger et al. (1988) investigated the concept further and concluded that “Stokes’ surfaces are commonly associated with deposits above and below the Stokes’ bounding surface which plainly reveal the influence of a near-surface groundwater control on wind sedimentation” and also that “Stokes’ surfaces and associated deposits are often laterally transitional to surfaces and deposits of associated depositional environments including interdunes, tidal flats, lagoons, beaches, lakes and non-eolian sabkhas”. Thus the sequence of structures observed in the basal eolian sandstones of the Unayzah A at South Haradh is interpreted to highlight a rising water table through eolian dunes. The local occurrence of contorted lamination is attributed to instability and failure of the sediment as it became saturated by the rising groundwater. The dunes were deflated down to the water table and then overlain by facies that represented the continued rise of the water table until it eventually rose above the depositional surface.

Irregularly Laminated, Argillaceous Very Fine-grained and Silty Sandstones

Description: Above the basal eolian sandstone described above (if it occurs at all) the lower part of the Unayzah A member is dominated by an interval that ranges in thickness from 40–70 ft (12–21 m) (Figure 3). It varies from red to grayish-brown and comprises silty, very fine-grained sandstones with less common, thin (cm-scale) siltstones. These rocks have very poor reservoir quality. The rocks are characterized by an abundance of highly irregular, argillaceous “crinkly” lamination which in places displays extreme disruption (Figure 5a). Locally these laminations display a shallow convex-upward aspect (Figure 5b). Elsewhere there is evidence for ripple forms and ripple cross laminations (Figure 5c). Very rarely the sediment is extremely contorted and has a strongly slumped appearance (Figure 5d). In all cases where this very fine-grained sandstone interval has been cored it contains rare, but persistent, very thin laminae of medium to coarse-grained, well-rounded sand grains. These laminae are only one or two grains thick: in some places these coarser laminae abruptly overlie a sharp mud-cracked surface and the coarser grains are seen to have fallen down into the cracks. In several wells and at well E in particular the uppermost few centimeters of the lower Unayzah A unit display a distinct fining-upwards from silty, very fine-grained sandstone to siltstone sensu stricto (Figure 3c, 52 ft; Figure 6).

Interpretation: In general the fine-grained nature of these sediments indicates that they were deposited in a relatively tranquil setting interpreted here to have been a standing body of water. No marine fossils have been recovered from this interval and it is thus considered to represent a lake that extended across the entire area of South Haradh in lower Unayzah A times. That much of the sediment was water-lain is evident in the ripple cross laminations and probably also in the localized contorted sediment indicative of sediment instability and slumping. The low-amplitude, convex-upward laminations have affinities to algal stromatolitic laminations. They are similarly interpreted as being algal in origin and represent very shallow conditions, possibly in close proximity to the lake.
margin. Crinkly silt layers similar to those seen in the lower Unayzah A member have been observed in relatively argillaceous parts of the Triassic Ormskirk Sandstone Formation of the East Irish Sea basin: these have been considered to support an interpretation of both biogenic mat and salt crust growth (Goodall et al., 2000). The distinctive, highly irregular and disrupted fabric that is common throughout the lower Unayzah A may be related to the development of such algal mats. Kocurek (1981) noted that interdune areas on Padre Island, Texas that were covered with algal mats were characterized by abundant degassing and fluid escape when loaded.

Notwithstanding the possible influence of associated algal mats, the more irregular disruptions seen within the lower Unayzah A compare very favorably with textures that have been described

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**Figure 3:** Core logs from three of the studied wells showing the nature of the lower part of the Unayzah A member (coloured). Note how in these examples the earliest deposits comprise high-angle cross-laminated sandstones that pass upwards abruptly into a thick development of very fine-grained sandstones and rare siltstones. The base of this cross-laminated sandstone is taken to be the base of the Unayzah A in these wells. Note: The legend presented here explains the symbols used in all the core logs presented in this and other figures throughout the current paper.
Figure 4: Core photograph of the cross-laminated sandstone seen at the base of the Unayzah A member in well E (see Figure 3c, 4–6 ft). Note the abrupt horizontal truncation of the cross laminations, interpreted as a “Stokes’ surface”, which is overlain by flat-bedded sandstones and a thin black siltstone. Note also the abundance of pink spherular concretions that appear to be concentrated mainly in the cross-laminated sandstone. Width of core is about 7cm.

Figure 5: Core photographs illustrating various features that are commonly found in the lower part of the Unayzah A member in South Haradh.

(a) Very fine-grained silty sandstone from well D showing well developed crinkly lamination that is very severely disrupted in places. Core is 7.3 cm wide.
(b) Very fine-grained silty sandstone from well D showing crinkly lamination that displays shallow, convex-upward aspect (especially in the lower part of the photograph). Note the thin horizon (arrowed) that is dominated by intra-formational clasts: these are attributed to brecciation of the crinkly laminations as a result of exposure and desiccation. Core is 7.3 cm wide.
(c) Well developed (wave) ripple forms in very fine-grained sandstone from well E indicative of shallow, water-lain conditions of deposition. Width of core is about 7 cm.
(d) Oversteepened bedding in well E suggesting sediment instability and slumping. Width of core is about 7 cm.
from interdune and sabkha deposits from a number of eolian successions elsewhere, both modern and ancient, and attributed to salt dissolution textures (e.g. Fryberger et al., 1983; Crabaugh and Kocurek, 1993; Smoot and Castens-Seidell, 1994; Goodall et al., 2000). Although it is true that in this study of the Unayzah A at South Haradh no evaporite minerals have been seen within any of these facies, this does not preclude their having been present at the time of deposition of these sediments. Subsequent dissolution of evaporite minerals, particularly halite, is to be expected in an interdune or sabkha environment where sediment preservation is intrinsically related to rising water table (see later discussion). Indeed Smoot and Castens-Seidell (1994) have noted that “although these fabrics may be associated with evaporites or their pseudomorphs, in some cases they may be the only indicator of saline conditions”.

From time to time (and from place to place) the very shallow water depths in this lower Unayzah A lake diminished to the point of temporary exposure as suggested by the occurrence of desiccation cracks in places within this gross facies. This is supported also by the presence of the very thin laminae of medium- to coarse-grained sand that are seen in places within the otherwise very fine-grained lake sediments (and which are locally seen to fall down the desiccation cracks). These laminae are interpreted as “quasi-planar adhesion stratification” (Hunter, 1980) or “adhesion laminations” (Kocurek and Fielder, 1982). Such structures form as a result of the adhering of dry, wind-blown sand to a wet or damp surface (such as a recently exposed lake bed). The evidence presented thus far would therefore indicate that the lake at South Haradh was very shallow and fluctuated in extent throughout lower Unayzah A times. It is thus considered to have been an ephemeral or playa lake. Notwithstanding the evidence for sporadic exposure, and consequent shrinkage of the lake, it is noteworthy that at several wells the lower Unayzah A playa lake sequence terminates upwards with an upward-fining passage from very fine-grained sandstone into siltstone (Figure 6). This can be inferred to represent a deepening (and therefore expansion) of the lake at that time, the significance of which is discussed later.

Depositional facies of the Upper Unit of the Unayzah A Member

In contrast to the very limited number of depositional facies seen in the lower stratal unit, the upper stratal unit shows a greater variety of facies types and assemblages. These are described below.

High-angle Cross-bedded Sandstones

Description: This facies is common throughout the upper Unayzah A member although it occurs in varying proportions among different wells throughout the unit. The rocks comprise fine- to medium-grained, well to very well-sorted sandstones, with very well-rounded and frosted grains of quartz sand. They generally display very good to excellent reservoir quality. These sandstones exhibit pronounced high-angle (over 27°), grain size-segregated cross-laminations (Figure 7a). Those laminations may be very closely spaced (“pin-striped”, sensu Fryberger and Schenk, 1988) and are commonly inversely graded. These sets of millimeter-scale “pin-striped” laminations very commonly are interstratified with
cross laminations that are a few centimeters thick. These cross-bedded deposits are all readily identified on downhole image logs, which, crucially, allows this facies to be recognized in uncored wells. The basal sets of the cross-bedded sandstones generally display lower dip angles and in several places are disturbed and show overturning and evidence of slippage (Figure 7b).

