Advances in Arabian stratigraphy: Origin and stratigraphic architecture of glaciogenic sediments in Permian-Carboniferous lower Unayzah sandstones, eastern central Saudi Arabia

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ABSTRACT

In the subsurface of eastern central Saudi Arabia, deposition of lower Unayzah sediments commenced in late Carboniferous (late Moscovian = late Westphalian-Stephanian) times during the earliest stages of the late Paleozoic Gondwanan glaciation. The Unayzah C member is the lowermost unit, and comprises quartzose sandstones laid down on an extensive glacio-fluvial outwash braidplain upon the pre-Unayzah unconformity (so-called “Hercynian unconformity”). They were overridden during (probably several) glacial re-advances, when the sediments were thrust over each other during the construction of push moraines ahead of the advancing ice sheets. The upper surface of the Unayzah C member represents the final sub-glacial contact of this long-lived series of glacial advances and retreats, and demonstrably represents a significant post-Unayzah C unconformity. Subsequent (early Permian) deposits represent the final glacial retreat phase. They include the Unayzah B member and a new, un-named middle Unayzah member that underlies the Unayzah A member.

The Unayzah B member is dominated by glaciogenic sediments, including highly deformed material attributed to seasonal push moraines (and hence representing minor glacial re-advances); ice-proximal, subaqueous outwash fans (high-energy lacustrine turbidites with associated dropstones, and massive diamicrites); and ice-distal, glacio-lacustrine deposits including laminites, stratified diamicrites, ripple cross-laminated sandstones and mudrocks with associated dropstones. In contrast, the un-named middle Unayzah member is characterized by widespread, fine-grained red-beds, representing low-lying alluvial floodbasin deposits. Embedded within these occur aeolian and fluvial sandstones. A significant drainage event is thus implied between the Unayzah B member and the un-named middle Unayzah member. It is marked by a sharp contact between the two members that represents a regionally correlatable disconformity. The end of lower Unayzah deposition is represented in places by paleosol development, indicating a further disconformable contact, separating the un-named middle Unayzah member from the overlying Unayzah A member. This study significantly extends the record of the advance and retreat of the Gondwanan ice sheets in southern Saudi Arabia, and provides sufficient confidence to propose a degree of stratigraphic correlation with coeval deposits in Oman.

INTRODUCTION

In eastern central Saudi Arabia (Figure 1a), a major unconformity known as the pre-Unayzah or “Hercynian” unconformity is identified in the subsurface, truncating lower Paleozoic formations ranging in age from Cambrian to early Carboniferous. It represents a significant erosional event during the middle Carboniferous, that lasted approximately from Serpukhovian to late Moscovian (= Namurian to early Westphalian) times (Al-Husseini, 2004), and which was consequent upon a major phase of late Paleozoic tectonism within the Arabian Plate. Several authors have discussed the origins and duration of this middle Carboniferous tectonic event (Husseini, 1992; McGillivray and Husseini, 1992; Wender et al., 1998; Al Hajri and Owens, 2000; Konert et al., 2001; Sharland et al., 2001; Al-Husseini, 2004). In general, many regions of Arabia developed either (1) NE--trending sags and swells, considered by Al-Husseini (2004) to have formed during the middle Carboniferous or earlier, or (2) were uplifted during an apparently short-lived compressional (transpressional) event into elongate, NS-trending fault-bounded blocks (Al-Husseini, 2004). Shortly following this tectonic event was the initiation in Arabia of the late Paleozoic Gondwanan glacial episode (Al-Husseini, 2004).
Figure 1: (a) Map of eastern central Saudi Arabia showing the wells studied. Note the lines of section for Figures 7, 23. Major oil fields are shown in green and gas fields in red. (b) Paleotectonic plate reconstruction of Gondwana in late Carboniferous (Kazimovian) times, showing the maximum extent of the South Polar ice sheet. The stippled area shows how this has been extended by this study (modified after Stampfli and Borel, 2004). (c) Map of the Arabian Peninsula, showing the principal study area for this paper, as well as areas in Oman (A), Yemen (B) and southwest Saudi Arabia (C) where glaciogenic sediments have been determined to occur at outcrop (see text for discussion).
Recent paleotectonic global reconstructions (e.g. Stampfli and Borel, 2004) place the northernmost extent of the Gondwanan ice cap in late Carboniferous (middle Stephanian = Kazimovian) times in the most southerly areas of the Arabian Plate, (Figure 1b), around southern Oman and southeast Yemen.

