Advances in Arabian stratigraphy: Comparative studies of glaciogenic Juwayl and lower Unayzah strata (Carboniferous–Permian) of Saudi Arabia

John Melvin and Arthur Kent Norton

ABSTRACT

The Juwayl Member of the Wajid Formation, which crops out in the Wajid region of southwest Saudi Arabia, and the Unayzah C and B members of the lower Unayzah Formation in the subsurface of eastern and central parts of the country are all demonstrably late Carboniferous to early Permian in age, based on palynological analysis. Comparative studies of these two stratal units confirm strong genetic similarities between them, suggesting stratigraphic equivalence between the lower part of the Juwayl Member and the Unayzah C member, and the upper part of the Juwayl Member and the Unayzah B member, respectively. The boundary between the lower and upper parts of the Juwayl was not specifically recognized in outcrop, being covered with thick deposits of modern desert sand. The lower Juwayl and the Unayzah C are both interpreted to have been deposited in large glacial valley systems. In the Unayzah C, subsurface isopach mapping suggests down-valley transport from the north, implying that at least some of the ice was situated in localized, upland (alpine) ice caps. Multiple phases of glacial advance and retreat occurred. Glacial outwash sands and gravels (representing retreat phases) were subsequently cannibalized and severely deformed by re-advancing ice and they are identified now only as relict deposits. Glaciotectonic deformation is manifest in the lower Juwayl at outcrop as high to low-angle thrust sheets, and throughout the subsurface numerous shear zones are recognized in the Unayzah C member, both in core as well as in downhole wireline log responses (spectral gamma-ray and image logs). The multiple phases of glacial advance and retreat produced push moraine nappe complexes within which wholesale explosive disruption and redistribution of the sediment is observed. This was a consequence of fluidization related to glacially-induced overpressuring. Potentially significant reservoir heterogeneity arises in the subsurface Unayzah C member in relation to the shear zones, by the creation of reservoir compartments of widely varying extent and with unknown but potentially very poor interconnectedness. The upper Juwayl Member is represented at the outcrop by pebbly sandstones and conglomerates that were laid down upon a braided fluvial, glacial outwash plain. These pass upwards into boulder-bearing siltstones (stratified diamictites) that were deposited in a glaciolacustrine setting. Similar depositional sequences are seen in the subsurface Unayzah B member in the western (basin-marginal) part of the study area. Locally, subsurface data from the Unayzah B in these western areas suggest sustained ice-contact conditions, interpreted as evidence for local sustained “alpine” ice caps throughout Unayzah B time. Farther east, the more basin-central deposits of the Unayzah B member comprise a wide variety of depositional facies, all of which are nonetheless attributed generally to a glaciolacustrine setting. These include: (1) minor ice-contact push moraine deposits indicative of minor glacial re-advance during overall glacial retreat; (2) thick sequences of ice-proximal sublacustrine gravity flow sandstones and massive diamictites; and (3) significantly more ice-distal sublacustrine sandstones and mudrocks, including stratified diamictites and dropstones. In both basin-marginal and basin-central settings, the Unayzah B facies associations everywhere display strong evidence for sustained melting during terminal retreat of the Gondwanan ice sheets. This resulted in sustained infill and deepening and eventual overspilling of the basin-central lakes leading to widespread flooding throughout the basin. This flooding was ultimately manifest also at the basin margins in the west of the study area. A high degree of reservoir heterogeneity occurs within the subsurface Unayzah B member as a result of the wide variety of depositional facies. Reservoir quality correspondingly ranges from excellent to non-reservoir.
INTRODUCTION

The occurrence on the Arabian Peninsula (Figure 1a) of late Carboniferous to early Permian glaciogenic sediments has been well documented from Oman (Braakman et al., 1982; Hughes Clarke, 1988; Levell et al., 1988; Al-Belushi et al., 1996; Aitken et al., 2004; Osterloff et al., 2004; Martin et al., 2008) and Yemen (Roland, 1979; Kruck and Thiele, 1983; Stephenson and Al-Mashaikie, 2010). In Saudi Arabia, the possibility that late Paleozoic glacial deposits were present was first recorded by S.B. Henry and R.A. Bramkamp in 1950 (cited in Powers et al., 1966). They described the occurrence of granite boulders up

Figure 1: (a) Map of the Arabian Peninsula showing the areas studied in this paper, outlined in red. Note also the areas highlighted as black ovals, showing the location in Oman (A) and Yemen (B) respectively where Carboniferous–Permian glaciogenic sediments have been determined to occur at outcrop. (b) Geological sketch map of part of the Wajid area in southwest Saudi Arabia showing the outcrop distribution of the Carboniferous–Permian Juwayl sediments (orange) and specific areas visited in the course of the current study. (c) Map of eastern-central Saudi Arabia showing representative wells with Carboniferous–Permian lower Unayzah core that were selected for the current study.
to 5 feet (1.5 m) in diameter that crop out in the southwestern Wajid region, specifically in the Khasm Khatmah and Jabal Umm Ghiran areas of the Al’Arid extension of the Tuwaiq escarpment (Figure 1b). The boulders were interpreted to be glacial erratics by those authors. Helal (1964) concurred with this view, considering the rocks to be typical tillite or diamicrite deposits and noting the presence of striations on some of the boulders. Not all authors agreed however, and Hadley and Schmidt (1975) concluded that the boulder-bearing sediments at Khasm Khatmah were of fluvial origin, and that they showed “none of the features common to a glacial environment”. Frakes et al. (1976) also considered that the published information was contradictory and inconclusive. McClure (1980) discussed the issues relating to these rocks in the Wajid region and concluded that the “glacial boulder deposits appear to have been reworked and redeposited in a fluvial and nearshore environment”. McClure et al. (1988) presented material and conclusions that came down more definitively in favor of a glacial origin for these sediments in the Khasm Khatmah area and at Jabal Umm Ghiran.

In the subsurface of eastern and Central Saudi Arabia (Figure 1c), the late Carboniferous to early Permian section is represented by the Unayzah Formation, which comprises a series of sandstones and related deposits that sit upon the so-called “Hercynian” unconformity (pre-Unayzah unconformity of Al-Husseini, 2004). McGillivray and Husseini (1992), Senalp and Al-Duaiji (1995), Sharland et al. (2001) and Al-Husseini (2004) have all alluded to a glaciogenic component of the Unayzah Formation, particularly in its lower part, but no specific details were presented in that regard by those authors. Subsequent studies by Melvin et al. (2005), Melvin and Sprague (2006) and Melvin et al. (2010) have recognized and documented a variety of glaciogenic facies within the rocks of the lower Unayzah.

The current work presents new data that shed light on the origin of the late Paleozoic sediments that crop out in the Wajid region of southwest Saudi Arabia (Figure 1b). Further, it presents a review of the character and origin of the lower Unayzah members in the subsurface, with reference to their occurrence in 20 representative cored wells (with new, additional data and some minor revisions) (Figure 1c). Crucially, it investigates the extent to which the rocks at the outcrop can be related to coeval Unayzah rocks in the subsurface in terms of similarities and differences pertaining to their depositional facies. Finally, it seeks to identify and characterize the nature of any heterogeneities that may occur in the context of their potential as hydrocarbon reservoir rocks.

**STRATIGRAPHIC SETTING**

Lithostratigraphy

The boulder-bearing strata mentioned above that crop out in the Wajid region comprise the uppermost beds of a clastic succession that was originally designated the Wajid Sandstone in 1948 by R.D. Gierhart and L.D. Owens (cited in Powers et al., 1966). Subsequent stratigraphic revision by Kellogg et al. (1986) placed them within the Juwayl Member of the Wajid Formation (Figure 2). Evans et al. (1991) recognized some equivalence between the Juwayl Member at the outcrop and the subsurface Unayzah Formation. They proposed abandoning the term “Wajid Formation” and further suggested that the Juwayl Member sedimentary succession should be renamed the Unayzah Formation. Their suggestion has not been pursued since publication of their findings. For the purposes of clarity and avoidance of confusion with the subsurface deposits (with which they will be compared here), the current work will refer to the sediments at the outcrop as the Juwayl Member.

Sharland et al. (2001) presented a complete subsurface sequence stratigraphy for the Phanerozoic of the Arabian Plate. As a framework for that study, those authors identified in the first instance a number of “Tectonostratigraphic Megasquences” (TMS). The Unayzah Formation comprises, in its entirety, TMS AP5 (Figure 2) and spans the period from the middle Carboniferous “Hercynian” tectonic event to the early late Permian rifting event that created the Neo-Tethys Ocean. Throughout the subsurface the Unayzah is highly variable in its occurrence, ranging in thickness from zero to over one thousand feet. It was originally subdivided informally into three members, namely the Unayzah A (youngest), Unayzah B and Unayzah C (oldest) (Ferguson and Chambers, 1991). This broad, informal subdivision found general acceptance among subsequent workers (e.g. McGillivray and Husseini, 1992; Senalp and Al-Duaiji, 1995; Wender et al., 1998; Aktas et al., 2000; Al-Qassab et al., 2001; Konert et al., 2001;
Al-Husseini, 2004). Melvin and Sprague (2006), in an extensive core-based study, confirmed and characterized the Unayzah B and C members, and also identified a new stratigraphic unit, which they referred to as the “un-named middle Unayzah member”. This occurs stratigraphically between the Unayzah B and A members, occupying 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 lowermost bounding contact of the Unayzah is the “Hercynian” unconformity, which represents a significant “Hercynian” tectonic event that occurred during the middle Carboniferous (Al-Husseini, 2004). This event was closely followed by the inception of the late Paleozoic ice age in Saudi Arabia, which is thought possibly to have lasted for up to 35 million years (Al-Husseini, 2004). Any glaciogenic features within the Unayzah are limited in occurrence to the lower (Unayzah C and B) members (Melvin and Sprague, 2006). The latter authors considered the Unayzah C member to represent syn-glacial events, with the terminal retreat of the ice sheets being reflected in the overlying deposits of the Unayzah B member. It is generally true that all four component lithostratigraphic members of the Unayzah Formation in the subsurface are separated from each other, as well as from overlying and underlying formations, by significant depositional hiatuses (Figure 2).

Figure 2: The late Carboniferous to late Permian stratigraphy of Saudi Arabia. The stratigraphic position of the Juwayl Member of the Wajid Formation, as it occurs at the outcrop in Wajid region, southwest Saudi Arabia, is shown compared with the Unayzah C and B members that occur in the subsurface of eastern-central Saudi Arabia. Those stratigraphic units, compared and discussed in the current study, are highlighted in blue. * TMS = Tectonostratigraphic Megasequences of Sharland et al. (2001). ** UmUm = Unnamed middle Unayzah member.
Biostratigraphy

In the outcrop sections of the Wajid region the inferred glaciogenic deposits of the Juwayl Member were originally considered to be “Permian or older” (Steineke et al., 1958). This was refined to “Lower Permian and older (?)” by Powers et al. (1966). These determinations were based primarily on the relative stratigraphic position of the sediments between datable overlying and underlying rocks. Cameron and Hemer (in McClure, 1980; McClure and Young, 1981) subsequently interpreted these boulder-bearing sediments at the outcrop to be late Carboniferous (Stephanian = late Moscovian to Gzhelian) to early Permian (Sakmarian) in age, based on palynological analyses. The same workers were able to assign a similar age to Juwayl Member sediments from shallow uphole wells drilled close to the Wajid outcrops.