**Interpretation:** The inversely graded, closely spaced (“pinstripe”) cross laminations are interpreted as wind ripple laminations (subcritically climbing translative strata: Kocurek and Dott, 1981) that formed on the slip faces of eolian sand dunes. The thicker cross laminations are ascribed to grain flow cross strata (sensu Kocurek and Dott, 1981) that formed by gravity sliding of sand down the dune slipfaces. The disturbed cross strata that are commonly seen in the lowest parts of cross-bedded sets may be attributed to sediment shear within semi-consolidated blocks of dune sand as a result of mass wastage down the dune slipfaces. However it is noteworthy that similar structures have been observed in the lower parts of eolian dune cross-bedded sandstones elsewhere that have been attributed to sediment instability and failure as a result of becoming water-logged by a rising paleo-water table (McKee et al., 1971).

**Low-angle to Flat-laminated Sandstones**

**Description:** This depositional facies is fairly common throughout the upper unit of the Unayzah A member, although it varies in proportion among the various wells. The rocks have good reservoir quality and consist of fine- to medium-grained, well sorted sandstones, with very well rounded and frosted grains of sand that occur in low-angle to flat, grain size-segregated laminations (Figure 7c). Many lamina-sets have a “pin-striped” appearance. Flat-based, lenticular (convex-up) accumulations of coarse-grained, well rounded sand are also observed within these deposits. In places very low-angle truncations can be discerned separating different sets of the low-angle laminated sandstone (Figure 7c). Local disruption of the laminations has also been observed.

**Interpretation:** The textural characteristics of these sediments as well as the noted occurrence of “pin stripe” laminations are all strongly suggestive of an eolian (wind-blown) origin of these low-angle laminated sandstones. The low-angle laminations, as well as the local occurrence of convex-upward lenses of coarser-grained, well rounded sand are compare favorably with features seen in eolian sand sheets, as they have been described by Fryberger et al. (1979). Local disruption of the laminations is attributed in most cases to plant roots. This is to be expected in an eolian sand sheet setting and suggests that the paleo-water table was not far below the depositional surface in these examples.

**Irregularly Laminated Fine-grained Sandstones**

**Description:** In general this facies is quite common within the upper part of the Unayzah A member regionally, but it appears to be rather less common among the cores that have been described in this study from South Haradh. It displays moderate to poor reservoir quality and consists of moderately sorted, fine- to medium-grained sandstones that contain a heterogeneous assemblage of depositional structures. These include irregular to highly diffuse, crinkly and variably continuous laminations (Figure 7d) as well as very thin (centimeter scale) beds with well-developed adhesion ripple laminations.

**Interpretation:** The occurrence in places of adhesion ripple laminations suggests that these sediments were laid down upon a damp substrate (cf. Kocurek and Fielder, 1982). The irregular nature of the laminations is reminiscent of textures observed in damp interdune, or sandy sabkha environments (e.g. see Fryberger et al., 1988). Given the association of these sediments with facies (described above) that were clearly deposited in an arid, eolian-dominated setting, these irregularly laminated sandstones of the upper Unayzah A are similarly interpreted to represent a damp interdune environment, in close proximity to the paleo-water table.

**Irregularly Laminated, Very Fine-grained and Silty Sandstones**

**Description:** This facies has poor reservoir quality. It occurs in thin intervals that rarely exceed 2 ft (0.6 m) in thickness and comprises thin siltstones and silty, very fine-grained sandstones that are characterized by very irregular and commonly crinkly laminations (Figure 7e). In some places the
laminations are interrupted by sub-vertical, downward-tapering features; elsewhere more irregular disruptions are seen. Thin (cm-scale) beds showing ripple forms and ripple cross lamination have also been observed in this facies.

**Interpretation:** The identification of ripples in places within this facies demonstrates that the sediment was to some extent water-lain. These bodies of water were clearly very shallow and susceptible to exposure from time to time as indicated by the subvertical tapering cracks that are interpreted as desiccation cracks. The more irregular disruptions compare strongly with textures that have been described earlier from the lower Unayzah A. Indeed, this facies is very similar in its overall appearance to the extensive playa lake deposits described in the lower stratal unit of the Unayzah A at South Haradh. The significant difference lies in its thickness of occurrence. Compared with the lower

![Figure 7](http://pubs.geoscienceworld.org/geoarabia/article-pdf/15/2/55/5444907/melvin.pdf)  
**Figure 7:** Core photographs illustrating various depositional facies that are commonly encountered within the upper part of the Unayzah A member at South Haradh.  
(a) Fine- to medium-grained sandstone from well A displaying well developed grain size-segregated cross lamination. Note: the white spots are diagenetic spherules. Core is 7.3 cm wide.  
(b) Severely overturned cross laminations identified near the base of a cross-laminated sandstone bed-set in well A (see Figure 8a, 61-63 ft).  
(c) Fine- to medium-grained sandstone in well A showing low-angle to horizontal laminations. Note the very low-angle truncation of the lamina-sets (arrowed).  
(d) Fine-grained sandstone from well E showing indistinct to crinkly lamination. Coin for scale (2.5 cm).  
(e) Silty, very fine-grained sandstone and siltstone in well E showing irregular and crinkly lamination.
Unayzah A playa lake deposits, this facies is much thinner wherever it occurs within the upper unit of the Unayzah A. This, and its observed association with facies displaying strong eolian affinities (see below) strongly suggests that it represents a wet interdune setting (interdune ponds) wherein the water table has (albeit temporarily) risen above the depositional surface.

**Facies Associations within the Unayzah A Member at South Haradh**

**Lower Stratal Unit of the Unayzah A**

The lower part of the Unayzah A member comprises only two major facies, namely high-angle cross-bedded sandstones of eolian origin (which are not everywhere present) and irregularly laminated, argillaceous, very fine-grained and silty sandstones that were laid down in a shallow playa lake setting (Figure 3). The eolian sandstones, where present, are thin and rest upon the basal surface of the Unayzah A member. In all cases they pass upwards abruptly into the playa deposits that dominate this lower stratal unit of the Unayzah A (Figure 3). The Stokes’ surface seen in core in well E (Figure 4) shows that the basal eolian system was terminated by rising water table and the substantial thicknesses of the overlying playa facies indicate that the lake deposits were sustained by high water tables for what was probably a significant period of time. Some degree of fluctuation in lake levels (and therefore of water table) is indicated nonetheless by the sporadic occurrence within the playa facies of adhesion structures and desiccation suggesting some degree of exposure in places from time to time. In several wells the very highest part of the playa lake facies (top of the lower Unayzah A) is marked by a subtle, but discrete upwards-fin of the sediment (Figures 3c and 6), which is interpreted as a maximum deepening of the lake at that time. It would follow that to the extent that this deepening event is recognized among many of the wells chosen for this study its upper contact also therefore marks the maximum areal extent of the lake at the end of lower Unayzah A time in South Haradh. It will be shown below that this horizon is of considerable stratigraphic significance to our understanding of the layering of this reservoir and so for ease of reference it is designated the MEL (Maximum Extent of the Lake) horizon. The MEL horizon marks the boundary between the lower and upper units of the Unayzah A at South Haradh.

**Upper Stratal Unit of the Unayzah A**

In contrast to the lower part of the Unayzah A, the upper unit is characterized by a greater number of depositional facies: these have been described above and clearly are all associated with one or another sub-environment to be found within an arid to semi-arid eolian depositional setting. All of these facies are to be found within the upper Unayzah A among the wells selected for this study: significantly the proportions in which they are represented vary greatly from well to well. To investigate this variability the upper Unayzah A in a number of the study wells was systematically analyzed in terms of its facies characteristics as reflected in both core and image log.