Widespread siliciclastic deposits of the Unayzah Formation were laid down upon the pre-Unayzah unconformity in central and eastern Saudi Arabia. These rocks contain very significant hydrocarbon reserves for Saudi Arabia, with a large number of oil and gas fields having been found in Unayzah reservoirs since the late 1980s. The Unayzah Formation in the Saudi Arabian subsurface varies considerably, ranging from zero to hundreds of feet in thickness, and has been subdivided informally into three members, namely the Unayzah A (youngest), B and C (oldest) (Ferguson and Chambers, 1991; McGillivray and Husseini, 1992) (Figure 2).

**STRATIGRAPHIC FRAMEWORK**

Although the Unayzah Formation in the Saudi Arabian subsurface has been described and informally subdivided by Ferguson and Chambers (1991), there exists no rigorous definition of its component parts, particularly in terms of any diagnostic wireline log signature. This is particularly true for the younger Unayzah A and B members that overlie the Unayzah C member (where it is present), and arises because of the intrinsic variability of the wireline logs between wells. Some examples are shown in Figure 3. As a result the published lithostratigraphic nomenclature is confusing and oftentimes misleading. Figure 2 highlights some of the historical differences in expression of the stratigraphy of the Unayzah Formation in the subsurface of Saudi Arabia. It will be shown in this study that the variability observed in the wireline signatures (Figure 3) results from extreme variation in thickness and facies among the members of the Unayzah, as well as from an abundance of erosional and non-depositional unconformities throughout the system. The recognition and interpretation of those facies, as well as of significant stratal surfaces can only realistically be achieved with the utilization of considerable amounts of continuous core. Thus, the present study derives from the description and interpretation of a large quantity of core material from the Unayzah Formation. In order to establish a suitable framework for the presentation of this work, a summary and discussion of historical stratigraphic studies of the Unayzah is presented below.

**Lithostratigraphy and Depositional Setting**

The Unayzah C member has been described by McGillivray and Husseini (1992) as locally forming part of the basal Unayzah Formation, representing “an older sequence that infilled paleotopography on the eroded pre-Unayzah surface”. Al-Husseini (2004) has noted that seismic data, calibrated to wells, identifies Unayzah C channels in central Saudi Arabia that are about 1.88 miles (3.0 km) wide and 250–400 ft (75-120 m) thick.

Where present, the Unayzah B member of Ferguson and Chambers (1991) comprises medium- to coarse-grained, braided stream or alluvial sandstones, according to McGillivray and Husseini (1992). Senalp and Al-Duaiji (1995) described the Unayzah Formation from wells in the Hawtah field in central Saudi Arabia (Figure 1a). They described the Unayzah B member in terms of a number of units consisting of matrix-supported conglomerates and medium- to very coarse-grained sandstones that were interpreted as canyon-fill debris flows and braided channel-fill facies, respectively. Aktas et al. (2000) and Al-Qassab et al. (2001) have interpreted the Unayzah B member in the Hawtah region as alluvial fan to braidplain fluvial deposits that filled structurally controlled, irregular topography. Senalp and Al-Duaiji (2001) introduced two informal subsurface stratigraphic formations, namely the Haradh (Unayzah C equivalent) and Jawb (Unayzah B equivalent). They interpreted their Haradh formation as fluvio-glacial braid plain (sandur) deposits with some minor aeolian influence; the Jawb formation was laid down in a glacio-lacustrine to shallow-marine environment at the end of the Gondwanan glaciation (Senalp and Al-Duaiji, 2001). The informal terms Haradh and Jawb formations have not found widespread usage among subsequent workers.