In the subsurface of eastern-central Saudi Arabia, a lack of macrofossils throughout the Unayzah Formation restricts biostratigraphic age dating techniques to palynological analyses. It is furthermore the case that many sections within the Unayzah are barren of any fossils, including palynomorphs. This is particularly so for the Unayzah C member. Owens et al. (2000) published details of a palynological assemblage recovered from an interval overlying, but very close to, the top of the Unayzah C member in a well in eastern Saudi Arabia. That assemblage was characterized by an abundance of reworked uppermost Famennian to basal Tournaisian land-plant spores in association with much smaller numbers of monosaccate pollen (including Potonieisporites, Plicatipollenites and Cannanoropollis). The latter are unknown from sediments older than Namurian (Serpukhovian–Bashkirian) and were therefore considered to represent the only flora likely to be indigenous to this assemblage. Owens et al. (2000) assigned an age of early Namurian (Serpukhovian) to the sampled interval, and also to the underlying sediments of the Unayzah C member. J. Filatoff (written communication cited in Melvin and Sprague, 2006) subsequently revised the interpretation of this palynological assemblage, which he designated the “Cm palynoflora assemblage”. By comparison with more regional data, he referred the Cm palynoflora to the Potonieisporites Assemblage of Love (1994). That assemblage has been recovered from the lowermost Al Khlata Formation in Oman (considered equivalent to the Unayzah C member in Saudi Arabia: Stephenson et al., 2003; Melvin and Sprague, 2006). There, it has been dated as late Carboniferous (Stephanian = late Moscovian to Gzhelian) in age (Osterloff et al., 2004).

Notwithstanding the above, there are currently no more than three wells identified across the subsurface of eastern-central Saudi Arabia wherein the Cm palynoflora assemblage occurs unequivocally within sediments of the Unayzah C member (N.P. Hooker, 2010, personal communication). Furthermore, Melvin and Sprague (2006) have shown that the Cm assemblage is just as likely to occur within the Unayzah B member (independently dated as early Permian: see below) as in the Unayzah C member. Uncertainties related to the potential for reworking of all components of this assemblage (including the long-ranging monosaccate pollen) are clear. Its use in age determination is thus considered limited, although its characteristic signature of substantial reworking of lower Paleozoic forms mixed with limited monosaccates (reworked or otherwise) has utility from a palynofacies point of view.

More recent work within Saudi Aramco has shown that facies equivalents of the Unayzah C that occur elsewhere in the subsurface of Saudi Arabia (i.e. outwith the current study area), and above the “Hercynian” unconformity host a number of discrete palynological assemblages. Those assemblages range from mid- to late Carboniferous in age and are identified within Saudi Aramco as C3 (latest Serpukhovian–Bashkirian) through C1 (late Moscovian–Gzhelian: equivalent to the Potonieisporites Assemblage of Love, 1994) assemblages (N.P. Hooker, written communication, 2009). It seems prudent at this stage to consider the age range of the Unayzah C member to be, at most, as long as latest Serpukhovian–Gzhelian, and certainly no younger than late Moscovian–Gzhelian.

Stephenson (1998) and Stephenson and Filatoff (2000) correlated the Unayzah B member in the subsurface of Saudi Arabia, and the upper part of the Al Khlata Formation in Oman, with the Converrucosporites confluens Oppel Zone. This palynological biozone was identified by Foster and Waterhouse (1988) in the Canning Basin of Australia, where, crucially, it was found in association with marine fauna that allowed correlation with the standard early Permian stages of the south Urals in Russia. Initially considered to be middle to late Asselian in age, subsequent revision by Archbold (1995, 2001) indicated the base of the zone to be latest Asselian with an upper limit extending into the
Tastubian (Early Sakmarian). On this basis, most current workers on the Arabian section consider the Unayzah B and upper Al Khlata sediments to be latest Asselian to Sakmarian in age (e.g. Stephenson, 1998; Stephenson and Filatoff, 2000; Stephenson et al., 2003; Stephenson et al., 2008). It should be noted however that recent work by Stephenson (2009) has identified the *C. confluens* Oppel Zone within the Ganigobis Shale Member of the Dwyka Group in Namibia. There it occurs in close proximity to an ash layer that has been radiometrically dated at 302.0 ± 3.0 Ma (Pennsylvanian; Gzhelian or Kazimovian) (Bangert, 2000). This discovery could have implications for the consistency of the stratigraphic range of the *C. confluens* Oppel Zone across Gondwana, and also for the diachroneity (or otherwise) of the late Paleozoic Gondwanan glaciation and its deposits.

The late Paleozoic stratigraphy of Saudi Arabia, as it is reflected both at outcrop and in the subsurface, is shown in Figure 2. The Unayzah C and B members represent the glaciogenic component of the Unayzah Formation in the subsurface (Melvin and Sprague, 2006) and collectively appear to be age-equivalent to the Juwayl Member at outcrop. It seems reasonable therefore, for the comparative purposes of this paper, informally to consider the Unayzah C member as broadly equivalent to the lower part of the Juwayl Member, and the Unayzah B member as similarly broadly equivalent to the upper part of the Juwayl Member. The following discussion will compare the Unayzah C member with the lower Juwayl Member, and the Unayzah B member with the upper Juwayl Member respectively. It should be noted that during this study, the boundary between the lower and upper parts of the Juwayl Member was not specifically observed at outcrop, being everywhere covered in thick deposits of modern desert sand. The comparison will be from a number of perspectives, namely: (1) sediment dispersal; (2) indications of glacial tectonics; and (3) sedimentological characteristics. This comparative exercise will establish the extent to which these stratigraphic units can be considered to be genetically, as well as temporally equivalent.

**COMPARISON OF LOWER JUWAYL AND UNAYZAH C MEMBERS**

**Sediment Dispersal**

*Lower Juwayl Member*

The outcrop pattern of the Juwayl Member in the Wajid region is shown in Figure 1b, as are a number of locations where the rocks were visited during this study and examined in some detail. Sandstones of the lower Juwayl are present at Wadi Bani Kharb (Figure 1b) where they occupy a deep incision that is about 1 km across and which cuts into flat-lying deposits of the Devonian Khusayyayn Formation. These lower Juwayl sandstones appear massive and are medium- to coarse-grained, moderately to poorly sorted and contain dispersed, pebble-sized intraclasts of muddy siltstone. They appear in map view as an elongate body that cuts across the strike of the underlying formations with an orientation of N150º–N330º. In places they display pronounced lineations that have all the characteristics of soft sediment striations such as have been described by Le Heron et al. (2005) from the Ordovician of the Murzuq Basin in Libya, where they were associated with glacial loading. The orientation of these lineations at the Wajid outcrop is also N150º–N330º.

The elongate plan view and the evidence for wide, deep incision associated with the lower Juwayl sandstones strongly suggests that they were deposited within a paleovalley system oriented in a NNW-SSE direction. The parallel orientation of the striations, that are inferred to have been associated with glacial ice, suggests further that the paleovalleys were occupied by valley glaciers.

*Unayzah C member*

In eastern Saudi Arabia a subsidiary study was conducted to investigate the subsurface distribution of the Unayzah C (Figure 3a) and Unayzah B (Figure 3b) members using all well penetrations through the Unayzah into underlying lower Paleozoic rocks. Numerous additional wells, which reached a total depth within the Unayzah C or B were also used to further constrain the minimum thicknesses of these units. Isopachs based on well log correlations of gross unit thicknesses of the Unayzah C member (Figure 3a) as well as the combined Unayzah C and B members (Figure 3c) reveal a distribution pattern consistent with a system of paleovalleys on the underlying lower Paleozoic
substrate, similar to that observed at the Juwayl outcrop. Elsewhere on the Arabian Plate a system of paleovalleys similar to those identified in eastern-central Saudi Arabia and the Wajid outcrop region can be interpreted using data published by Osterloff et al. (2004).

Figure 3: (a) Isopach map based on well data showing the subsurface distribution of the Unayzah C member, eastern Saudi Arabia. (b) Isopach map based on well data showing the subsurface distribution of the Unayzah B member, eastern Saudi Arabia. (c) Isopach map based on well data showing the subsurface distribution of the combined Unayzah B+C members, eastern Saudi Arabia. Superimposed on the isopachs are the axes and sediment transport directions within the inferred glacial paleovalleys. (d) Isopach map of the Al Khlata Formation in Oman (equivalent in Saudi Arabia to the Unayzah B+C members) (after Osterloff et al., 2004). The current authors have superimposed on this map their interpreted axes of glacial paleovalleys in this region of Oman. See text for discussion.
Figure 3d shows the gross thickness of the glaciogenic Al Khlata Formation in Oman, which is equivalent to the combined Unayzah C and Unayzah B members in Saudi Arabia (Melvin and Sprague, 2006) (see Figure 3c). Osterloff et al. (2004) attribute this thickness distribution in Oman to a combination of syn-depositional subsidence related to withdrawal of the underlying Ara Salt and erosional paleorelief on the pre-Al Khlata unconformity (equivalent to the “Hercynian” unconformity). While it seems possible that the kilometer-scale circular features (Figure 3d) could be attributed to halokinetics, we interpret the more elongate features, which are over one hundred kilometers long and tens of kilometers wide, to be paleovalleys of similar scale and genesis as those identified in the subsurface of eastern Saudi Arabia (Figure 3c). This pattern of late Carboniferous to early Permian paleovalleys, incised into pre-Hercynian rocks and filled with glaciogenic sediments, is identified farther in many widely separated areas across the former Gondwanaland continent (e.g. Isbell et al., 1997; Eyles and de Broekert, 2001; Dykstra et al., 2006; and Bussert and Schrank, 2007).

In addition to the isopachs constructed from the available well control in the study area in eastern Saudi Arabia, a Hercynian subcrop map was also generated (Figure 4a). This subcrop map highlights areas of Hercynian uplift and consequent erosion of the older, lower Paleozoic substrate. Superposition of Figure 3c and Figure 4a shows the distribution of paleovalleys across the Hercynian landscape (Figure 4b). This distribution pattern demonstrates a strong underlying geological control on paleovalley location: major paleovalley axes appear to be preferentially located over the subcropping Devonian Jauf Formation and Silurian Qusaiba Member of the Qalibah Formation (Figure 4b). This substrate control is thought to be related to the relatively high proportion of mudrock in these formations and its consequent increased susceptibility to erosion. This phenomenon has been observed and documented in modern continental settings in Pleistocene tunnel valleys by Sanderson and Jorgansen (2009) and Janssen et al. (2012).