**Well A**

In the north of the study area at well A the upper Unayzah A unit is seen in core to comprise discrete packages of sandstone that are of very similar thickness and that are dominated by two depositional facies (Figure 8a). Thus one package type comprises bed-sets of low-angle laminated sandstones that are 15–18 ft (4.5–5.4 m) thick and interpreted as predominantly eolian sand sheet deposits (e.g. Figure 8a, 8–25 ft; 42–61 ft). In places the low-angle laminations become somewhat diffuse suggesting that some of the sandstones were transitional to an environment more suggestive of a damp interdune setting. Alternating with the low-angle laminated sandstones are bed-sets that are 18–21 ft (5.4–6.3 m) thick. These comprise high-angle eolian dune cross-bedded sandstones and within which the individual sets of cross bedded sandstone are 4–6 ft (1.2–1.8 m) thick (e.g. Figure 8a, 25–42 ft; 61–82 ft). In two cases the basal sets display highly contorted laminations (Figure 8a, 25–28 ft; 61–64 ft). In at least two places (Figure 8a, 61 ft; 82 ft) these cross-bedded sandstones are abruptly overlain by very thin (1–3 cm) horizons of very silty, crinkly laminated sediment (Figure 8b) interpreted as water-lain interdune deposits. This facies relationship has the same significance as a Stokes’ surface, representing the termination of eolian dune sedimentation by deflation down to a rising paleo-water table. The role of a rising water table in the preservation of these sediments is evident also in the occurrence at the base of two of the bed-sets of cross-bedded dune sandstones of severely deformed and overturned laminations (Figure 8a, 25–28 ft, 61–64 ft). This type of soft sediment deformation in
Figure 8: Aspects of depth-corrected core-to-log correlations in the upper Unayzah A in well A.

(a) Core log showing well-defined bed-sets of sandstones displaying, respectively, high-angle grain size-segregated cross-laminations (e.g. between 25–42 ft and 61–82 ft) and low-angle laminations (e.g. between 8–25 ft and 42–61 ft). Cross-laminated bed-sets are terminated abruptly and horizontally by Stokes’ Surfaces, indicating deflation down to a rising water table. For key to symbols see Figure 3.

(b) Core photo showing the abrupt termination of cross-laminated eolian dune sandstone at a Stokes’ Surface, overlain by very thin silty laminations indicative of a shallow interdune pond.

(c) Image log data with gamma-ray log showing how the sandstone bedsets appear to have a gamma-ray log expression, and in particular how the high-angle, cross-laminated bedsets are clearly identified in the groups of high-angle “tadpole plots” derived from the image log dataset. The upper contacts of the cross-laminated bedsets are marked by an abrupt leftward shift in the “tadpole plot” data as indicated by blue dashed lines. Blue dotted lines highlight abrupt rightward shifts in the “tadpole plot” data, interpreted as representing the maximum development of relative “wetness” in the facies relations prior to an abrupt return to the relative dryness of the superseding “dry” eolian dunes. Less extreme shifts in the dip (and locally also the azimuth) data are marked by red dotted lines and are interpreted as lower (second?) order bounding surfaces between individual sets of cross-laminated sandstone. The line of correlation A-A’ correlates the illustrated Stokes’ Surface (rising water table) in the core with the dip data in the image log dataset. The MEL horizon marks the base of the upper Unayzah A.
eolian sandstones has been recognized in other formations elsewhere and attributed to a rise in the water table soon after deposition, causing instability, slippage and internal deformation (e.g. McKee et al., 1971; Doe and Dott, 1980; Horowitz, 1982; Oxnevad, 1991).

Figure 8c juxtaposes the image log “tadpole plots” of depositional dip from the upper Unayzah A interval in well A with the depth-corrected core data (Figures 8a, b). A line of core-to-log correlation A-A’ is drawn at the level where the thin silt horizon (Figure 8a, 82 ft; Figure 8b) sits abruptly on top of the bedset of eolian cross-bedded dunes. The high angles (over 27°) of the eolian dune cross-bedding are seen in the “tadpole plots” below this horizon, which itself is clearly evident as an abrupt leftward shift of the “tadpoles” (Figure 8c), demonstrating its own very low angle of dip. Thus a method appears to exist whereby a rise in the paleo-water table can be identified from the “tadpole plot” pattern in the image log (given that the facies have already been identified and interpreted from core).

Indeed it is clear from the image log “tadpole plots” in Figure 8c that a number of deviations in the distribution of “tadpoles” occur, which give rise to the recognition of three types of stratal boundaries within the upper Unayzah A in this well. The first type of deviation has been described above, whereby high-angle dips are abruptly overlain by a sharp leftward shift in the “tadpoles”. Blue dashed lines have been constructed through such shifts (Figure 8c), which are interpreted as Stokes surfaces. These resulted from rising paleo-water table down to which eolian deflation occurred, and above which depositional facies of a relatively “wetter” character were deposited. The second type of deviation in the “tadpole plot” data is manifest as a sharp rightward shift of the “tadpoles”. Examples of this are highlighted in Figure 8c as blue dotted lines. These surfaces separate low-angle laminated sediment (representing relatively “wet” facies) that is abruptly overlain by high-angle laminated sediment most likely representative of eolian dune sandstones. They therefore imply a maximum development of relative “wetness” prior to an abrupt return to the “dry” conditions of the eolian dunes. The third type of deviation displays leftward and rightward shifts of the “tadpole plots” (as well as some local associated shifts in azimuth) within the high-angle image log dataset. These shifts are not as pronounced as those already described above. Correlation with the core log shows that they more likely represent set boundaries within the eolian dune cross-bedded sandstones (Figure 8a). Such boundaries can be interpreted as lower order (second order?) bounding surfaces within the dunes (sensu Brookfield, 1977). They are identified in Figure 8c as red dotted lines drawn through these minor shifts in dip.

Wells B and C

Figure 9a shows the descriptive core log from the upper Unayzah A in well B. Although there was disappointingly poor core recovery it is clear that the upper Unayzah A interval in this well is dominated by eolian dune cross-bedded sandstones. No image log was run in this well but well C, although not cored did have an image log. Well C is located only 600 m from well B (Figure 1c) and so for the purposes of this study the two wells are considered as a complementary pair. The image log data from well C are presented in Figure 9b. The upper Unayzah A interval in this well is dominated by high-angle depositional dips that are interpreted as eolian dune cross-bedding. Abrupt and extreme leftward shifts in the image log dataset (identified by blue dashed lines) are relatively rare. Where they do occur, by analogy with well A these are interpreted as strong candidates for Stokes surfaces within the eolian dune sandstones and are therefore taken to represent probable rises in the paleo-water table in this location. At one level (at approximately 12,071 ft on the image log) the tadpole plots show a pronounced rightward shift in their distribution. The surface represented by this shift is shown as a blue dotted line and is interpreted to reflect the maximum development of relative “wetness” in the depositional facies, above which there is an abrupt return to relatively “dry” eolian dune cross-bedded sandstones. A number of more moderate shifts (both leftward and rightward) within the high-angle dip data are also observed, and by analogy with well A (discussed above) these are interpreted as probable second order bounding surfaces within bedsets of cross-bedded strata. They have been highlighted by constructing red dotted lines through them wherever they occur (Figure 9b). The overwhelming preponderance of eolian dune cross-bedded sandstones at the localities of wells B and C strongly suggests deposition within an eolian erg system.
**Well D**