The Unayzah B of Ferguson and Chambers (1991) is overlain by the Unayzah A, but the distinction between the two has not always been clearly defined. In large part, this can be attributed to the palynologically barren nature of these rocks (see below). Melvin and Heine (2004) have described...
Figure 2: The late Carboniferous-Permian stratigraphy of Saudi Arabia and Oman. Note: (1) Historical attempts to represent the lithostratigraphy of the Unayzah Formation, and the various terminologies centred around the middle of the sequence. (2) The critical palynozonation of Stephenson et al. (2003) and Stephenson (2006), providing a linkage between the stratigraphies of Oman and Saudi Arabia. (3) The Carboniferous-Permian lithostratigraphy of Oman. The subject of the present paper is shaded in yellow. At the time of going to press, new work by Angiolini et al. (2006) places the Lower Gharif and OSPZ3 (and hence any correlative units) within the Sakmarian.
how the Unayzah A in many places is represented by sediments that are characteristic of a very arid depositional setting, and specifically, very commonly consist of abundant aeolian deposits. Those authors believe that the base of the Unayzah A is an unconformable surface (Melvin and Heine, 2004). Wender et al. (1998, p. 283) showed the ‘Unayzah A reservoir’ separated from the ‘Unayzah B reservoir’ by a unit, about 200 ft (60 m) thick which they called the ‘Unayzah Siltstone Member’. That siltstone unit is equivalent to the red siltstone described from the lower part of the Unayzah A in central Saudi Arabia by Ferguson and Chambers (1991), and subsequently referred to as the ‘lower Unayzah A submember’ by Al-Husseini (2004) (Figure 2). The current paper will demonstrate that in many places there is a stratigraphic break within this siltstone-prone unit that is of regional significance, representing the top of a newly recognised stratigraphic member within the lower Unayzah Formation of the Saudi Arabian subsurface. In terms of the existing lithostratigraphic framework, therefore, this paper will address the origin and stratigraphic architecture of the lower Unayzah, namely the Unayzah B and C members as defined by Ferguson and Chambers (1991), as well as the lowermost part of the siltstone unit previously described as the ‘Unayzah Siltstone Member’ (Wender et al. 1998) and the ‘lower Unayzah A submember’ (Al-Husseini, 2004) (Figure 2).

Biostratigraphy and Age Interpretation

Dating the Unayzah Formation has historically proved challenging. The primary biostratigraphic tool has been limited to palynology, due to a lack of macrofossils in these predominantly terrestrial deposits. Furthermore, many sections within the Unayzah are barren of any fossils, including palynomorphs.

This is particularly true of the Unayzah C member. Owens et al. (2000) published details of a palynomorph assemblage from Haradh-601 well (well 9 in this study). The samples came from an uncored, high gamma-ray interval in the well that abruptly superseded a very thick section that was characterized by a monotonously clean, low gamma-ray interval (Figure 3) and which is attributed to the Unayzah C member in this paper. The assemblage was characterized by an abundance of reworked uppermost Famennian to basal Tournasian land-plant spores, as well as smaller numbers of monosaccate pollen (including Potonieisporites, Plicatipollenites and Cannanoropollis) (Owens et al., 2000). The latter are unknown in sediments older than Namurian (Serpukhovian-Bashkirian), and were considered therefore probably to represent the only flora likely to be indigenous to this assemblage. On this evidence, Owens et al. (2000) assigned an age date of early Namurian (Serpukhovian) to the sampled interval. Consequently, the underlying Unayzah C member has historically also been dated as late Carboniferous, Serpukhovian (early Namurian) in age.

J. Filatoff (written communication, 2004) has more recently presented a revised interpretation of these palynological data. Incorporating data from other wells from eastern and central Saudi Arabia, he has described the palynomorph assemblage discussed above as comprising abundant reworked forms of lower Carboniferous (Visean) spores, Devonian spores and early Silurian acritarchs, as well as the monosaccate pollen. He referred to this assemblage as the ‘Cm palynoflora’ and agreed that sensu stricto it can be dated as Serpukhovian (early Namurian) (J. Filatoff, written communication, 2004). However, comparison with more regional data shows that palynomorph recoveries from similar facies in the lowermost Al Khlata Formation in Oman also comprise low-diversity assemblages of predominantly monosaccate pollen (Potonieisporites Assemblage of Love, 1994). Those assemblages have been dated as late Carboniferous, late Moscovian (late Westphalian) to middle Kasimovian (early Stephanian) in age (Osterloff et al., 2004a). This later age dating has appeal from a pan-Gondwanan point of view, in that data from Australia, Oman and now (if the ‘Cm palynoflora’ is included) Saudi Arabia, all demonstrate that maximum glaciation in the late Carboniferous is marked by impoverished, low-diversity palynofloral assemblages dominated by monosaccate pollen (J. Filatoff, written communication, 2004).