It is notable that in some locations, paleovalleys trend across Hercynian structures demonstrating a pre-Hercynian antecedent drainage. Prior to the onset of peak Hercynian deformation in the mid-Carboniferous, the early Carboniferous Berwath Formation was deposited in a broad, tide-

![Figure 4](http://pubs.geoscienceworld.org/geoarabia/article-pdf/18/1/97/5446596/melvin.pdf)

Figure 4: (a) Geological subcrop map (based on well data) of eastern Saudi Arabia at Hercynian (pre-Unayzah C) time. (b) Map showing the distribution of the axes of the glacial paleovalleys (derived from Figure 3c) superimposed upon the Hercynian subcrop map (Figure 4a).
dominated coastal plain environment (Al-Husseini, 2004). It seems possible that some large fluvial-
estuarine systems were able to maintain base level throughout Hercynian uplift to facilitate this
cross-cutting relationship and that the glaciers that were ultimately responsible for deposition of the
Unayzah C member preferentially followed this pre-existing drainage, at least in part. In general,
paleovalley orientations (Figure 3c) suggest a dominant transport direction from west to east. It is
notable, however, that in places the isopach contours show closure to the north (Figures 3a, c), thereby
suggesting flow of the glacial ice from the north towards the south and east. This is interpreted to
suggest that local highlands harbored significant ice sheets. In particular, it is considered likely that
the Al-Batin Arch (Faqira et al., 2009) that occurs west and north of the study area (Figure 1c) was a
significant topographic high that was covered at least periodically by ice.

Indications of Glacial Tectonics

Lower Juwayl Member
As has been discussed above, the Juwayl Member sediments at Wadi Bani Kharb occupy a deep
incision that was cut into underlying Devonian Khusayyayn sandstones (Figures 5a, b). Within
this inferred glacial paleovalley, the lower Juwayl sandstones are intensely deformed close to the
paleovalley margins (Figure 5c). Additionally, a number of sub-horizontal features can be seen in the
main cliff face where they are limited in occurrence to only the lower Juwayl Member (Figure 5d). At
least three of these horizons are clearly discerned, truncating the subjacent strata at a very low angle.
Near the top of the outcrop the highest of these horizons of dislocation is overlain by sandstones
that show severe deformation with tight overfolds displaying sub-horizontal axial planar orientation,
all of which are further dislocated by moderately high-angle (reverse?) faults (Figures 5e, f). All of
these features at Wadi Bani Kharb represent zones of intense shear and thrusting; this deformation is
spatially restricted to the lower Juwayl Member and is attributed to glacial tectonics within this lower
Juwayl glacial paleovalley.

Elsewhere, for example at Jabal Fard al Ban and its environs (Figure 1b), the landscape is dominated
by numerous relatively small, conical hills (Figure 6). At the summit of Jabal Fard al Ban the strata
are almost vertical (Figure 6) and this appears to be similarly the case for many of the other jabals in
the area. These sub-vertical strata most commonly consist of finer-grained, silty sediment. In contrast,
coarser-grained lower Juwayl sandstones lower down on Jabal Fard al Ban and in front of the vertical
strata are almost horizontally bedded (see next section). The steeply-dipping beds are interpreted to be
the product of glacial thrusting, forming push moraines ahead of (or beneath) an advancing ice sheet.
Similar stratal discordancies have been observed in the Ordovician Mamuniyat Formation of the Al
Kufrah Basin in southeast Libya by Le Heron et al. (2010). Those authors similarly attributed these
features to glaciotectonic deformation (thrusting). At Jabal Fard Al Ban the effect of this deformation
on the stratal organization and sedimentary properties of the lower Juwayl Member in this area is
considered crucial to the reservoir architecture of these sediments and is discussed in a later section.

Unayzah C member
A total of 2,543 feet (763 m) of core has been recovered from the Unayzah C member in a number
of wells across eastern-central Saudi Arabia. Some selected examples are shown in Figure 1c.
Representative core descriptions are illustrated in Figure 7. Distinctive zones of deformation in the
Unayzah C member (so-called “shear zones”) were first recorded in core and illustrated by Melvin
and Sprague (2006). Subsequent work by Melvin et al. (2010) has discussed how, in every well across
the study area from which core has been recovered to date from the Unayzah C member (representing
distances of several hundred kilometers: see Figure 1c), these rocks to some extent display these
deformed horizons. Examples are shown here from wells 7, 6, 16 and 13 (Figures 7a to 7d). They are
characterized by a mixture of brittle, plastic and soft-sediment deformation styles that display strong
elements of low-angle shearing including small-scale thrust faulting, common examples of boudinage
(stretching) and low-angle overfolding. They range in thickness from less than one foot (meter) to
(rarely) over 40 ft (12 m) and separate intervening intervals of apparently undeformed sandstones that
are commonly many tens of feet (meters) thick. In general the shear zones display sharply delineated
upper and lower contact relationships with those sandstones. The likelihood that the thicker shear
zones represent the product of multiple, or compound deformation events is considered high and
work is ongoing to investigate and more fully characterize these intervals.
Figure 5: Outcrop photographs of the lower Juwayl Member at Wadi Bani Kharb. (a) The western end of Wadi Bani Kharb showing the very irregular, high-angle contact between well bedded Devonian Khusayyayn sandstones (on the left) and much more massive-looking lower Juwayl Member (Carboniferous–Permian). The bush in the foreground is about 5 ft (1.5 m) high. (b) The eastern end of the outcrop (about 1 km east of the location of Figure 5a) showing a similar high-angle contact between the Khusayyayn (on the right) and the lower Juwayl Member. The red boxed area is reproduced in more detail in Figure 5c. (c) Severely deformed sediments of the Juwayl Member very close to its contact with the Devonian Khusayyayn Formation (see boxed area in Figure 5b). Hammer (circled) for scale (30 cm). (d) General view of the upper part of the outcrop, showing a number of discrete sub-horizontal horizons (arrowed) within the lower Juwayl Member, interpreted to be low-angle zones of glacially induced dislocation (see text for discussion). Area within the red box is the subject of Figure 5e. (e) Telephoto view of the top of the outcrop (boxed in Figure 5d). Above the low-angle zone of dislocation (arrowed) the rocks are heavily deformed (see Figure 5f). (f) Overlay sketch of the outcrop shown in Figure 5e. Above the low-angle zone of dislocation (arrowed in Figure 5e) note the extreme deformation with almost flat-lying overfolds, which are further dislocated by relatively high-angle reverse faulting.
In all the cored wells where they occur, the shear zones are reflected on wireline gamma-ray logs as zones of high API gamma-ray activity (Figure 8a). Originally this was thought to represent shaley intervals within the Unayzah C sandstones. However inspection of cores, where available, demonstrates that the deformed zones consist almost entirely of sandstone lithologies (Figure 8b) and that mudstone facies are extremely rare. The increasing use of spectral gamma-ray logging tools, calibrated to core data in the example from well 14 (Figure 8a), reveals little deflection of the potassium curve across the zones of shear. High potassium values would be expected if the high API readings from the gross gamma-ray readings were indeed a reflection of the presence of clay-rich mudrocks. Instead the elevated gamma-ray readings appear to be related to enhanced concentrations of thorium. Rather than representing shale horizons, it is thought possible that these high readings on the gamma-ray logs could be somehow related to relatively high concentrations of heavy minerals within the shear zones (T. Pearce, 2011, personal communication). In addition to this gamma-ray log signature, the shear zones are also commonly associated with a strongly chaotic response on downhole image logs (M.H. Prudden, 2004, personal communication). The combined application of image log data with spectral gamma-ray log data enables the tentative identification of shear zones with a relatively high degree of confidence in uncored wells. The apparently undeformed, commonly “massive” sandstones (Figure 8c) that occur between the shear zones are characterized by monotonous, very low API gamma-ray readings (Figure 8a), and non-chaotic image log responses.

The widespread occurrence of these shear zones throughout the Unayzah C member, both geographically and stratigraphically has been related by Melvin and Sprague (2006) and Melvin et al. (2010) to the formation of glacial push moraine complexes such as have been described by van der Wateren (1985, 1987) along the so-called Rehburg Line in northern Europe. This line extends over 500 kilometers from the North Sea in the west to Hanover, Germany in the east (Bennett, 2001) and marks the approximate extent of glacial ice during the Rehburg Phase (Drenthe advance) of the Saalian
Figure 7: Core logs from the Unayzah C member in a number of representative wells across the subsurface study area. Note the common occurrence of low-angle shearing (e.g. well 7, 0–10 ft; well 6, 10–34 ft and 45–51 ft; well 16, 57–69.5 ft and 90–92 ft; well 13, several occurrences throughout). Well 13 is also characterized by an abundance of dispersed mudclasts throughout the cored section. Otherwise primary sedimentary structures are conspicuously lacking in these sandstones. Instead they appear structureless or “massive” with only rare soft sediment deformation visible (e.g. well 16, 1–12 ft). Note: distribution of stylolites, fractures and indications of shearing are highlighted in pink. Grain size (at base of all core logs) as follows: G=gravel; S=sand; z=silt; m=mud. UmUm= Un-named middle Unayzah member.
Figure 7: Core logs from the Unayzah C member in a number of representative wells across the subsurface study area. Note the common occurrence of low-angle shearing (e.g., well 7, 0–10 ft; well 6, 10–34 ft and 45–51 ft; well 16, 57–69.5 ft and 90–92 ft; well 13, several occurrences throughout). Well 13 is also characterized by an abundance of dispersed mudclasts throughout the cored section. Otherwise primary sedimentary structures are conspicuously lacking in these sandstones. Instead they appear structureless or “massive” with only rare soft sediment deformation visible (e.g., well 16, 1–12 ft). Note: distribution of stylolites, fractures and indications of shearing are highlighted in pink. Grain size (at base of all core logs) as follows: G=gravel; S=sand; z=silt; m=mud. UmUm= Un-named middle Unayzah member.
Figure 8: Subsurface expression of glaciotectonic deformation in the Unayzah C member. (a) Wireline gamma-ray logs from well 14 showing a thick interval of very high API deflection in the bulk gamma-ray trace (in black). The red trace is the potassium curve from the spectral gamma-ray log in this well and significantly shows no comparable deflection over the relevant interval. This demonstrates that the high API values in the bulk gamma-ray log are not related to the presence of mudstone beds. This interval of high gamma-ray values was also covered by core in this well as shown. (b) Sandstone core sample showing a high degree of brittle and plastic deformation and located within the high gamma-ray interval (“b” on the gamma-ray log in Figure 8a). Examination of the entire core shows a thick shear zone displaying similar deformation throughout, and which correlates exactly with the high gamma-ray interval on logs. Width of core is about 5 cm. (c) Rocks of the Unayzah C member that are equivalent to intervals displaying very low gamma-ray signature in this well do not display such deformation and instead are characterized by “massive” featureless sandstone. The location of the sample shown is arrowed (“c”) on the gamma-ray log in Figure 8a. Width of core is about 5 cm.