In well D the upper Unayzah A interval was cored but there was no image log. Figure 10 shows the descriptive core log from this well. Two important observations can be made about the upper Unayzah A interval at this location: i) there are no eolian dune cross-bedded facies preserved; and ii) above the very fine-grained sandstone deposits of the lower Unayzah A the sequence is characterized by a cyclical development of facies (Figure 10) wherein each cycle is about 16–18 ft (4.8–5.4 m) thick. The cycle...
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Figure 10: Core log through the upper Unayzah A member in well D. Above the MEL horizon (base of upper Unayzah A) three distinct depositional cycles are identified, namely between 7.5–25.5 ft; 25.5–42 ft; and 42–67 ft. Each cycle commences with laminations of relatively coarse-grained sand laid down as adhesion laminations in a damp environment. These are superseded by very fine-grained sandstones showing increasingly “wet” affinities, representing progressive, relative upwards migration of the water table. Maximum wetting is achieved at the top of each cycle, and is marked by a blue dotted line. The sequence is abruptly terminated upwards by the pre-Khuff unconformity (PKU) at 67 ft. For key to symbols see Figure 3.
Figure 11: Core log through the upper Unayzah A member in well E. A number of distinct depositional cycles are identified, occurring in two different facies associations. Above the MEL horizon (at 2 ft) two cycles occur, between 2–12 ft, and 12–22 ft. These are very similar in character to those identified in well D (see Figure 10). Each commences with laminations of relatively coarse-grained sand representing adhesion deposits in a damp environment; these pass upwards into very fine-grained sandstone facies showing increasingly “wetter” affinities. These two cycles represent lake-marginal settings. They are overlain by about 10 ft of eolian dune cross-bedded sandstones and about 25 ft of no core recovery (32–57 ft). The upper part of the core (57–90 ft) shows well developed cycles that commence with fine- to medium-grained sandstones (residual dunes and sand sheets) and pass upwards into very fine-grained sandstones that display the characteristics of “wetter” interdune facies. All cycles demonstrate successively rising water table and the dotted blue lines represent the level of maximum wetting for each cycle. For key to symbols see Figure 3.
The lower part of the cored interval bears very strong comparison with the lower Unayzah A interval where it has been described from other wells. Thus these very fine-grained sandstones show abundant irregular to crinkly laminations and common disruption within the sediment. Evidence for desiccation in the form of mud-cracks is not common. The rocks are considered to have been laid down in a predominantly subaqueous, albeit very shallow, playa lake environment that was probably quite saline. The cores of this lower part of the Unayzah A in well G also show pervasive development of small (1–2 mm) grey to pink-colored diagenetic spherules: the abundance of these spherular concretions diminishes abruptly above the lowest 11 ft in the core (Figure 12, 11 ft).

Above this level in the core there is also a subtle but distinctive change in the sedimentology of the rocks. Certainly the general lithology (argillaceous, very fine-grained and silty sandstone) remains the same but a greater degree of ordering becomes apparent within the sediment. Three sub-facies are recognized that seem to occur in a regular cyclical arrangement wherein each cycle is about 9–10 ft thick. Each cycle commences with thinly bedded (sub-cm scale), very fine-grained sandstones (Figure 13a) that are interpreted as being water-lain. These pass upwards into extremely disrupted sediment that shows signs of internal collapse; small scale listric faults are commonly observed (Figure 13b). This disruption is interpreted as representing the growth very close to the surface of the sediment of pervasive salt crusts whose disruption and collapse is attributed to dissolution consequent on a rising water table. The disrupted sediments pass upwards into very fine-grained sandstones that display variably diffuse laminations but which are commonly punctuated by downward-penetrating and tapering cracks interpreted as desiccation cracks (Figure 13c). Each of these depositional cycles therefore represents the infilling of very shallow standing bodies of water (playa lakes) to the point of emergence and desiccation. At that point in each case the water table rose, dissolving any evaporitic deposits as it did so and ultimately creating a new shallow lake setting and the accommodation space required for the cyclical process to be repeated. Each of these flooding surfaces that identifies the boundary between successive cycles is marked as a blue dotted line in Figure 12.

As described above the lower part of this thick playa lake succession in well G shows few physical signs of emergence and is also characterized by an abundance of spherular concretions that diminish abruptly above a specific level in the core (Figure 12, 11 ft). Those concretions are considered to be indicative of early diagenesis in a relatively permanent aqueous medium. Conditions changed above the level at which the concretions are significantly reduced in number. It is only above that level that the cyclical development of sub-facies described above commences. In general, although still representative of playa lake conditions, those cycles characterize a relatively drier depositional setting, with each cycle showing evidence of exposure and desiccation, and the abundance of haloturbation within the cycles suggesting much more evaporative

Figure 12: Core log through Unayzah A sediments in well G. The sedimentary succession shown here comprises silty, very fine-grained sandstones throughout. Below 11 ft the sediment is relatively homogeneous and in particular is characterized by an abundance of diagenetic spherules (asterisks). Above this level (11 ft) a number of cycles are seen each of which passes upwards from thinly bedded sandstones through disrupted sandstones into sandstones that commonly display desiccation cracks. These cycles represent successive infill of a shallow lake system, where each new cycle commences with a flooding event (identified by a blue dotted line) that can be interpreted as a significant rise in the water table. For key to symbols see Figure 3.
conditions. Based on these distinctions it is therefore proposed that even in well G, where, except in its very uppermost part, the Unayzah A member is dominated by playa lake facies, it is nonetheless possible to identify a level of maximum development of that lake system, namely the MEL horizon. Specifically the MEL in well G is believed to be identifiable as that level below which spherular concretionary development occurs in the lower Unayzah A interval, and above which the characteristic development of upward-drying cycles occurs in the upper Unayzah A interval (Figure 12, 11 ft). Each of those cycles was terminated and preserved by flooding associated with an appropriate rise in the paleo-water table in this locality.

Sedimentological Evolution of the Unayzah A Member at South Haradh

From all of the foregoing discussion of depositional facies and facies associations, it is clear that the Unayzah A at South Haradh can be subdivided informally into two distinct genetic depositional units in this area. The lower unit commenced with a thin and discontinuous interval of eolian dune sandstone that was abruptly overlain by a thick development of relatively fine-grained sediment that displays evidence of having been deposited in an extensive ephemeral (playa) lake. A significant surface has been identified at the top of this interval of lake sediments which is believed to mark the deepest and widest extent of the lake: that surface is identified as the MEL horizon at South Haradh. Above the MEL horizon in each of the wells examined in this study, the upper Unayzah A unit displays a number of different facies, all of which can be attributed to deposition in an eolian environment *sensu lato*. Most of those facies occur in all of the wells, but they occur in widely varying proportions from well to well. A traverse through the wells from north (well A) to south (well G) reflects a change from a preponderance of essentially “dry” eolian sandstone facies (eolian sand sheets and dunes) (Figures 8 and 9) through mixed facies showing both “dry” and “wet” characteristics (e.g. well E) (Figure 11) to deposits that are dominated by “wet” playa lake facies (well G) (Figures 12 and 13).
This areal variability can be interpreted as reflecting a passage from erg center deposits in the north through erg-marginal deposits at well E into sustained playa lake deposition in the south of the study area. Associations of these facies throughout the upper Unayzah A interval all display a cyclicity that is attributable to fluctuations in and, specifically, episodic rises in the paleo-water table.

STRATIGRAPHIC ARCHITECTURE OF THE UNAYZAH A MEMBER AT SOUTH HARADH

Although from the perspective of reservoir stratigraphy the data thus far point strongly to a bipartite subdivision of the Unayzah A member at South Haradh into a lower and an upper unit, among all the wells the high degree of variability of facies within the upper interval poses problems regarding the predictability of their distribution in the subsurface. Thus although the information derived from this study may explain (because of these facies variations) the historical difficulties experienced in attempts at lithostratigraphic correlation (from wireline logs) within the Unayzah A, there remains the issue of evaluating the extent to which it can be used to understand better the three-dimensional stratigraphic architecture of the reservoir.