Stephenson (1998) and Stephenson and Filatoff (2000a) were able to correlate the upper part of the Al Khlata Formation in Oman and the Unayzah B member in the subsurface of central Saudi Arabia with the Coverrucosisporites confluens (Granulatisporites confluens) Zone of Foster and Waterhouse (1988), suggesting an early Permian (Asselian-Sakmarian) age for those rocks (Figure 2). Further to that work, Stephenson et al. (2003) have produced a palynological zonation scheme that
Figure 3: Wireline log traces of the Unayzah section in selected wells, showing the very high degree of variability in log pattern and thickness, making the subsequent correlations highly tentative and equivocal. One such possible correlation is presented here. * Note: the Cm palynoflora first described by Owens et al. (2000) occurred in the high gamma interval between 14,500-14,550 ft in well 9. See text for discussion.
enables correlation of all the various members of the Unayzah Formation (and the basal part of the overlying Khuff Formation) in Saudi Arabia with the Al Khlata, Gharif and lower part of the Khuff formations of Oman. Thus, the Unayzah C member has been assigned to Zone OSPZ1 by Stephenson et al. (2003), and, although sometimes cited as Westphalian D – Stephanian (Al-Hajri and Owens, 2000), it is considered to be Stephanian in age (Stephenson et al., 2003). The Unayzah B member is characterized by palynomorph assemblages of the OSPZ2 Zone (Stephenson et al., 2003), and is early Permian (Asselian-Sakmarian) in age (Stephenson and Filatoff, 2000a; Stephenson et al., 2003; Stephenson, 2004). These stratigraphic relationships are summarized in Figure 2.

Regional Considerations

The glaciogenic nature of the late Carboniferous to early Permian Al Khlata Formation of Oman has been well documented (Braakman et al., 1982; Hughes Clarke, 1988; Levell et al., 1988; Al-Belushi et al., 1996; Aitken et al., 2004; Osterloff et al., 2004a). Permian (possibly early Permian) glacial deposits have also been documented from northern Yemen (Roland, 1979; Kruck and Thiele, 1983). Within Saudi Arabia, glaciogenic sediments of the Juwayl Member of the Wajid Formation crop out close to Yemen, in the southwestern Wajid region (Figure 1c). Those rocks comprise inter alia well-defined diamictite, and boulder-sized clasts of sedimentary, igneous and metamorphic rocks that exhibit well-developed facets, striations and grooves (Helal, 1965; Kellogg et al., 1986; McClure, 1980; McClure and Young, 1981; McClure et al., 1988). Cameron and Hemer (in McClure, 1980; McClure and Young, 1981) interpreted these glaciogenic sediments of the Juwayl Member of the Wajid Sandstone as late Carboniferous (Stephanian) to early Permian (Sakmarian) in age. Evans et al. (1991) derived a similar age for Juwayl Member sediments encountered in shallow uphole wells drilled close to these outcrops.

Glaciogenic sedimentary rocks of late Carboniferous to early Permian age have thus been documented from across the southern part of the Arabian Peninsula, from Oman to Yemen to the southwestern outcrop belt of the Wajid Sandstone in Saudi Arabia (see Figure 1c). Evans et al. (1991) combined all the data at their disposal and were able to project the subsurface Unayzah Formation to two outcrops in the Wajid area that had been interpreted as glacio-fluvial by McClure (1980). The subsurface Unayzah B and C members have been dated as early Permian to late Carboniferous in age, respectively (see preceding discussion), and they are therefore coeval with the proven glacial deposits from the other areas. Senalp and Al-Duaiji (2001) presented the informal units Haradh formation (Unayzah C equivalent) and Jawb formation (Unayzah B equivalent), and considered them in general to represent glacio-fluvial and glacio-lacustrine settings, respectively.