Glaciation (van der Wateren, 1995). The architecture of these Pleistocene push moraine complexes consists of a number of subhorizontal nappes that have been displaced horizontally by the ice, in some cases by as much as 6 kilometers. The nappes are bounded above and below by a number of shear zones (Bennett, 2001). Other glacially deformed complexes have been described and illustrated from the Pleistocene of Denmark by Pederson (2005), and the internal complexities they reveal have potentially significant implications for reservoir heterogeneity within the Unayzah C member in Saudi Arabia (see later discussion).

Some doubt has been cast by workers in Oman (Martin et al., 2008) on this interpretation that the deformed intervals within the Unayzah C member represent zones of glaciotectonic deformation. Those authors suggest instead that the shear zones may have a non-glacial origin, such as mass movement of sediment (for example, by slumping down the frontal slopes of glaciolacustrine deltas?). Indeed the current authors have been shown deformed sandstones within the Al Khlata Formation.
at outcrop in Oman that have been inferred to have been deposited by just such a process (J. Aitken, 2007, personal communication). That example, however, bears little comparison to the features under discussion from the Unayzah C. In the Oman case the rocks occur within the upper Al Khlatea and therefore are better compared with the Unayzah B in Saudi Arabia. The likelihood of glaciolacustrine settings is much higher in that stratigraphic unit (see later discussion). Furthermore, the inferred slide deposits in Oman are found in association with a large number of different glaciogenic depositional facies and from our observations do not appear to dominate the facies spectrum. In contrast, within the Unayzah C the rocks recovered from the subsurface are almost universally characterized by the occurrence in places of the shear zones as described herein. It seems most likely that such a widespread distribution of these features would be genetically related to an equally widespread causal mechanism. Such a mechanism is readily identified as being very likely associated with deformation linked to an ice sheet of regional extent.

We acknowledge the concerns nonetheless. The unequivocal identification of glaciotectonic thrust sheets is challenging, particularly in a widely distributed, subsurface data set with all the constraints on interpretation that that implies. Isbell (2010), in an outcrop study of deformed glaciogenic sediments in the Permain Metschel Tillite in Antarctica acknowledged that in glaciogenic settings, compressional features can result from either sliding-slumping or glaciotectonic deformation. That author addressed the issue of differentiation between the two processes. Although some of his criteria for the recognition of glaciotectonic compression can be addressed in core (e.g. occurrence of widespread compressional features such as low-angle to subhorizontal overfolding, low-angle shear planes and common low-angle thrust faulting), many of the other criteria cannot be identified within the limits of 10 cm-wide core. Those larger-scale criteria relate to the mappability of the extent of features related to the thrust sheet complexes per se. Examples include: (1) the extent of truncation of underlying strata throughout the zone of deformation; (2) the recognition of thrust complexes where older thrust sheets rest on top of younger sheets; and (3) recognition of thrust complexes that typically contain excavated blocks of bedrock (Isbell, 2010). This problem of scale is further compounded in the case of the Unayzah C rocks by the very lengthy duration of the late Paleozoic glaciation in Saudi Arabia and the consequent likelihood of multiple phases of glacial advance and associated deformation and cannibalization. Work is ongoing with attempts to address these issues and it is hoped that the results can be published at a future time.

### Sedimentological Characteristics

#### Lower Juwayl Member

In general, the rocks of the lower Juwayl Member comprise pebbly, medium- to coarse-grained and moderately to poorly sorted sandstones. As discussed above, at Wadi Bani Kharb they contain a moderate abundance of dispersed mudclasts (Figure 9a). In general, they consist of a limited number of depositional facies which, in the present study, were best exposed at the outcrop at Jabal Fard al Ban (Figure 1b). There, several laterally discontinuous beds show evidence of primary depositional structures such as cross-bedding and low-angle laminations (Figure 9b). These are generally disturbed to some minor extent by fluid remobilization of the sediment (Figure 9b). The discontinuous strata are isolated from each other in the outcrop by sandstone that is much more massive in nature. This “massive” sandstone displays evidence of being highly fluidized in that it shows sand-on-sand loading (ball-and-pillow structure) (Figure 9c), as well as abundant large-scale indications of flowage around and envelopment of the apparent remnants of original primary stratification (described above) (Figure 9d).

Elsewhere at this location the massive sandstones form large irregular pods (Figure 9e) that contain rafted clasts of the stratified sediment that are up to two meters in length and appear to have a random orientation and distribution (Figure 9f). These sediments at Jabal Fard al Ban are all crop out abruptly below and in front of the vertically bedded strata (Figure 6) that were interpreted above as having been glacially upthrust by the passage of advancing ice. At a jabal about 1 kilometer to the northeast of Jabal Fard al Ban there is similar evidence of thrusting in the lower Juwayl (Figure 10a) where, immediately below the thrust plane, the sandstones also display evidence of flowage that seems to be closely associated with the thrusting (Figure 10b). Other examples display highly contorted...
Figure 9: Outcrop examples of the lower Juwayl Member illustrating various depositional and post-depositional features. (a) Example from Wadi Bani Kharb showing abundance of pale grey dispersed mudclasts (arrowed). Scale is 15 cm long. (b) Relict (discontinuous) sedimentary structures in sandstones at Jabal Fard al Ban showing low-angle stratification and some cross-bedding. The latter is nonetheless oversteepened and shows signs of dewatering. Scale (circled) is 15 cm long. (c) Sandstone at Jabal Fard al Ban showing internal loading with flame structure suggesting highly fluidized sediment. The rock is otherwise apparently “massive”. Scale is 15 cm long. (d) General view of the outcrop at Jabal Fard al Ban showing discontinuous wedges of relict bedding that are draped and enveloped by apparently “massive” sandstone that exhibits a strong expression of flowage. (e) Very large pod of apparently “massive” sandstone at Jabal Fard al Ban that contains an assortment of intraformational rafts of sandstone showing extreme range in size and orientation. (f) Apparently “massive” sandstone that contains a number of rafts of (relict) bedded sandstone up to 1 m in length, in apparently random orientation within the host.
and fluidized sandstones extending some distance in front of upthrust blocks (Figure 10c). Close inspection of this disturbed sediment reveals not only soft sediment contortions, but features which bear close similarity to glacially induced soft sediment striations described from the Ordovician of Libya by Le Heron et al. (2005) (Figure 10d).

**Unayzah C member**

In the subsurface, the Unayzah C member is widely represented by medium- to coarse-grained (and locally conglomeratic) sandstones that are moderately to poorly sorted and display pervasive quartz cementation (Melvin and Sprague, 2006). These sandstones are arranged vertically in multi-storey bedsets that are commonly several tens of feet (meters) thick (Figure 7). Within these bedsets,
individual beds in places appear to fine upwards from sharp, erosional basal contacts, locally strewn with intraformational pebbles and small cobbles of laminated (and locally deformed) mudstone (e.g. well 7: Figure 7a, 11–12 ft; well 16: Figure 7c, 79–80 ft) and/or fine- to medium-grained, laminated (as well as non-laminated) sandstone (e.g. well 7: Figure 7a, 11–12 ft; well 13: Figure 7d, 3–4 ft and 6–8 ft). In places, these upward-fining sandstones may display low-angle to flat, planar lamination or less commonly, trough cross-lamination (e.g. well 7: Figure 7a, 32–35 ft and 60 ft).

In some wells individual beds contain abundant mudclasts from 1 cm up to 3 cm long that are uniformly dispersed throughout the bed and oriented sub-parallel to bedding (e.g. well 13: Figure 7d). In general however, primary depositional structures, as well as any grain size trends, are heavily obscured and the rock most commonly displays only a structureless, apparently “massive” appearance (Figure 7, 8c). In places an extremely diffuse, sub-vertical fabric can be discerned that passes upwards into irregular, discontinuous and argillaceous, crinkly laminations that are commonly enhanced by stylolitization. These argillaceous laminations have the appearance of incipient dish structures and their association with the diffuse, sub-vertical fabric suggests that the sediment has experienced a considerable degree of dewatering and fluid remobilization. In well 16 a degree of soft sediment folding is observed associated with very poor sorting within the sandstones (Figure 7c, 1–12 ft), also suggestive of a degree of fluid remobilization. Very rarely, thin (dm-scale) beds of pale grey-green sandy siltstone separate the sandstone bedsets.

Melvin and Sprague (2006) discussed the nature of the upper contact of the Unayzah C member. That contact has been cored in a number of wells and in every case it is seen to be extremely sharp. In well 8 (Figure 7e, 58 ft) it is also highly irregular, with re-entrants that are filled by diamicite of the overlying Unayzah B member. Beneath that contact, the uppermost one foot (30 cm) of the Unayzah C member displays a high degree of brecciation, with a network of abundant, intersecting and clay-lined fractures. This was interpreted by Melvin and Sprague (2006) as an immature paleosol horizon. In most wells where the upper contact has been cored, the Unayzah C member is overlain by the Unayzah B member (e.g. Figures 7a, d, e). However, in well 6 it is overlain by the unnamed middle Unayzah member and in well 11 it is directly overlain by the Unayzah A member (Figure 7f).

**Discussion**

From the foregoing comparative descriptions of the lower part of the Juwayl Member and the Unayzah C member it is clear that there are very many points of similarity between the two stratal units. These similarities are so strong that it is proposed here that the two units be considered equivalent to each other, both stratigraphically and genetically.

Consideration of the sediment dispersal systems for both the lower Juwayl Member and the Unayzah C member has demonstrated that in both cases the sediment was transported down valleys that appear to have been quite linearly extensive, and also very deep. At outcrop, the lower Juwayl Member paleovalleys trend NNW-SSE and in some places reveal striated sediment which, by comparison with similar features identified in Ordovician glaciogenic deposits in Libya (Le Heron et al., 2005), would appear also to have been affected by the very close proximity of glacial ice. The inferred glacial paleovalley system mapped in the subsurface of eastern Saudi Arabia (Figure 3a, c) is of particular interest in that the valley contours close generally in a westerly and northerly direction, implying that down-valley transport would also have been from the west and north. This observation has two significant implications.