Howell and Mountney (1997), in a study of the Permian Rotliegend Group of the Southern North Sea of offshore northwest Europe, highlighted the limitations of lithostratigraphic correlations in those rocks for providing useful information regarding depositional facies distributions and paleogeographies. They proposed developing an alternative, time stratigraphic interpretation of their deposits. This necessarily invoked the principles of sequence stratigraphy that were first developed by Posamentier and Vail (1988) and Van Wagoner et al. (1990) from their consideration of marine and marginal marine rocks in relation to changes in relative sea level. The rocks of the Rotliegend are predominantly continental in origin and as Shanley and McCabe (1994) have observed, away from the marine realm, other controls upon depositional processes progressively overprint the effects of sea-level change. Howell and Mountney (1997) recognized this and pointed out that although changes in relative sea level cannot be identified within the continental intermontane Rotliegend basin, nonetheless those deposits can still be considered within a time-stratigraphic framework by applying other aspects of the sequence stratigraphic model. Such aspects include: (1) the systematic correlation of changes in depositional processes caused by extra-basinal parameters; (2) the recognition of time stratigraphic surfaces; and (3) the concept of the rate of accommodation space creation versus the rate of sediment supply as a control (Howell and Mountney, 1997).

Regarding the above, when reviewing all the variability of depositional facies within the Unayzah A at South Haradh, there is one aspect in all of the studied wells that appears to be constant. The end of the playa lake depositional system that characterizes the lower Unayzah A interval is everywhere marked by the MEL horizon that has been interpreted as representing the deepest and most areally extensive phase of the lake. Furthermore, in the upper Unayzah A interval a cyclicity of facies is identified in every well, that is independent of the actual facies observed and which is interpreted in every case to relate to episodic rises in the paleo-water table (see previous discussion). The MEL surface is itself indicative of a groundwater rise and given its great lateral extent can therefore be effectively considered, at least within the study area at South Haradh, as a surface of time-stratigraphic significance in its own right. Therefore a stratigraphic section was constructed through all of the wells studied in South Haradh from north to south (Figure 14a) using the MEL horizon as a datum. This section represents a distance of some 65 kilometers.

Within the upper stratal unit of the Unayzah A (i.e. above the MEL horizon), all of the various stratal boundaries are displayed in Figure 14a that were earlier independently identified and discussed for each of the studied wells (see Figures 8–12). These include: (1) Stokes’ surfaces, each indicating a rise of the paleo-water table, and interpreted from core and/or image log (blue dashed lines); (2) surfaces reflecting maximum development of wetting due to continued rise of the paleo-water table (as interpreted from facies associations in core, and/or inferred from image log: blue dotted lines); and (3) inferred lower order surfaces identified in core within bedsets of eolian dune cross-bedded sandstones and/or from image log (red dotted lines). Most strikingly, it is clear that at least four of these surfaces (each identified with a “W” symbol in Figure 14a) appear almost exactly to align
with each other from well to well across the entire study area; furthermore they are all also exactly parallel to the MEL horizon. The latter observation is not surprising since, as stated above, the MEL is itself a reflection of the most extensive rise in groundwater level. It is noteworthy that the second “W” horizon above the MEL includes a red dotted portion at well C (Figure 14a). Since in all of the other wells this horizon marks a rise in the paleo-water table, it seems probable that at well C, this particular stratal boundary is not a lower (second?) order stratal surface as earlier inferred (from the well data alone), but rather a higher order boundary of stratigraphic significance.

A similar stratigraphic section was constructed in an east-west direction across the field, employing similar criteria and with similar results (Figure 14b). Thus a reservoir stratigraphy at South Haradh can be constructed that is not lithostratigraphic in nature but is allostratigraphic in concept utilizing externally controlled and time-constrained data, namely sequential rises in the paleo-water table.

When the distribution of depositional facies as they are known from core in the studied wells is overlain upon the stratigraphic section shown in Figure 14a the southwards passage from eolian dune sandstones through mixed eolian dune and interdune facies to ephemeral (playa) lake deposits is well displayed within the upper Unayzah A unit (Figure 15). The correlative rises in water table discussed above and identified as “W” horizons in Figure 14a are further demonstrated to correlate through, and irrespective of, the different depositional facies tracts (Figure 15). It can be seen that, whereas the first, third and fourth “W” horizons above the MEL are represented in wells A and C by dashed lines (representing Stokes’ surfaces), in wells D through G they are represented by dotted lines (representing horizons of maximum wetting identified from facies associations) (Figures 14a, 15). This demonstrates that in the northern wells (wells A and C), where the gross facies associations imply somewhat drier conditions, the maximum expression of wetness due to the rising paleo-water table is limited to being manifest only as a Stokes’ surface. In contrast the depositional cycles identified in the more southerly wells (D through G: see Figures 10 to 12) reflect a fuller development of wetting in their facies relationships. Furthermore the abundance of cycles is greater in this southern area (particularly at well G), although their size (thickness) is less (Figure 14a).

From the foregoing, it is very clear that significant stratigraphic compartmentalization dominates the reservoir distribution across the South Haradh area (Figure 15). Thus eolian dune sandstones (which in general have optimum reservoir quality) can be envisaged in the subsurface as being encased in other sandstones of varying depositional facies and generally poorer reservoir quality. If these eolian dune reservoir sandstones are sufficiently isolated from each other it is then possible further to envisage each one to have its own local gas-water contact. These well data allow a conceptualized sketch map to be constructed across South Haradh that illustrates the variable distribution of depositional (and reservoir) facies across the area (Figure 16).

**DISCUSSION**

Kocurek and Havholm (1993) have suggested that eolian depositional systems can be viewed as a spectrum in which the end members are dry, wet and stabilized eolian systems. Specifically, wet eolian systems have been defined as those in which the water table or its capillary fringe is shallow and the moisture content at the interdune surfaces is at least sufficient to raise grain threshold values to the point where the surface is largely protected from deflation, thus increasing preservation potential (Crabaugh and Kocurek, 1993). Both Kocurek and Havholm (1993) and Crabaugh and Kocurek (1993) reasoned that the presence of accumulations interpreted as interdune flat in origin is in itself indicative of a wet eolian system. Crabaugh and Kocurek (1993) noted how relative changes in the water table can result from subsidence of the sediment column through a static water table whereas absolute changes can result from a climatic change (to more humid conditions) or the inland response to eustatic sea-level rise. The same authors, investigating the Middle Jurassic Entrada Sandstone in Utah, described how sediment accumulation in a wet eolian system occurs with a relative rise in the water table, and that these accumulations are characterized by the presence of climbing sets of eolian dune sand and interdune flat deposits. They are bounded by supersurfaces of bypass or erosion that form when the water table becomes static or falls (Crabaugh and Kocurek, 1993). Carr-Crabaugh and Kocurek (1998) subsequently concluded that water table rise is the fundamental mechanism that enables the accumulation and long-term preservation of wet eolian systems.
This concept of a basic continental sequence stratigraphy in wet eolian systems of sequences of low-angle climbing dunes and interdunes, separated by essentially flat supersurfaces associated with paleo-water table levels was further investigated by Mountney and Thompson (2002). They pointed out that the Crabaugh and Kocurek (1993) model of a sequence of dunes and interdunes that display a regular, positive angle of climb probably reflects an exceptional set of controlling conditions. Such accumulations require that the rate of rise in the water table is in constant ratio with the rate of migration of the dunes (Mountney and Thompson, 2002) and this in turn requires that an overall positive sediment budget is maintained. This model most likely represents only one end-member of a spectrum of depositional styles in wet eolian systems (Mountney and Thompson, 2002). Other models can be identified whereby, for example, sets of cross-bedded dune strata display climbing at a positive and reasonably constant angle but which are punctuated by spatially isolated lenses of wet interdune strata that relate to short-lived flash floods and did not migrate. An example of such a system was described from the Navajo Sandstone by Herries (1993). Langford and Chan (1988, 1989) have described the sedimentary architecture of the Cedar Mesa Sandstone of Utah, USA. There, extensive wet and flooded interdune deposits apparently accumulated in response to a high, static water table coupled with ongoing, but non-climbing migration of dunes fed by a restricted sand supply. Indeed, Loope (1984, 1985) has suggested that wet interdune strata within the Cedar Mesa came into being following deflation (negative climbing) to the water table. These complexities highlight the interplay between the relative height of the water table and the depositional surface, as well as the eolian sand supply (sediment budget). Mountney and Thompson (2002) summarized these inter-relationships in a diagram which illustrated the roles of subsidence, eolian sediment supply and water table in controlling the nature of the preserved stratigraphic record. Their diagram is reproduced for reference in Figure 17.