Glacially related deposits are receiving an increasing amount of attention with the growing realization of their importance as significant hydrocarbon reservoirs. Examples are readily identified in the Ordovician of Libya (Davidson et al., 2000), as well as the Permian-Carboniferous of Oman (Levell et al., 1988; Osterloff et al., 2004a) and the Cooper Basin in Australia (Chaney et al., 1997). The purpose of this paper is to demonstrate and systematically document the glaciogenic nature of the depositional facies of lower Unayzah reservoirs as they occur in the subsurface of Saudi Arabia. Their relationships will be described in the context of a stratigraphic architectural framework. Then, an attempt will be made to establish a stratigraphic correlation with Permian-Carboniferous rock units in Oman, recently described by Osterloff et al. (2004a).

Fourteen representative wells have been selected for study from the subsurface of eastern central Saudi Arabia (Figure 1a). These were chosen because within them, the relevant intervals of interest (i.e. the lower Unayzah, B and C members) were extensively cored, and prior experience has demonstrated that little understanding can be gained regarding either the depositional origin or the internal stratigraphy (architecture) of this interval using wireline log data alone. A total of 2,277 ft of lower Unayzah core was examined in detail in this study, of which 1,355 ft represent the Unayzah B, and 922 ft represent the Unayzah C. The core descriptions are featured throughout the text as appropriate, and a ‘master legend’ for these core logs is presented in Figure 4.
SEDIMENTOLOGY OF THE UNAYZAH C MEMBER

Depositional Features

The Unayzah C member displays a highly monotonous, ‘clean’ gamma-ray signature that is locally interrupted by very thin, sharp spikes of significantly higher gamma-ray activity (see Figure 3). It is extremely variable in thickness, reflecting deposition upon a strongly undulating surface viz. the pre-Unayzah unconformity. Thus, although absent in some places, it can be present as several hundred feet of sediment only a few kilometers away. The Unayzah C member consists predominantly of highly indurated, quartzose sandstone wherein the detrital framework grain composition is everywhere 95–98% monocrystalline quartz (S.G. Franks, personal communication, 2004). These sandstones are generally medium- to very coarse-grained (and locally conglomeratic), moderately sorted and arranged in multi-storey bedsets that are commonly several tens of feet thick (Figure 5). Within these, individual beds fine upwards from sharp, commonly erosional basal contacts, locally strewn with intraformational mudclasts and/or pebble to cobble sized clasts of laminated (as well as unlaminated) fine-grained sandstone (Figures 5a and 6a). These upward-fining sandstones may display low-angle to flat, planar lamination, or less commonly trough cross-lamination (Figure 5). Locally, individual beds contain abundant mudclasts, up to three centimetres long, that are uniformly dispersed throughout the bed, and oriented more or less parallel to bedding (Figure 6b). However, primary depositional structures within these sandstones are commonly heavily obscured. In places the rock is characterized only by an extremely diffuse fabric that passes up into discontinuous, crinkly, argillaceous laminations (Figure 6c). Those crinkly laminations may be enhanced by stylolitization (see below). Rarely, thin (cm-scale) beds of grey-green, sandy siltstone separate the sandstone bedsets (Figure 6d).

Interpretation

The character of these multi-storey bedsets is strongly suggestive of an environment that was dominated by processes of repeated erosion and deposition. The multiple scoured contacts imply a strongly channelized environment, and the sedimentary structures are suggestive of high-energy conditions (in the upper-lower to upper flow regime). Very high energy is also suggested by the thick beds with abundant dispersed mudclasts. The commonly observed diffuse fabric in many of these sandstones is ascribed to dewatering, consequent upon very rapid deposition, and the associated argillaceous crinkly laminations probably represent elutriated fines associated with that dewatering. The thin siltstone beds commonly give rise to the high gamma-ray spikes on the wireline logs, and represent rare periods of very low-energy deposition.