First, this suggests that there was glacial ice at least as far north as the central part of the Ghawar structure in Saudi Arabia (see Figures 1c; 3a, 3c). On the Arabian Plate, this extends considerably the distribution of the ice that was associated with the Gondwanan South Polar ice cap in late Paleozoic times, compared with previously published paleogeographic data (e.g. Stampfli and Borel, 2004). Second, the evidence for southerly-directed transport adds further complexity to the issue in that it implies the existence of a significant source of ice that was in some way detached from the main South Polar ice sheet as a northern promontory, or even a separate glaciated mountain range to the north. This suggestion of a relatively isolated “alpine” ice cap substantiates a similar view proposed

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by Melvin et al. (2010). Kruck and Thiele (1983) have interpreted late Paleozoic ice movements in Yemen towards the southeast and Al-Belushi et al. (1996) controversially proposed glacial transport in Oman towards the southwest. In consequence, those authors proposed the existence of local ice sheets located generally to the north of these regions. Farther afield, several authors have similarly proposed the existence across Gondwana, during the late Paleozoic glaciation, of a number of smaller, isolated ice sheets, e.g. in South America, South Africa, India and Australia (Eyles, 1993; Isbell et al., 2008; Wopfner and Casshyap, 1997; Fielding et al., 2008a; Birgenheier et al., 2009). Such observations have led some authors to question the entire concept of a single South Polar ice sheet in late Paleozoic times, preferring instead to consider a less widespread and discontinuous glaciation with more isolated ice sheets or ice caps (Dickens, 1996; Isbell et al., 2003; Isbell, 2010).

Both the lower Juwayl and the Unayzah C members also exhibit clear evidence of deformation that can be readily interpreted as glaciotectonic in origin. Thrusted strata have been observed at Jabal Fard al Ban (Figure 6). Their relationship with associated sediments at that location points strongly to a glacial origin for that thrusting (see below). At Wadi Bani Kharb the observed deformation structures are strictly confined to the lower Juwayl Member sediments within the observed paleovalley feature at that location (see Figures 5a–f). In the subsurface the shear zones that occur universally throughout the Unayzah C member are similarly confined only to that stratal unit: they have not been observed in either underlying, or overlying formations. The origins of the tectonic features observed both at outcrop and also in the subsurface are therefore attributed to processes that occurred uniquely during the time of formation of those members. Those processes are believed to have been associated with the ice sheets of the late Paleozoic glaciation that prevailed at the time across the South Polar Gondwanan continent.

The effect of this deformation on the internal sedimentary and stratal architecture of the lower Juwayl is most clearly demonstrated at Jabal Fard al Ban (Figure 1b). There, the original (primary) sedimentary structures are represented within residual, discontinuous beds of stratified sandstone (Figure 9b). In particular, the sets of cross-stratified sandstone and low-angle quasi-planar laminations are interpreted to represent glacial retreat-phase deposition on braid bars in a glaciofluvial outwash setting. It is thought likely that the entire section was originally composed of such sediment. As the ice re-advanced across these earlier retreat-phase outwash deposits, some of the finer-grained sediment was preferentially thrust up (e.g. Figure 6). These upthrust beds formed relatively impermeable barriers and the pore fluids in the sandstones in front of them were subjected to intense over-pressuring by the over-riding ice. This resulted in large-scale remobilization of those fluids and the consequent development of abundant loading (ball-and-pillow structure) (Figure 9c) and other soft sediment deformation (Figures 10c, d) within the sandstones. Locally, the proximity of the ice was reflected in soft sediment striations (Figure 10d). In other places, some of the beds of outwash sand retained their structural integrity (as a result of possibly being frozen), and rather than being fluidized, they responded to the over-pressuring by explosive disruption, resulting in the irregular distribution of randomly oriented rafts of sandstone within the otherwise “massive” host sediment (Figures 9e, f). Similar examples of the development of ball-and-pillow structure and related hydrodynamic brecciation have been presented from glaciogenic sediments of the Pleistocene Lonstrup Klint Formation in Denmark (Pederson, 2005). The brecciation in those cases was attributed to polysequential diapirism related to the glaciotectonic thrusting that is pervasive in those Pleistocene sediments (Pederson, 2005).

The large-scale features observed at the outcrop at Jabal Fard al Ban are enlightening in the context of their contribution to clarification of the understanding of the evolution of the Unayzah C member in the subsurface (where, clearly, tangible evidence is limited only to borehole data). Melvin and Sprague (2006) analyzed the sedimentological evidence from cores and concluded that the Unayzah C member sandstones were most probably laid down in a braided fluvial outwash system associated with retreat phases of the late Paleozoic glaciation on the Arabian Plate. Those authors considered deposition to have been very rapid, inferred from the common occurrence of dewatering features in the cores. The dewatering is manifest not only as the soft sediment deformation and related diffuse fabrics described earlier, but also in the apparently “massive” nature that dominates the sandstones throughout the Unayzah C member (e.g. Figures 7, 8c). From the evidence discussed above from
the outcrop at Jabal Fard al Ban, it now seems likely that most of the dewatering features in the subsurface Unayzah C member resulted, not from rapid rates of sedimentation, but rather from the effects of glaciotectonics. Specifically, it is likely that the glacial thrusting associated with the widely recognized shear zones within the Unayzah C led to the creation of over-pressured compartments in the sandstone within which explosive fluidization took place. This results in a model for the stratal architecture of the Unayzah C member that is illustrated in Figure 11. Based on all of the foregoing, the evolution of both the lower Juwayl Member at outcrop and the subsurface Unayzah C member (now considered to be the same stratal unit) is summarized below.

Following the mid-Carboniferous tectonic event on the Arabian Plate and the near-coincident inception of the late Paleozoic Gondwanan South Polar glaciation, the ice ultimately extended at least as far across as the southern half of the Arabian Plate. It is also probable that a northern high-altitude ("alpine") ice cap existed. The ice age was long-lived and possibly persisted for up to 35 million years (Al-Husseini, 2004). It seems likely that throughout this time a number of glacial advances, retreats and re-advances took place, as has been proposed by Melvin and Sprague (2006) and Melvin et al. (2010). Each of the retreat phases led to deposition of large volumes of glaciofluvial outwash sands and gravels across the area in widespread braidplains. During subsequent re-advances of the ice sheets, the retreat phase deposits were over-ridden and cannibalized, with the creation of many glacially-induced push moraine nappes. During this process the earlier retreat phase sediments were considerably modified by glaciotectonic deformation and explosive fluidization related to glacially-induced over-pressuring. Ultimately this repeated process gave rise to a thick pile of superimposed units (nappes) of significantly modified glaciofluvial sands (with gravels), separated by distinct shear zones. This multi-phase nature of the late Paleozoic glaciation has been identified and documented from elsewhere across the Gondwanan continent, e.g. in Oman (using palynological analyses: Osterloff et al., 2004); in the Pagoano Basin in northwest Argentina (using U-Pb isotopic dating: Gulbranson et al., 2008); and in eastern Australia (using ion microprobe analysis of zircons: Fielding et al., 2008b). The uppermost surface of the Unayzah C member in the subsurface is considered to be an unconformity and represents the sub-glacial surface at the time of final advance in Saudi Arabia of the late Paleozoic Gondwanan ice sheet.
Implications for Reservoir Heterogeneity

This model for the evolution of these rocks, and for the subsurface Unayzah C member in particular, has significant implications in terms of Unayzah C reservoir characterization and development. The recognition of glaciotectonic shear zones both at the outcrop and in the subsurface suggests the possibility of compartmentalization within the reservoir associated with these zones of dislocation. This is further supported by the sedimentological evidence (discussed above) for pressure compartments within the lower Juwayl Member at Jabal Fard al Ban.

Well 15 (Figure 1c) penetrated and cored the Unayzah C member, which is a gas reservoir in that location. Within the reservoir the cores reveal the presence of a well-developed shear zone that is characterized by relatively high API gamma-ray traces in the wireline logs (Figure 12). Two cased-hole tests were performed at the well, one below the shear zone and one above. The lower test interval did not produce any flow; the test interval above the shear zone flowed commercial quantities of gas (Figure 12). From the core, the two test intervals were each represented by fairly typical - and almost identical - massive Unayzah C sandstones. These results appear to confirm the likelihood of significant compartmentalization within the Unayzah C member that appears to be directly related to the presence of glaciotectonic shear zones. This represents a level of heterogeneity within these reservoirs that is clearly of considerable economic significance.

COMPARISON OF UPPER JUWAYL AND UNAYZAH B MEMBERS

Sediment Dispersal

Upper Juwayl Member

In the lower Juwayl Member (discussed above) the sediment dispersal systems were readily identified as being related to valleys which available evidence,

Figure 12: Potential role of glacial tectonics in reservoir compartmentalization within the Unayzah C member. The diagram shows the wireline gamma-ray log through the Unayzah C in well 15. The relatively high API values on the gamma-ray trace (red ellipse) correspond exactly to a glaciotectonic shear zone that was identified in the core. Two cased-hole tests were conducted over the Unayzah C reservoir: one below the shear zone and one above it, as shown. The lower test interval did not flow and the upper test interval flowed economically significant quantities of gas. It is clear from these results that the glaciotectonic shear zone within the Unayzah C reservoir have significant potential to compartmentalize the reservoir.
though limited, would suggest were ice-filled, i.e. sediment transport was effected by outwash related to valley glaciers. No such specific evidence is available regarding the upper Juwayl Member: sedimentary distribution in this stratal member is of necessity determined from analysis of the depositional facies per se (see below).

**Unayzah B member**
The mapped expression of this member (Figure 3b) is limited, but is highly suggestive of a relatively constrained setting such as deep lakes. This can be corroborated by analysis of the depositional facies and their distribution throughout the subsurface in the study area (see discussion below).

**Indications of Glacial Tectonics**

**Upper Juwayl Member**
There are no indicators of glacial tectonics in the upper Juwayl Member in any of the outcrop areas investigated in this study.

**Unayzah B member**
A total of 1,533 ft (459.9 m) of core has been recovered to date from the Unayzah B member across eastern-central Saudi Arabia and a number of representative wells are shown in Figure 1c. The core evidence reveals only rare occurrences of possible glaciotectonic deformation (Figure 13). In well 3a (Figure 13a) the Unayzah B member is 65 ft (19.5 m) thick and consists predominantly of very fine-grained sandstones and siltstones with subordinate poorly sorted pebbly sandstones in its upper part. It is characterized throughout by an abundance of small-scale faults and low-angle shear planes: similar pervasive deformation of this member has been observed in well 2. These wells are distinctive in having such wholesale deformation throughout the Unayzah B member, although no such deformation has been seen within the subcropping.

Figure 13: Core logs through the Unayzah B member. (a) In well 3a the entire Unayzah B section is characterized by intense deformation, manifest in shear zones, multiple small-scale dislocation and faulting, and local soft sediment deformation. This is interpreted to be the result of exposure of the sediment to prolonged ice-contact in this location. (b) In well 7 the entire Unayzah B member was cored. Of significance are the two zones of intense deformation (between 26.5–42 ft and 55–68 ft) that are attributed to minor glacial readvance resulting in minor push moraines during a period of overall glacial retreat. Note: Cm indicates the locations in core of proven occurrence of the heavily reworked Cm palynofloral assemblage (see text for discussion). Note: UmUm = Unnamed middle Unayzah member.
formation in either well. Melvin and Sprague (2006) interpreted this as being attributable to sustained ice contact in these locations. These wells occur relatively close to each other in the western part of the study area (Figure 1c), and the likely significance of this apparently geographically constrained characteristic is discussed further in a later section.