Mountney and Jagger (2004) re-investigated the Cedar Mesa Sandstone in south-east Utah. They studied lateral variation within a 20m thick eolian sequence that was bounded by deflationary supersurfaces and extended along 16 kilometers of outcrop. Their detailed paleo-environmental interpretations demonstrated that the Cedar Mesa exhibited a progressive and gradational lateral transition from a dry eolian erg center, through a mixed dry-wet eolian-dominated erg margin to a fluvially-dominated erg margin that was subject to periodic fluvial incursions (Mountney and Jagger, 2004). Clearly, there are strong similarities between the Cedar Mesa depositional system and the system described above for the Unayzah A reservoir in the study area.

By analogy with the Cedar Mesa Sandstone, it is likely that the variability in the depositional facies that constitute the upper Unayzah A at South Haradh is related to a variety of factors, both spatial and temporal in nature. Those factors include: (1) the level of the water table relative to the depositional surface in any given location; (2) the rate of rise of the water table; (3) availability of sediment (sand) for transport by the wind; (4) transporting capacity of the wind; and (5) rates of subsidence. Ideally it would be desirable to be able to separate each of these various factors for independent evaluation of their role when reconstructing the development of the subsurface three-dimensional stratigraphic architecture of the Unayzah A reservoir. However, in some cases there is not enough robust information available to consider such independent evaluation, for example regarding the contribution of rates of subsidence. It is noteworthy that when producing their own comprehensive diagram that related the different roles of the different parameters affecting eolian stratigraphic architecture, Mountney and Thompson (2002) were constrained to keep subsidence a constant (see Figure 17). In other cases, there is a very strong inter-dependency between parameters, to the extent that mutual isolation for analytical reasons is rendered impracticable. This is particularly true when considering sediment supply in relation to the water table. In wet eolian systems in particular the two are intimately and even definitively linked (see, for example, Crabaugh and Kocurek, 1993; Kocurek and Havholm, 1993). In the case of the Unayzah A reservoir at South Haradh it appears that the single most identifiable, and therefore most important, extrinsic (i.e. external to the system) factor controlling depositional architecture is the role of the paleo-water table relative to the depositional surface. Furthermore, it is the paleo-water table that singularly provides the area-wide datum (in the MEL horizon: see Figures 14 and 15) upon which the analysis and discussion can be based.

Thus, following the maximum development of the lower Unayzah A playa lake, an eolian erg system was developed above the MEL horizon in the north of the study area. The multiply stacked sets of eolian dune cross-bedded sandstones in wells B and C (Figures 9 and 15) demonstrate that interdune
Figure 14: See facing page for caption.
Figure 14 (facing page): Stratigraphic sections through the Unayzah A member incorporating the studied wells at South Haradh and using the MEL horizon as datum. (a) N-S line of section from well A to well G. Note: (1) the undulating surface at the base Unayzah A (BUA); (2) the highly non-uniform character of the gamma-ray logs especially in the upper part of the Unayzah A; iii) the persistent correlation through the wells of a number of the various cycles that were independently identified in the upper Unayzah A (i.e. above the MEL) in each well, and independently attributed to rising water table (W) in every case; iv) truncation of the Unayzah A at its upper surface by the pre-Khuff unconformity (PKU). (b) W-E section from well H to well I showing very similar features. Inset map shows the two lines of section.

Figure 15: N-S stratigraphic section through the Unayzah A member at South Haradh, using the MEL horizon as datum and incorporating depositional facies as described and interpreted in each well from cores and, as appropriate, image logs. Note: (1) In the lower Unayzah A unit, the variable thickness of the basal eolian sandstone and the extensive ephemeral (playa) lake deposits across the entire study area prior to establishment of the MEL horizon. BUA = Base Unayzah A; (2) In the upper Unayzah A (i.e. above the MEL) the change from eolian dune and sand sheet facies in the northerly wells to ephemeral (playa) lake-dominated deposits at well G in the south; (3) The effective isolation (compartmentalization) of optimum reservoir facies (eolian dune), identified in particular at well C.
flats were reduced to a minimum in this area. Such a situation prevails when the water table is relatively low, which increases sediment availability to the wind and thereby enhances the likelihood of eolian dune growth. This proceeds to the point where interdune areas are reduced to isolated interdune hollows resulting in a dry eolian erg system (Kocurek and Havholm, 1993). It is implicit in this scenario also that the wind remained relatively saturated with sand with respect to its potential transport capacity in order to sustain the development of the dunes (a concept that has been discussed by Kocurek and Havholm, 1993). Wells B and C are therefore considered to have been located erg-central to the Unayzah A eolian depositional system at South Haradh.

At the location of well A there is the interesting development of nearly equal thicknesses of eolian dune cross-bedded sandstone facies and low-angle eolian sand sheet (or “dry interdune”) facies. It has already been demonstrated that the eolian dune development was terminated by rising water table through the dune deposits (Figure 8). That that groundwater rise was probably quite rapid is supported by the evidence of contorted laminations at the base of two of the dune cross-bedded bed-sets. Similar features were reported from the Cedar Mesa Sandstone by Mountney and Jagger (2004).

Figure 16: Sketch map of depositional facies distribution in the upper Unayzah A member at South Haradh based on the facies analysis undertaken at the subject wells in this study.

Figure 17: Diagram showing the relationships between subsidence, eolian sediment supply and water table and their consequent control on the nature of the preserved stratigraphic record. Note that in this case the rate of subsidence has been held constant. Modified after Mountney and Thompson (2002).
From the location of well E southwards to well G the facies associations in the upper Unayzah A show a tendency toward increasing “wetness” in the system (Figure 15). In the area around well E the facies associations in the upper Unayzah A have been described earlier as initially displaying depositional cycles characteristic of ephemeral (playa) lake margins. These pass upwards into cycles that show affinities with a fluctuating eolian erg-margin (Figure 11). In both cases the cycles preserve a record of rising water table and can be interpreted as indicative of a wet eolian system. The establishment of erg-marginal deposits over playa-marginal deposits suggests that possibly overall the cyclical rate of water table rise diminished with the passage of time. Each of the observed erg-marginal cycles in this well displays upwards-increasing wetness with facies ranging upwards from residual eolian dunes and sand sheets (“dry” interdunes) to “wet” interdune ponds. This suggests that the relative water table itself fluctuated in a cyclical manner. As has been noted earlier, the cyclicity was asymmetric, or pulsed, in that each cycle shows signs of gradually increasing wetness, before abruptly returning to a state of relative “dryness” at the base of the succeeding cycle. When the water table was relatively high there was an appropriate reduction in the supply of sediment available for eolian transportation. This would have prompted a reduction in dune size per se and a concomitant enlargement of the interdune areas. This fluctuation of depositional sub-environments marked the margins of the eolian erg system in this area. The southerly increase in “wetness” becomes complete at the location of well G (Figures 12 and 15). It was in this location that the playa lake which had dominated the paleo-environment at South Haradh during lower Unayzah A time achieved its final, much-reduced expression. Even during upper Unayzah A times the lake margins fluctuated, with periods of infill and exposure being episodically (and rapidly?) flooded by successive rises in the paleo-water table as discussed earlier (Figures 12 and 13).