The depositional system of the Unayzah C member was dominated by channels characterized by high-energy, sandy bedload sedimentation. The repeated superposition of the channel sandstones in the vertical logged profiles implies repeated lateral switching of the channels: in other words the sediment

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**Core Log Legend**

| Legend | Description |
|--------|-------------|
| ![Mud cracks](image) | Mud cracks |
| ![Root scars](image) | Root scars |
| ![Vertical burrows](image) | Vertical burrows |
| ![Wisy lamination](image) | Wispy lamination |
| ![Climbing ripples](image) | Climbing ripples |
| ![Ripples](image) | Ripples |
| ![Trough cross-lamination](image) | Trough cross-lamination |
| ![Low-angle dipping lamination](image) | Low-angle dipping lamination |
| ![Cross-lamination](image) | Cross-lamination |
| ![Horizontal parallel lamination](image) | Horizontal parallel lamination |
| ![Graded bedding](image) | Graded bedding |
| ![Soft-sediment loading](image) | Soft-sediment loading |
| ![Flame structures](image) | Flame structures |
| ![Dish structures](image) | Dish structures |
| ![Soft-sediment deformation](image) | Soft-sediment deformation |
| ![Sandy laminae](image) | Sandy laminae |
| ![Floating sand grains](image) | Floating sand grains |
| ![Mud clasts](image) | Mud clasts |
| ![Pebbles, cobbles](image) | Pebbles, cobbles |
| ![Horizontal stylolites](image) | Horizontal stylolites |
| ![Dipping stylolites](image) | Dipping stylolites |
| ![Vertical fractures](image) | Vertical fractures |
| ![Thrust planes](image) | Thrust planes |
| ![Brittle deformation](image) | Brittle deformation |

**Grain size**

| Size | Description |
|------|-------------|
| G    | Gravel      |
| S    | Sand        |
| S    | Silt        |
| M    | Mud/clay    |

Figure 4: Comprehensive legend for the various core logs that are presented throughout this paper.
was laid down in a high-energy, braided-stream environment. The thin siltstone beds that occur sporadically within the Unayzah C member represent low-stage deposits of fine-grained sediment upon the upper surfaces of the channel braid bars. The thin nature and generally rare occurrence of these siltstones implies that the channelized environment prevailed, and that there was little opportunity for the development of any sustained, fines-dominated overbank setting. In other words, the braided stream system was essentially laterally unconstrained, and a laterally extensive braidplain setting can be envisaged during the deposition of the Unayzah C member. This conclusion is substantiated by the widespread distribution of the Unayzah C member across the study area (Figure 7).

Figure 5: Core logs illustrating the Unayzah C member from wells 7, 8 and 11. * Note the abundance of ‘structural features’ (stylolites, fractures, etc.) is highlighted in pink; these are uniquely limited to the Unayzah C member. In particular, note the intense thrusting (shear) and overfolding in the lowest 10 ft in well 7 (see Figure 6a). The Unayzah C can be overlain by sediments of either the Unayzah B member (wells 7 and 8) or the Unayzah A member (well 11).
Figure 6: Core photographs illustrating representative features of the Unayzah C member.
(a) The lowermost 14 ft (4.2 m) of core from well 7 (see Figure 5a). Note the dominance of structural shear and other deformation between 14,108 ft and 14,115 ft, and the almost flat-lying overfolds in the siltstone unit between 14,115 ft and 14,116 ft. This deformed interval is overlain by a conglomerate of mudclasts and laminated sandstones (14,104.5 to 14,106.5 ft) that is followed by undeformed massive sandstones from 14,104.5 ft to the top of the core.
(b) Medium- to coarse-grained sandstone from well 13, containing abundant, dispersed mudclasts throughout.
(c) Medium-grained, cemented sandstone displaying an abundance of sub-horizontal, locally coalescing, crinkly, argillaceous, stylolitic laminations.
(d) Example of medium-grained, cemented sandstone in well 7, showing some stylolitised partings, and a thin (2 cm) band of pale green-grey sandy siltstone. The siltstone contains irregular streaks of very fine sandstone suggestive of shearing.
(e) Medium-grained, cemented sandstone showing similar low angle stylolitic partings, cut by high angle to vertical fractures. In some cases, the fractures appear to emanate from the stylolites; elsewhere they cross-cut them. Note also the very diffuse fabric in the lower part of the photograph, suggestive of pervasive dewatering.
(f) Uppermost part of the Unayzah C member in well 8, displaying pervasively fractured fabric suggestive of an incipient paleosol (lower part of the photograph). The contact with the overlying poorly sorted diamicrite of the Unayzah B member is extremely irregular (dashed line) suggesting lithification, or freezing, of the uppermost Unayzah C member prior to any subsequent deposition.
Post-depositional Features