In well 7 two clearly identifiable intervals are seen showing deformation within the Unayzah B member. They are characterized internally by severe structural dislocation (Figure 13b: 26.5–42.0 ft; 55.0–68.0 ft), but are nonetheless stratabound by regularly stratified sediments. The lower interval comprises argillaceous sandstones that are generally fine- to very fine-grained, but they are very poorly sorted, and contain abundant dispersed grains of coarse- and very coarse-grained sand as well as granules and pebbles (i.e. they are diamictites). The sediment is intensely disrupted and sheared throughout, with localized pods and streaks of coarse debris interfolded with finer-grained sediment. The upper deformed interval in well 7, in its lower part, consists of about 7 ft (2.1 m) of well laminated, medium- to coarse-grained sandstones that show severe dislocation and indications of listric thrusting (Figure 13b, 55–62 ft). These are overlain by about 6 ft (1.8 m) of micaceous siltstone that contains abundant dispersed grains of fine- to coarse-grained sand and is characterized by numerous high-angle shear planes (Figure 13b, 62–68 ft). The allochthonous “Cm palynoflora assemblage” (see earlier discussion) has been recovered from this siltstone as well as from the very poorly sorted sediment that occurs between the two deformed intervals (i.e. Figure 13b, 42.0–55.0 ft).

Melvin and Sprague (2006) interpreted these deformed intervals in well 7 as the remains of two minor push moraines. Boulton et al. (1999) identified four broad categories of push moraines where the style of deformation involves either fans of imbricate thrusts, or superimposed sub-horizontal nappes produced by overthrusting. The smallest of these are no more than 5 m high and can be found in both terrestrial and subaqueous environments (Boulton et al., 1999; Bennett, 2001). The characteristics and size of the deformed intervals within the Unayzah B member in well 7 suggests that they represent two small push moraines of this type that were formed by imbricate thrusting. Significantly these deformed units are stratabound by undeformed sediments that are interpreted (below) as being glaciolacustrine in origin.

Sedimentological Characteristics

Upper Juwayl Member

The upper Juwayl Member is exposed at Khashm Khatmah in the Wajid region in southwest Saudi Arabia (Figure 1b). The rocks comprise pink to buff-colored pebbly, medium to coarse-grained sandstones with subordinate pebble- and cobble-bearing conglomerates. These are arranged in stacked, multistorey and upward-fining bedsets. Each bedset commences with a sharp, erosional lower contact that is commonly, but not everywhere, overlain by conglomerates. These are moderately to poorly sorted with sub-rounded to sub-angular clasts and occur in beds that have variable lateral extent (Figure 14a). The conglomerates are directly overlain by pebbly sandstones arranged in multistorey units comprising sets, up to 5 ft (1.5 m) thick, of large scale planar-tabular cross-stratification and low-angle to flat planar stratification (Figure 14a). These pebbly sandstones may be superseded by trough cross-stratified sets which pass upwards to fine-grained sandstones comprising multiple lamina sets of ripple cross-lamination (Figure 14b). These fine-grained sandstones represent the upper limit of each of the sandstone bedsets and are abruptly truncated by the sharp, erosional basal contact of the overlying unit (Figure 14b). Taken as a whole, this package of stacked bedsets, each of which is demonstrably upward-fining (see Figure 14a, b), does itself fine upwards, such that the proportion of conglomerate and pebbly sandstone diminishes upsection. It also appears to be the case that stratigraphically higher in the section there is an increase in the proportion of medium-scale trough cross-stratification relative to the large-scale, planar laminated beds and the planar-tabular cross-stratification.

Towards the top of the exposed section of the upper Juwayl Member at Khashm Khatmah, these sandstone bedsets ultimately pass upwards into olive-grey rocks that are generally much finer-grained, namely silty, fine- to very fine-grained sandstones. These rocks are generally well bedded (Figure 14c), but are characterized throughout by apparently randomly dispersed boulders. These
boulders are up to 2.5 ft (0.75 m) in size, sub-rounded to rounded and comprise a variety of lithologies, including granite (Figure 14d). In places, discontinuous and overturned (slumped) rolls of fine-grained sandstone occur within these strata. These rocks are readily classified as stratified diamicites. North of Khashm Khatmah, at Jabal Umm Ghiran (Figure 1b), there occur poorly exposed and highly weathered outcrops of boulder-bearing siltstones and very fine-grained sandstones. These boulders are commonly granite and it was from these rocks that Helal (1964) described striations on some of the boulders, inferring a glacial origin. These outcrops are laterally equivalent to the boulder-bearing diamicites observed at the top of the section at Khashm Khatmah.
Unayzah B member

As mentioned above, a considerable amount of core has been recovered from the Unayzah B member. This core from across eastern-central Saudi Arabia (Figure 1c) reveals a wide variety of depositional facies within this stratal unit: some representative core logs are reproduced in Figure 15. At the western end of the subsurface area of interest at well 19 (Figure 1c), the Unayzah B member is seen clearly to sit upon the Unayzah C member (Figure 15a). There, it comprises about 43 ft (12.9 m) of pebbly sandstone beds with thin interbeds of sandy siltstone. The sandstones are medium- to coarse-grained with scattered pebbles and occur in beds that have sharp, locally scoured bases. They display planar lamination and crudely-developed cross-stratification, with trough cross-stratification appearing in the stratigraphically higher beds. These beds are arranged in two upward-fining and -thinning bedsets that present an overall fining profile culminating in red sandy siltstones (Figure 15a). These siltstones contain dispersed granules and small pebbles and as such display a diamictitic texture. The pebbly sandstone-dominated rocks are interpreted to be the deposits of two phases of sedimentation in a braided fluvial depositional setting. The diamictitic siltstones are suggestive of deposition in a glacial lake, and by association the pebbly sandstones are considered to represent glaciofluvial outwash deposits.

Farther east, the Unayzah B member (exemplified in Figures 13b and 15b–15f) is manifest as a number of depositional facies, all of which are substantially different from the pebbly sandstones seen in well 19 (Figure 15a). These facies have been described in detail by Melvin and Sprague (2006), who concluded that although the facies per se are highly varied in character, they nonetheless share a commonality in representing, in some form, subaqueous deposition in a glaciolacustrine environment.

The various sub-lacustrine sub-environments are summarized as follows:

Glaciolacustrine gravity flows: This facies is common in the subsurface Unayzah B member, being identified in core in wells 3b, 5, 7, 9, 10, 12, 13 and 18. Examples are illustrated from well 7 (Figure 13b, 13–26 ft) and wells 9, 18 and 10 (Figures 15b, c, d). It comprises beds that have sharp bases, and consist of variably argillaceous medium- to fine-grained sandstones. These are commonly graded and in several places display abundant fluidization features including dish structures and elutriation pillars (cf. Lowe and LoPiccolo, 1974) (e.g. well 9: Figure 15b) and elutriation sheets (e.g. well 18: Figure 15c, 34–42 ft). In well 10 an anomalously large pebble was observed on the upper surface of one of the beds and was interpreted by Melvin and Sprague (2006) to be a glacial dropstone (see Figure 15d, 16 ft).

Up to 250 feet (75 m) of these deposits are seen in well 9. There, they are arranged in at least two packages, 50–60 feet (15–18 m) thick, each of which displays an upward-thinning and -fining profile (Figure 15b). In well 13 (Figure 1c) Melvin and Sprague (2006) described at least 40 ft (12 m) of graded, mud clast-rich sandstones from core in the Unayzah B member that were interpreted as high-energy gravity flow deposits. These are organized into upward-thinning and -fining bedsets, which further display an overall upward-thinning and -fining character (Melvin and Sprague, 2006).

The general sedimentological characteristics of this facies, as well as its facies associations, support an interpretation of gravity-flow deposition that was commonly extremely rapid, as suggested by the abundant fluidization features, and which took place in a subaqueous setting in standing bodies of water. They represent sublacustrine glacial outwash deposits at times of significant glacial meltout. The large-scale upward-thinning packages described from well 9 (Figure 15b) probably each represent waning sediment input as a result of retreating glacial ice. It follows that more than one glacial source of the sediment was required and Melvin et al. (2010) have speculated on whether this may imply either multiple glacial sources, or some degree of readvance of the ice during the overall retreat phase. In well 13, the upward-thinning and -fining characteristics were interpreted as representing increasingly distal character upsection and so are suggestive of an overall transgressive depositional setting, probably related to a progressive deepening of the lake into which they had been deposited (Melvin and Sprague, 2006; Melvin et al., 2010).
Figure 15: Core logs from the Unayzah B member in a number of representative wells across the subsurface study area. (a) Well 19 is dominated by pebbly sandstones (brown) deposited as braided-fluvial glacial outwash. These occur in two upward-fining cycles (18−39 ft and 39−59.5 ft respectively). The top of each cycle consists of siltstones and very fine-grained sandstones (grey) which in the upper cycle contain “floating” pebbles indicative of glaciolacustrine diamictite. (b) Well 9 displays facies representing deposition in a glaciolacustrine environment including fluidized sediment gravity flows (green) (0−130 ft). (c) Well 18 also displays glaciolacustrine facies including stratified diamictites (with dropstones) (grey) (0.5−34 ft) and fluidized sediment gravity flows (green) (34−42 ft). UmUm = Unnamed middle Unayzah member. See facing page for continuation.
Massive diamictite: This facies is seen in core from the Unayzah B member in wells 1, 5, 7, 10 and 12. Some examples are shown from wells 10, 12 and 5 (Figures 15d, e, f). It varies in thickness from about 6 ft (1.8 m) in well 10 (Figure 15d, 44.0–50.5 ft) to 14 ft (4.2 m) in well 12 (Figure 15e, 7.0–20.5 ft) to over 200 ft (60 m) in well 5 (Figure 15f). In general the rocks comprise argillaceous siltstones and very fine-grained sandstones within which occurs an abundance of dispersed coarser-grained...
detritus (Figure 16a). This coarser-grained fraction ranges from coarse-grained sand to pebbles and locally cobble-sized clasts. In well 7 (Figure 13b, 30-42 ft) this very poorly sorted (diamictitic) texture is associated with severely deformed rocks as has been discussed above. The pebble-sized (and coarser) components may constitute up to 5% of the rock, comprising clasts of quartz, feldspar, granite, black chert, grey siltstone, fine-grained sandstone and mudstone. The rocks generally display a “massive” appearance, with very little evidence for any internal stratification. Melvin and Sprague (2006) discussed the origins of this facies within the Unayzah B member and concluded that it most likely represents the sublacustrine remobilization of glacially derived sediment as debris flows on to the bottom of glacial lakes.