Mountney and Jagger (2004) have noted how the size of the damp/wet interdune units in the Cedar Mesa Sandstone increased proportionally at the expense of the eolian dune units from the erg center to the erg margin. They attributed this to a reduction in sediment availability towards the erg margin, as well as to the sediment saturation level (actual transport rate: potential transport rate) of the wind. The foregoing facies analysis of the upper Unayzah A unit suggests that sediment supply, as well as fluctuating water tables, was also a critical factor at South Haradh in determining the distribution of the various eolian depositional facies. Furthermore, it is likely that other extrinsic (allogenic) factors played a role. At a regional scale, the Unayzah A member is not necessarily everywhere dominated by eolian depositional systems. Melvin et al. (2005) have shown how in many places ephemeral fluvial sedimentation predominates, reflecting progradation of terminal fans into low-lying ephemeral (playa) lakes. The periodic introduction of such short-lived, but significant additional volumes of water would have locally enhanced the levels of the water table and sustained flooding within the playa lake system in, for example, the area of well G. This also explains the presence of a higher number of (albeit smaller) flooding cycles in the vicinity of this well (see Figures 12 and 15). In the longer term, and at an absolute scale it is possible that rising water table within the Unayzah A member sandstones was a reflection of the encroachment of an, albeit distant, rising sea level. Sharland et al. (2001) discussed how, around the time of deposition of the uppermost Unayzah Formation (i.e. the Unayzah A) the initiation of tectonic opening of the Neo-Tethys Ocean took place in the region of Oman. Those authors considered that the ensuing transgression took place increasingly later from southeast to northwest “possibly indicating a very rapid ‘unzipping’ effect” in that direction. It seems not unreasonable that a tectonically pulsed, northwesternwards advance of the rising sea would have been heralded by evidence for a pulsed, sustained rise in groundwater levels in the lands that lay ahead of the transgression. This possibility has been discussed further by Melvin et al. (2010, in press).

APPLICATION AND TESTING OF THE CONCEPTUAL MODEL

The foregoing geological analysis illustrates how the Unayzah A member comprises a number of depositional facies, all of which are sandstones but which display widely ranging differences in reservoir quality. It goes a long way to explaining some of the difficulties that arose when early attempts were made to construct a lithostratigraphic correlation scheme through this member. In identifying the realities of stratigraphic compartmentalization it also explains in part why within the gross Unayzah A reservoir possibilities arise for several levels of gas-water contacts. The essential attributes of this conceptual model have been successfully applied in object-based geocellular models at South Haradh, as well as at other gas fields with Unayzah A reservoirs in eastern Saudi Arabia (Raba’a and Heine, 2006).
It remains to identify the means whereby the model can be applied as a predictive tool for locating wells to target optimum reservoir facies (namely, high porosity eolian dune sandstones) and the attendant development of hydrocarbons within the Unayzah A reservoir at South Haradh.

**Impedance Modeling**

The economic development of the Unayzah A reservoir at South Haradh was suspended in late 2001 due to the difficulties inherent in successfully locating high quality reservoir. It had become clear from the well data then available that porosity distribution was limited to relatively thin zones, such that with only a few exceptions its identification was below seismic resolution. The problem was compounded by the common occurrence of contamination of the seismic data with noise from interbed multiples, as well as the realization that water was being encountered in unexpected locations updip of gas.

At the same time as sedimentologic evidence for a stratigraphically discontinuous Unayzah A reservoir was being compiled from core on a centimeter scale, as described above, seismic evidence on a decameter scale was converging on a similar solution. An initial seismic impedance model was developed from scant well data combined with 3-D seismic data which suggested patchy, possibly disconnected areas of low impedance and thus, high porosity (Figure 18). It was believed that this patchy porosity distribution was a direct reflection of depositional facies within the Unayzah A reservoir. Thus a pilot program was proposed for deepening to the Unayzah A reservoir in selected wells at South Haradh that had been planned initially to target the younger Khuff Formation. This program would test, at minimal extra cost, the evolving model of a stratigraphically heterogeneous Unayzah A reservoir by attempting to predict the distribution of optimum reservoir quality facies from the seismic impedance data.

Well J was the first such well recommended for deepening. The location, which had been originally selected for Khuff penetration, was also situated above a strong low-impedance anomaly associated with the Unayzah A reservoir (Figure 19). Although amplitude data were not consistent with the predicted anomaly, the impedance nonetheless suggested that high porosity would be encountered. Consequently, well J was deepened to the Unayzah and the results from limited wireline logging indicated a thick (124 ft: 37.2 m) sequence of water-wet sandstone dominated by what appeared to be high-angle cross-bedded eolian dune sandstone facies and eolian sand sheet facies. Although disappointing from the standpoint of fluids encountered, the exercise was deemed a success in terms of having encountered the predicted depositional facies and their reservoir quality.

The second well to be deepened was well K, which, although similarly planned originally to target Khuff gas, was also located above a significant impedance anomaly associated with Unayzah A reservoirs (Figure 19). Additionally, this location showed a significant amplitude anomaly at the Unayzah A level, further suggesting that the well was an attractive candidate for deepening. Initial evaluation of the seismic data suggested that the impedance anomaly at well K appeared connected to that seen at the water-bearing well J location; however, non-fault related reflection discontinuities were noted between well J and the proposed location (Figure 20), and with the growing understanding from sedimentological studies suggesting the likelihood of stratigraphic compartmentalization, well K was ultimately deepened to the Unayzah. The well encountered 116 gross ft (34.8 m) of gas-bearing sandstones in the Unayzah A, with 72 ft (21.6 m) of overlap with well J. From these results two possible conclusions could be drawn. Firstly, that the discordant gas-water contacts are the result of small structural discontinuities that are below seismic resolution; or second, that the Unayzah A reservoir distribution is indeed the product of highly variable depositional facies distribution and that direct sandstone-to-sandstone correlations are insufficient to present a complete picture of Unayzah A stratigraphy.

A further test of the stratigraphic/seismic hypotheses was conducted by deepening well L. This well was planned for another Khuff target sitting above a low-impedance, high-amplitude anomaly in the Unayzah A just south of and down dip of well E (Figure 19). At the location of well L there was even less indication from the seismic data of any possible structural deformation and compartmentalization whereas there were good indications of stratigraphic discontinuity. Similar to well J, well E (see previous discussion) had been a reservoir success encountering 102 gross ft (30.6 m) of sandstone;
Figure 18: An extraction slice through a 3-D acoustic impedance inversion model highlights what appear to be discrete stratigraphic bodies in a portion of South Haradh. “Islands” of green/red/yellow (presumed higher porosity) areas give way to broader areas of blue and purple (low porosity areas). Tests of these areas, including drilling at well M, have largely confirmed the connection between modeled impedance and porosity. This particular slice, in conjunction with other evidence, led directly to the drilling of the anomaly at well L which proved gas at a level beneath the gas/water contact seen at well E.

however, as it had proved to be mostly water-bearing, it had been completed in the Khuff. When well L was deepened, a gross thickness of 101 ft (30.3 m) of gas-charged reservoir was encountered; the well was fully 81 ft (24.3 m) down dip from known water with only 21 ft (6.3 m) of overlap.

One final well, which was deepened to the Unayzah A, was well M. There, the results added strength to both the geological and geophysical hypotheses of stratigraphic compartmentalization in this reservoir. The well, which was drilled in an area of high impedance at the Unayzah A level and therefore predicted low porosity, was situated midway between well J and well L (Figure 18). Well M resulted in a Unayzah section as predicted with little reservoir quality sandstone.

Although the deepening of well L and well M does not conclusively demonstrate proof of the hypothesis of stratigraphic compartmentalization for Unayzah A reservoir distribution, these and other wells that have subsequently been drilled with a high level of success serve today as the working model for all field development at South Haradh. Certainly, combining the sedimentological data with that from geophysical investigations appears to make a significantly robust case in favor of stratigraphically-isolated reservoir sand bodies.

CONCLUSIONS

Detailed geological studies based on the evaluation of core material with supporting input from image logs have resulted in a conceptual reservoir stratigraphic model of the Unayzah A reservoir at South Haradh that to a large extent explains many of the problems that were encountered during the early development phase at the field. The model is allostratigraphic in concept, being related to identifiable rises in paleo-water table, some of which are correlatable across the extent of the field.
Figure 19: Cross section through acoustic impedance inversion data showing wells discussed in the text. “Warm” colors represent areas of high porosity whereas “cooler” colors suggest lower porosity. The modeled Unayzah A sands are shown as white/yellow/red (black arrow). Well J confirmed a significant porosity section but was water-charged; well K, at a similar structural level, was gas-bearing. Well E, down dip of well K showed evidence of a gas-water contact whereas well L, down dip of well E is completely gas-charged. White arrows point to significant discontinuities within the Unayzah A.