The Unayzah C sandstones are generally tightly cemented by quartz, and this in places comprises between 15–25% of bulk rock volume (S.G. Franks, personal communication, 2004). They also display an abundance of stylolites, which enhance the crinkly elutriation seams described above. These stylolites thus most commonly adopt a nearly bed-parallel orientation (Figure 6c). However, some of them are cut by much higher-angle stylolites, as well as a variety of high-angle, open, partially open and closed fractures (Figure 6e). These structural features are highly characteristic of the Unayzah C member, and are believed to contribute significantly to its reservoir quality and behavior. They readily distinguish it from the other members of the Unayzah Formation, wherein they do not occur to any significant extent (see Figure 5).

In addition to these features, distinctive zones of sub-horizontal shear, with associated low-angle overfolds, and ranging in thickness from two feet (0.6 meters) to over twenty feet (6 meters), have been observed in core in the Unayzah C member in a number of wells (e.g. wells 6, 7, 13, 14). These shear zones are characteristically overlain and underlain by sandstones that are devoid of any such deformation. In well 14 the shear zone identified in core correlates with an interval of multiple high gamma spikes on the gamma-ray log. Another example of such a shear zone is well displayed in core from well 7 (Figures 5a and 6a). There, the lowermost 10 ft (3 m) of core displays an abundance of low-angle shear planes, as well as overfolds, within the sandstones (Figure 5a, 0-10 ft; Figure 6a). Within this disrupted interval there occurs a dark grey, silty unit about one foot thick within which are seen elongate, stretched and overfolded laminae and lenses of sandstone (Figure 6a). The 10-foot zone of severe deformation is succeeded by about 2 ft (0.6 m) of conglomerate, comprising pebble and cobble-sized intra-formational clasts of laminated sandstone, non-laminated sandstone and siltstone (Figures 5a and 6a). That conglomerate is overlain by sandstones (Figure 5a) that show stylolitization and minor fracturing, but none of the intense deformation that is present in the shear zone immediately beneath the conglomerate. These shear zones are highly distinctive wherever they are seen in core, and in several wells clearly correlate with intervals that display a strongly chaotic signature on image logs (M.H. Prudden, personal communication, 2005). This has enabled tentative identification of the shear zones in uncored wells: in such cases the chaotic zones are separated by considerable thicknesses (several tens of feet) of normally stratified sediment, as has been observed in the cored examples.

Although the Unayzah C member has been penetrated to the pre-Unayzah unconformity in several wells, nowhere has its lowermost contact at that unconformity been cored. However, the uppermost contact has been cored in a number of wells and it is everywhere extremely sharp. In well 8, the contact is also extremely irregular, with re-entrants that are infilled by sediment of the overlying Unayzah B member (Figures 5b and 6f). Beneath that contact, the uppermost one foot (30 cm) of Unayzah C member displays a high degree of brecciation, with a network of abundant, intersecting clay-lined fractures (Figure 6f). This is interpreted 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 (Figures 5a and 5b). However, in well 11 it is directly overlain by distinctive facies of the Unayzah A member (Figure 5c).

Discussion

It is clear that the Unayzah C member is characterized by: (1) an abundance of structural features, that are not observed in the Unayzah B member (or Unayzah A member) (Figure 5); (2) a very sharp upper contact, that locally is associated with some degree of pedogenesis; and (3) it can subcrop either the Unayzah B or the Unayzah A members. This evidence points strongly to the upper surface of the Unayzah C member being an unconformity, representative of an unknown, but probably significant period of time. Figure 7 is a stratigraphic section, with the top of the lower Unayzah as a datum, showing the unconformable nature of the contact at the top of the Unayzah C member.