Ripple cross-laminated sub-lacustrine outwash sandstones: This distinctive facies has only been recorded in the Unayzah B member in core from well 10 (Figure 15d, 25.0–44.0 ft). It directly overlies an interval of sublacustrine gravity flow sandstones (discussed above) (Figure 15d, 0–25.0 ft) and is itself superseded by a massive diamictite (Figure 15d, 44.0–50.5 ft). It comprises fine- to very fine-grained sandstones that display multiple, well developed, thin (1–3 cm) laminasets of climbing ripple-drift cross-lamination. These occur in three packages ranging in thickness from 11 ft (3.3 m) to 3 ft (0.9 m). Melvin and Sprague (2006) discussed how the laminasets represented in the lower two packages (Figure 15d, 25.0–42.0 ft) can be ascribed to Jopling and Walker’s (1968) Type A ripple-drift cross-lamination: each package grades abruptly upwards into a thin (5–10 cm) interval of dark grey silty mudstone. The uppermost package is characterized by laminasets that display Jopling and Walker’s (1968) Type B ripple-drift cross-lamination.

Melvin et al. (2010) have discussed how this arrangement of the facies is essentially “transgressive” in nature and can be interpreted as being indicative of rising lake level at the location of well 10. The manner in which these depositional packages of ripple cross-laminated sandstones each terminate upwards in thin intervals of finer-grained mudrock is reminiscent of similar features observed in Quaternary subaqueous glacial outwash deposits in Canada. There, Gustavson et al. (1975) demonstrated how ripple-drift laminasets predominate as “summer layers” and alternate with finer-grained “winter layers” of mudrock. These phenomena occur on glaciolacustrine delta slopes as well as sublacustrine kame deltas deposited at the terminus of englacial tunnels on the bottom of glacial lakes. Similarly Rust and Romanelli (1975) described how graded, rippled units on a subaqueous esker fan can be considered to represent “proximal varves” and therefore also carry an implication of seasonality in their depositional history. In the Unayzah B member at well 10, the stratigraphic associations of the rippled sandstones with sublacustrine gravity flows (with dropstones) (below) and sublacustrine diamictites (above) lead to the conclusion that they were deposited as subaqueous outwash debris at the distal end of a glacial outwash fan on the bottom of a glacial lake.

Interstratified pebbly siltstones and laminated mudstones (Stratified diamictite): This facies has been identified in core in the Unayzah B member in wells 3b, 4, 7, 8, 12 and 18. Examples are shown from well 8 (Figure 7e), well 7 (Figure 13b, 68–85 ft) and well 18 (Figure 15c, 0.5–34 ft). In well 7 the rocks are heterolithic in character, wherein the “background” sediment comprises fissile, grey to red claystone interlaminated on a sub-centimeter scale with grey silty mudstone. Samples of these fine-grained rocks have proved to be barren of any palynomorphs. Within these mudrocks there occur thin intervals characterized by common to abundant dispersed grains of coarse to very coarse sand, granules and small pebbles (Figure 16b). This coarser detritus consists of quartz, feldspar and granite as well as common distinctive lithic clasts that are very poorly sorted (diamictitic) in nature. These lithic clasts were considered by Melvin and Sprague (2006) to be “till pellets” sensu Ovenshine (1970). Individually, the coarser horizons in well 7 range from 0.5 to 10 cm in thickness and most commonly display indistinct or diffuse boundaries. In well 18 this facies is represented by 33.5 ft (10.05 m) of dark grey, sandy to pebbly mudstone that sits directly on top of the upper contact of the Unayzah C member. The abundance of dispersed coarse-grained material in this well varies, but is particularly high close to the middle of the interval (Figure 15c, 9–19 ft). There also the sediment is clearly severely disrupted, showing overfolding (Figure 16c), and is associated with a large (cobble-sized) clast of cemented sandstone that disrupts the adjacent sediment. This is interpreted to be a large glacial dropstone (Figure 16d). Similar features have been observed in the Unayzah B member in well 3b (Figure 1c). In well 7 the uppermost 17 ft (5.1 m) of the Unayzah B member is represented by this
stratified diamictite facies (Figure 13b, 68–85 ft). In this well, the proportion of coarser-grained detritus diminishes upsection, i.e. the facies as a whole appears to fine upwards. In well 8 the entire Unayzah B member comprises diamictite and is only 2 feet (0.6 m) thick (Figure 7e). As such, it does not fully satisfy the criteria for being a “massive” diamictite as defined above: neither is it fully stratified, in

Figure 16: Core photographs illustrating aspects of the diamictite facies in the Unayzah B member. (a) Massive diamictite from well 12 showing the very poorly sorted nature of the sediment and apparently random orientation of the clasts; (b) Stratified diamictite from the upper part of the Unayzah B member in well 7 (cf. Figure 13b, well 7, 67–85 ft). Note the very fine-grained and fissile mudstone “host” rock within which occur thin (cm-scale) horizons of very poorly sorted muddy sandstone showing diffuse bed boundaries. (c) Highly contorted stratified diamictite in well 18 (cf. Figure 15c, well 18, 15 ft). The high concentrations of coarser sand grains imply deposition at a time of maximum rainout (i.e. maximum melting conditions) and the contortions are thought to have been generated by grounded ice in a glacial lake. Width of core is about 7 cm. (d) Cobble-sized clast of grey sandstone deforming subjacent laminations, suggesting it was emplaced as a glacial dropstone (cf. Figure 15c, well 18, 13 ft) Width of core is about 7 cm.
the sense of the preceding discussion. It is essentially a sub-facies of the stratified diamictites, and was interpreted as a “rainout” diamictite by Melvin and Sprague (2006) and Melvin et al. (2010). Although volumetrically of very minor occurrence, this diamictite in well 8 has considerable significance in the interpretation of the evolution of the Unayzah B member, as will be discussed in a later section.

The lack of recovery of any palynomorph material from samples of this facies suggests lacustrine as opposed to marine sedimentation. The physical characteristics of the rocks were interpreted by Melvin and Sprague (2006) to represent stratified diamictite. In such rocks, the coarser-grained beds (and any associated large dropstones) are formed by rainout of ice-bound sediment at times of seasonal thaw, whereas colder periods give rise to the mud-dominated sediment as a result of suspension settling of fines through the water column. The deformation of the coarse-clast-rich interval in well 18 (Figure 16c) most likely took place as a result of grounded icebergs disrupting the lake bottom sediment during a time of thaw. The recognition of common, poorly sorted lithic clasts (“till pellets”) is significant. Ovenshine (1970) described such features from a modern setting at Glacier Bay in Alaska and concluded *inter alia* that where they can be identified in ancient rocks they “uniquely identify the existence of glacier ice very near to the environment of deposition”. In some wells (e.g. wells 4, 7, 12 and 18) rarer, thin (2–10 cm) beds are present that display a very poorly sorted diamictite texture, but wherein the lower bed boundaries are not diffuse, but sharp, and in several cases loaded. These beds have been interpreted as the products of small debris flows on the bottom of glacial lakes (Melvin and Sprague, 2006).

**Mudrock facies: Distal glaciolacustrine deposits:** This facies occurs in a number of wells where the Unayzah B member has been cored. It consists of grey-green siltstones to dark grey mudrock and is best developed in well 10 (Figure 15d, 50.5-70.0 ft) at the top of the Unayzah B member. Melvin and Sprague (2006) showed how in that well the lowermost 10 ft (3 m) comprises a series of stacked, very thin (cm-scale), dark grey muddy siltstone beds; these are overlain by about 9.5 ft (2.85 m) of dark grey, silt-prone mudrock. This mudrock fines up progressively, becoming decreasingly silt-prone until in its uppermost 4 cm it is a pale grey claystone. Samples from this mudrock interval have all proved to be palynologically barren (J. Filatoff, personal communication, 2004) and are considered to represent lacustrine (as opposed to marine) sedimentation.

The very thin muddy siltstone beds were considered in relation to their facies associations in this well and interpreted by Melvin and Sprague (2006) to be ultra-distal gravity flow deposits laid down in a glacial lake. The upward-fining profile displayed by the overlying mudrocks indicates that in well 10, at the end of Unayzah B member time the lake became increasingly deeper, or the source of sediment became increasingly distant with time. In other wells (e.g. wells 13 and 18) intervals of grey-green muddy siltstone have been recorded that occur just above the contact with the underlying Unayzah C member and which contain rare dispersed, pebble-sized clasts that appear locally to be “nested” together (Figure 7d, 88 ft; Figure 15c, 1 ft). These pebbly accumulations are interpreted to be clusters of dropstones deposited as rainout debris on the bottom of glacial lakes.

**DISCUSSION**

The sedimentary characteristics of both the upper Juwayl Member and the Unayzah B member indicate that, although collectively represented by a wide range of depositional facies, they are both characterized by deposits that can be attributed to processes related to glacial outwash, albeit ranging in character from sub-aerial to sub-aqueous, and from ice-proximal to ice-distal. There is also evidence for a sustained glacial presence in some locations. This is interpreted from the pervasive deformation of the Unayzah B member in wells 2 and 3a (Figure 13a). Significantly, palynological analysis of samples from the Unayzah B member in these two wells (and others in the surrounding area) reveals palynomorph assemblages that show distinctive cold climate and montane affinities (N.P. Hooker, personal communication, 2008). The proximity of these wells to the paleo-high known as the Al-Batin Arch (Faqira et al., 2009), as well as the palynological evidence and the deformation seen in the cores, are all factors that lend support to the likelihood that in these locations in the west of the study area there continued to exist during Unayzah B times localized upland (alpine) centers of glaciation, as was originally tentatively suggested by Melvin and Sprague (2006).
The upper Juwayl Member at outcrop does not appear to have direct facies equivalence across the entire area of interest with the subsurface Unayzah B member. It does however have very strong similarities with the Unayzah B member in the westerly-situated well 19. This well occurs relatively close to the outcrop at Khasm Khatmah (see Figure 1), and so can be considered as being relatively close to the basin margins.

The upper Juwayl Member at outcrop and the Unayzah B member in well 19 have both been interpreted above as comprising predominantly high-energy braided fluvial sediments. By association with related facies (specifically, the directly supradjacent diamictitic siltstones: see below) they are consequently considered to represent deposition on a glaciofluvial outwash braidplain. Multiple upward-fining bedsets suggest shifting loci of deposition and this may be a reflection of either multiple sources of sediment (namely, melting glacial ice), or possibly a suggestion of minor re-advance of the ice during a phase of overall glacial retreat. That this overall retreat of the ice was indeed taking place is indicated in the overall upward-fining nature of the fluvial succession in both the upper Juwayl Member at outcrop and the Unayzah B member at well 19. In both cases, this overall upward-fining signature culminates in the deposition of very fine-grained sediment that contains dispersed coarse-grained clasts (which are granite boulders in the case of the most proximal examples at Khasm Khatmah and Jabal Umm Ghiran). These fine-grained sediments are interpreted as glaciolacustrine stratified diamictites, indicating that by the end of deposition of both the upper Juwayl Member and the Unayzah B member, in these locations the braidplains had become inundated by the rising meltwaters of the terminally retreating late Paleozoic ice sheet.