Figure 20: Cross section showing reflectivity between well J and well K. The yellow tracked horizon represents the base of the Khuff D carbonate and marks the beginning of Khuff carbonate deposition. The strong positive reflection (blue) immediately beneath the base of the Khuff D carbonate pick marks the top of the Unayzah A reservoir. Note the discontinuity in the Unayzah A reflector between the two wells (arrow) and the stronger amplitude response at well K. Well J proved a thick, water-bearing sandstone package whereas well K showed similar lithology but was completely gas-charged. Although changes in reflectivity may be subtle, they nonetheless appear to show stratigraphic discontinuities between dune packages.
Permian Unayzah eolian sandstones, Saudi Arabia

The lower part of the Unayzah A comprises a thin discontinuous basal eolian sandstone that passes abruptly upwards into a very fine-grained and silty sandstone unit that can be up to 70 ft (21 m) thick. This is considered to be essentially non-reservoir and was deposited in a widespread playa lake depositional system that extended across the entire study area at South Haradh. This lake fluctuated in extent through time and the upper surface of its deposits is identified as representing both maximum depth and maximum extent of the lake. This surface is thus known as the MEL surface within the Unayzah A at South Haradh and separates its lower and upper units.

The upper unit of the Unayzah A comprises a number of depositional facies of varying reservoir quality that can be ascribed to an eolian depositional environment sensu lato. Although several of these facies occur in many of the studied wells, their proportions and associations relative to each other vary significantly from well to well. In general, the northern area of South Haradh is dominated by eolian dune sands, which pass southwards through mixed residual dune and interdune facies into residual playa lake facies. Notwithstanding the facies variations among wells, each of the wells displays a marked cyclicity of facies that is everywhere interpreted to be related to fluctuations in the paleo-water table. When a stratigraphic section is constructed through the wells using the MEL surface as a stratigraphic datum it is clear that several of these cycles can be correlated across the entire study area. Furthermore, these correlations are recognized irrespective of the facies through which they pass. This in turn demonstrates a significant degree of stratigraphic compartmentalization within the upper Unayzah A.

The various depositional facies seen in the upper Unayzah A in the study area can be assigned to a “mixed” eolian depositional system. This reflects the passage from “dry” eolian, erg-central facies in the north to “wet” eolian, erg-marginal and playa lake-dominated deposits in the south. These characteristics are highly analogous to mixed eolian deposits described from the Permian Cedar Mesa Sandstone of SE Utah. The variability of occurrence of facies in the Unayzah A is related to a number of factors including: (1) the relative height of the paleo-water table in relation to the depositional surface; (2) the rate of fluctuation of the water table; (3) the availability of sand for transport by the wind; (4) the transporting capacity of the wind; and (5) rates of subsidence. Facies distribution is also affected by other, short-term extrinsic influences, such as the proximty of the eolian depositional system to the influence of ephemeral fluvial sediments, which at a regional scale is known to have occurred from place to place during upper Unayzah A times. Long-term factors that may have controlled the pulsed nature of water table fluctuations in the upper Unayzah A were possibly associated with distant sea-level rise associated with the creation of the Neo-Tethys Ocean at the eastern margins of the Arabian Plate.

The conceptual depositional and stratigraphic model described herein for the Unayzah A reservoir has been successfully applied in object-based geocellular modeling at the study area, as well as at other gas fields in eastern Saudi Arabia where the reservoir consists of Unayzah A sandstones. The stratigraphic compartmentalization that is recognized within the upper Unayzah A reservoir as a consequence of this work explains in large part the noted occurrence of disparate gas-water contacts. The model has been applied in an integrated fashion with geophysical (impedance) data to locate reservoir quality sandstones and hence optimize gas reservoir development.

ACKNOWLEDGEMENTS

We thank the Saudi Arabian Ministry of Petroleum and Mineral Resources and the Saudi Arabian Oil Company (Saudi Aramco) for granting permission to publish this paper. Our thoughts on the Unayzah A reservoirs have benefited from many discussions with colleagues at Saudi Aramco. In particular we thank Ron Sprague, Roger Price, Kent Norton, Mark Prudden, George Grover and AbdulKader Afifi of Saudi Aramco’s Exploration Organization for their insights. We also thank the anonymous reviewers of this paper for their constructive comments on our work. We nonetheless accept sole responsibility for the ideas expressed herein. Our thanks go to Gene Cousart of Saudi Aramco’s Graphic Design Unit for his patience with us during preparation of the figures for this paper. Also, we are most appreciative of the tireless efforts expended by Hadi Al-Uraij and the Saudi Aramco Core Layout Team in laying out the many hundreds of feet of core examined in this study.
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ABOUT THE AUTHORS

John Melvin is Team Leader for the Gas Fields Special Studies Team within Saudi Aramco’s Gas Fields Characterization Division. There, his primary technical responsibilities lie in describing and interpreting the clastic sedimentology and reservoir stratigraphy of Permian Unayzah and Basal Khuff Clastics reservoirs, as well as Devonian Jauf reservoirs. Prior to holding this position, he worked on the sequence stratigraphy of the Upper Ordovician and Silurian rocks of Saudi Arabia in Aramco’s Geological R&D Division. He obtained his PhD from the University of Edinburgh in Scotland, and then spent over 20 years with BP employed as an Applied Sedimentologist. There he was involved in a large number of exploration and development reservoir studies in the North Sea and Alaska. He then spent 6 years as a Consulting Sedimentologist and Stratigrapher, successfully concluding reservoir studies in Egypt, Libya, Colombia and the North Sea, before joining Saudi Aramco in 2001. John has published several articles on applied sedimentology, and is a member of the AAPG, Dhahran Geoscience Society, IAS and PESGB.

john.melvin@aramco.com

Brian P. Wallick is a Geophysical Consultant in the Gas Fields Characterization Division of Saudi Aramco. He holds a PhD in Geophysics (Earth and Atmospheric Science) from Purdue University, a Master of Science Degree in Geology from the University of North Dakota and a Bachelor of Science Degree in Geology from Indiana University. After graduation, he joined Mobil Exploration and Producing, US as a production team member where he worked on both shelf and deepwater clastic reservoir geophysics in the Gulf of Mexico. After a short work assignment with Sonat/El Paso in Houston, he took up a position with Saudi Aramco where he has now worked for almost 9 years. During that time, he has developed considerable geophysical expertise in the characterization of Permian dune sand reservoirs.

brian.wallick@aramco.com

Christian J. Heine earned his BSc from Penn-State (1978, USA), MSc degrees in Geology from University of Tennessee (1983, USA) and Petroleum Engineering from Tulane University (1991, USA) and successfully defended his PhD in 2004. He began his career with Mobil Oil in Dallas in 1982 and was posted in several USA cities including Lafayette, Houston and New Orleans. While in New Orleans with Mobil, Chris was an Associate Professor at Tulane (1990 and 1991) in the Petroleum Engineering Department. Chris was seconded to Saudi Aramco in 1991, and in 1996 he joined the company permanently. Chris was the primary Geologist for the newly discovered aeolian Unayzah reservoir since 1991 starting with the Central Arabia ‘super light’ oil development. In 1997 he joined the non-associated gas development where he provided the geological input for the Devonian Jauf reservoir. Chris joined the Upstream Ventures Department and provides geological technical support to the Joint Venture companies. For the last 18 years, Chris has been very active in the Saudi Aramco training program where he teaches several courses for both the geology and petroleum engineering programs. He has lead over 30 geological field trips. He is an active member of the Dhahran Geoscience Society and the AAPG where he has served as a delegate for over 10 years and has served on several AAPG committees. From 2006-2009, Chris served as the Vice President of the AAPG Middle East Region.

christian.heine@aramco.com

Manuscript Submitted June 29, 2009
Revised October 5, 2009
Accepted October 13, 2009
Press version proofread by authors January 17, 2010