East of well 19 (i.e. basin-central to the study area) the depositional facies identified in the subsurface within the Unayzah B member are varied, but universally indicate sedimentation within an environment dominated by glacial lakes. Those lake sediments contain evidence locally (e.g. well 7) of stratabound intervals of deformation attributed to minor push moraines, suggesting minor glacial re-advance in places during an overall phase of glacial retreat. Nonetheless, in every cored well examined from the more easterly locations, consideration of the relative associations of the different facies presents strong and consistent evidence for rising lake levels throughout the time of deposition of the Unayzah B member. That evidence is widely manifest in gross upward-fining sedimentary successions, as well as facies associations (however disparate the facies) that consistently display an increasingly distal aspect towards the top of the Unayzah B member. These widespread signs of rising lake levels are in turn interpreted to reflect ongoing retreat (melting) of the late Paleozoic ice sheets across the entire area of the southern half of the Arabian Plate. Notwithstanding the widely differing characteristics between the glaciolacustrine depositional facies of the basin center and the basin-marginal glaciofluvial deposits seen at well 19 and at the outcrop at Khasm Khatmah, it does seem possible to draw equivalence among all of these different depositional settings and to relate the stratigraphic development of the subsurface Unayzah B member to that of the upper Juwayl Member at outcrop. This study as a whole has therefore successfully demonstrated stratigraphic equivalence between not only the lower parts of the Juwayl Member and the Unayzah C member (as discussed previously), but also the upper parts of the Juwayl Member and the Unayzah B member. Based on all of the foregoing, a model for the evolution of the upper Juwayl Member and the Unayzah B member is presented below.
debris flows) (e.g. massive diamicrites at well 5). Despite local evidence for minor glacial re-advance (e.g. well 7) this major phase of terminal retreat of the ice sheets was sustained across the southern areas of the Arabian Plate. The meltwaters filled the deepest erosional depressions, deepening the lakes and eventually spilling over the intervening sills and interfluvies, changing the landscape from one of multiple glacial lakes to one of fewer, but much more laterally extensive lakes. An example of spillover is inferred from the thin (2 ft: 0.6 m) rainout diamicite that represents in its entirety the Unayzah B member at well 8 (Figure 7e). This period of widespread expansion of the glaciolacustrine environment, as a consequence of the continuing melting and retreat of the ice sheets, ultimately was manifest at the basin margins where the glaciofluvial braidplains were themselves inundated by the rising floodwaters. The end of the late Paleozoic ice age in Saudi Arabia is represented by the abrupt contact between the Unayzah B member and the overlying un-named middle Unayzah member. The latter stratal unit comprises a very different suite of depositional facies (Melvin and Sprague, 2006), and its contact with the Unayzah B member has been interpreted by Melvin et al. (2010) as representing a dramatic drainage event marking the end of the late Paleozoic glaciation in Saudi Arabia.

Implications for Reservoir Heterogeneity

Previous discussion has already demonstrated that any heterogeneity within the lower Juwayl Member and the Unayzah C member is heavily influenced by the effects of glacial tectonics. This is not the case in the upper Juwayl Member and Unayzah B member, and evidence for any glacial tectonics in these units is extremely limited and geographically localized. There is nonetheless, significant potential for a high degree of heterogeneity within these two stratigraphic units, specifically with regard to reservoir quality (considered empirically to be reflected as porosity and permeability). This heterogeneity is manifest in the widely disparate character and distribution of the depositional facies encountered from the outcrop and throughout the subsurface in the wells examined. Thus in the west, basin marginal successions might be expected to have promising reservoir potential, in terms of both reservoir distribution and reservoir quality in the glaciofluvial outwash sands and gravels. Local seals and baffles might be expected in associated glaciolacustrine siltstones and diamicites. Farther east and basinward, the great variety of glaciolacustrine facies presents the potential for a wide range of reservoir quality. Moderate to good quality reservoirs are to be expected, for example, in some of the sublacustrine gravity flow sandstones, although the volume and areal distribution of such rocks will be limited to the bottom of individual glacial lakes. Moderate to poor reservoir quality can be expected in ripple cross-laminated sandstones, and their distribution will be limited. Poor quality reservoir facies of moderate extent will be represented by massive and stratified diamicites, and rocks serving as internal seals (i.e. non-reservoir) will be represented by fine-grained glaciolacustrine mudrock. Reservoir connectivity in these various glaciolacustrine facies will necessarily be limited.

CONCLUSIONS

There is strong evidence to suggest that the Carboniferous-Permian lower Juwayl Member of the Wajid Formation, which crops out in southwest Saudi Arabia, and the subsurface Unayzah C member in eastern-central parts of the country are essentially the same stratal unit, formed during the syn-glacial stages of the late Paleozoic Gondwanan glaciation in Arabia. Similarly, the upper Juwayl Member and the Unayzah B member present convincing evidence of their stratigraphic equivalence, and represent an extremely heterogeneous depositional facies mosaic that was laid down during the terminal retreat phase of that glacial event.

The lower Juwayl Member and the Unayzah C member were both deposited in deep, elongate glacial valleys. In the latter case there is evidence to suggest some sediment transport from a northerly direction and this in turn leads to the possibility that at least some of the ice resided in localized, upland (alpine) ice caps. In gross terms, however, the area of active glaciation extended across at least the lower half of the Arabian Plate.
There is abundant evidence for glaciotectonic deformation within the lower Juwayl Member and the Unayzah C member. This is manifest at outcrop as high to low-angle thrust sheets and in the subsurface the Unayzah C member is characterized by the widespread occurrence of shear zones. These are readily identified in core, as well as in uncored wells from downhole wireline log responses such as spectral gamma-ray logs and image logs.

Multiple phases of glacial advance and retreat are interpreted from the data. These led to widespread deposition of glaciofluvial outwash sands and gravels (retreat phases) that were subsequently cannibalized and severely deformed by re-advance of the ice. This created push moraine nappe complexes and wholesale explosive disruption and sediment redistribution resulting from glacially induced overpressuring.

Although these processes led to a degree of post-depositional homogenization of the sediment in the lower Juwayl and Unayzah C members, there is nonetheless high potential within these rocks for reservoir heterogeneity to be widely developed. Boundaries to flow in the subsurface will be developed, particularly in relation to the glaciotectonic shear zones that characterize the Unayzah C member, creating reservoir compartments of widely varying extent and distribution, and with unknown, but potentially very poor interconnectedness.

The upper Juwayl Member at outcrop is represented by pebbly sandstones and conglomerates that were laid down upon a widespread glaciofluvial outwash braidplain. These deposits pass upwards into boulder-bearing siltstones (stratified diamictites). These characterize a glaciolacustrine setting that is representative of the terminal flooding stages of the final retreat of the late Paleozoic Gondwanan ice sheets. In the subsurface, similar facies are identified in the Unayzah B member in wells located in the western part of Central Saudi Arabia. Locally, subsurface data from the Unayzah B member in the west of the study area suggest sustained ice-contact conditions. This is interpreted as evidence for local sustained “alpine” ice caps in these areas throughout Unayzah B times.

Farther east in the study area, the subsurface Unayzah B member is represented by a wide variety of depositional facies, all of which can be interpreted as having been deposited within a glaciolacustrine setting. These facies comprise: (1) some minor ice-contact push moraine deposits, indicative of some minor glacial re-advance during the overall terminal retreat phase of the late Paleozoic glaciation in Arabia; (2) thick sequences of ice-proximal sublacustrine outwash sandstones including high density turbidites, fluidized gravity flows and debris flows (massive diamictites); and (3) intermediate to ice-distal, sublacustrine sandstones and mudrocks including multiple lamina sets of ripple cross-laminated sandstones, stratified diamictites and mudstones with dropstones.

Everywhere the Unayzah B member has been encountered in the subsurface the depositional facies associations show strong evidence for sustained and terminal retreat of the Gondwanan ice sheets. This is manifest in sustained infill and deepening, and eventual overspilling of the basin-central glacial lakes, leading to widespread flooding throughout the basin. This flooding is ultimately identifiable in the facies relationships in basin marginal locations in the western subsurface, as well as in the upper Juwayl Member at the outcrop belt. Stratigraphically, the upper contact of the Unayzah B member/upper Juwayl Member represents the end of the late Paleozoic glaciation in Saudi Arabia.

The upper Juwayl Member and the Unayzah B member display a high degree of heterogeneity in terms of their reservoir properties. This is a function of the great variety of depositional facies by which they are characterized as a stratal unit. Thus, good quality sandstones can be expected in basin-marginal, glaciofluvial outwash deposits and possibly in some more basin-central, sublacustrine, high density gravity flows. Moderate to poor quality reservoirs will characterize other, more argillaceous gravity flow sandstones and massive diamictites. Poor quality reservoir (to non-reservoir) can be expected in stratified diamictites and mudstones: since these depositional facies occur in general towards the top of the Unayzah B member, they can be expected to act instead as effective local seals to the reservoirs below.
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ABOUT THE AUTHORS

John Melvin is a Geological Consultant in Saudi Aramco’s Reservoir Characterization Department (RCD), where he is responsible for a major new Mentorship Program aimed at developing expertise in siliciclastic sedimentology and stratigraphy among young Saudi geoscientists. Prior to this he was Team Leader, Special Studies Team in Aramco’s Gas Fields Characterization Division. There, he characterized the clastic sedimentology and stratigraphy of Carboniferous–Permian Unayzah and Basal Khuff Clastics reservoirs, as well as Devonian Jauf reservoirs, in the process completing the description and interpretation of over 22,000 feet of core. This work provided critical input to reservoir modeling of Saudi Aramco’s Paleozoic gas reservoirs. Earlier stratigraphic projects with Aramco involved core and outcrop studies of the Lower Paleozoic in Saudi Arabia, including the Ordovician Qasim and Sarah formations and the Silurian Qusaiba Member of the Qalibah Formation. John obtained his BSc (Honours) and PhD degrees from the University of Edinburgh in Scotland. He then spent over 20 years with BP where he conducted many reservoir studies for both exploration and development in the North Sea and Alaska. There followed 6 successful years as a Consulting Specialist in clastic reservoirs in Egypt, Libya, Colombia and the North Sea, before joining Saudi Aramco in 2001. John has published several articles on applied sedimentology and stratigraphy and is a member of the AAPG, IAS, Dhahran Geoscience Society and PESGB.

john.melvin@aramco.com

Arthur Kent Norton has 25 years of exploration experience with Saudi Aramco involving assignments in most of Saudi Arabia’s petroleum systems. His focus the last decade has been Paleozoic non-associated gas plays and more recently emphasis on frontier exploration in northwest Saudi Arabia. He received his BSc in Geology from the University of California at Davis (USA) in 1979 and his MSc in Geology from Northern Arizona University (USA) in 1990. He is currently a member of the AAPG and DGS.

arthur.norton@aramco.com

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