The stacked beds of upward-fining sandstones that dominate the Unayzah C member display the characteristics of high-energy, braided stream channel deposits, and have been interpreted as such in the earlier discussion. Taken in isolation, such rocks convey no relationship per se to deposition.
Figure 7: Stratigraphic sections (see Figure 1a) showing the thickness variations and continuity of the Unayzah C member, in relation to the Unayzah B member and related deposits. Note the extent of downcutting into the Unayzah B by the pre-Khuff unconformity in wells 2, 3 and 4.
in a glacially dominated setting. However, the abundance and nature of post-depositional structural dislocation (shear zones) may be of considerable relevance in that regard. This issue can be more effectively discussed following an assessment of the Unayzah B member and associated deposits of the uppermost lower Unayzah, which follows below.

SEDIMENTOLOGY OF THE UNAYZAH B MEMBER AND ASSOCIATED DEPOSITS

In contrast to the Unayzah C member, which displays a very distinctive wireline log signature (Figure 3), the Unayzah B member has such a highly variable log signature from well to well that application of this criterion alone for its recognition has historically proved extremely difficult and highly ambiguous. This at times has led to serious miscorrelation of this important stratigraphic unit. In the present study, it was clear from examination of the available cores that have penetrated the Unayzah B member that the variability of its wireline log signature is singularly related to a very high degree of variability among its component depositional facies. Although in this study the sample wells are separated by very great distances (Figure 1a), we believe that from the analysis of the cores, and its integration with wireline log data, it is possible to characterize this stratigraphic unit, such that we can gain a firm understanding of its origins, and of its likely distribution (architecture) in the subsurface. From the 1,355 ft of Unayzah B core examined, a number of depositional facies have been identified in both sandstone and siltstone that represent a range of depositional environments. Those include periglacial (permafrost) features, syn-glacial tectonic deformation and deposition, and a variety of pro-glacial and post-glacial depositional settings.

Sediment Fracture Fill Features (Periglacial Deformation)

Description

In well 4, core recovery shows that the Unayzah B member is only 26 ft (7.8 m) thick (Figure 8). It rests directly upon the pre-Unayzah unconformity, above graptolitic shales of early Silurian (Rhuddanian) age (M. Howe, written communication, 2005). Abruptly overlying the unconformity is an interval about two feet (0.6 m) thick dominated by elongate, flat pebble-sized clasts of black shale and abundant dispersed granules and small pebbles of quartz and granite. This conglomerate is in turn overlain by about three feet (0.9 m) of fine- to medium-grained sandstone. Laminations in this sandstone are laterally truncated by a pronounced, very sharply defined vertical boundary that extends downwards through the sediment for about 2.5 ft (0.75 m) (Figure 8, 7-10 ft). Adjacent to that vertical contact, the rock comprises a poorly sorted admixture of sand, and centimetre-sized mudclasts that have a generally horizontal orientation.

Figure 8: Core log through the Unayzah B member in well 4, showing the pre-Unayzah unconformity (PUU) with the underlying Silurian shales, and the (unknown) loss of section above as a result of erosion at the pre-Khuff unconformity (PKU). In particular, note how, between 7.5 and 10 ft there occur deep cracks that are infilled by lumps of sandstone and mudstone.
**Interpretation**

It appears that the sharp, vertical boundary represents a brittle crack of some sort, down which a variety of debris (sand and mudclasts) has fallen. It is tentatively interpreted as a frost contraction wedge in a periglacial setting. The sandstone was deposited, and then frozen. The freezing caused fracturing of the sediment, and that fracture was subsequently infilled by younger sands and mudclasts. Similar features are common in modern periglacial settings (French, 1996; Ruegg, 1983), and have been recorded in Proterozoic glaciogenic sediments from Greenland by Moncrieff and Hambrey (1990).

It is recognized that some caution should be exercised in expressing this interpretation. Burbridge et al. (1988) have demonstrated that features resembling ice-wedge casts in late Pleistocene (late Quaternary) subaqueous outwash near St. Lazare, Quebec, Canada are more correctly interpreted as water-escape phenomena related to sediment collapse, consequent upon the melting of entrapped ice within the outwash sediments. Worsley (1996) discussed such potential misidentifications, and suggested criteria for the identification of ice-wedge casts versus water-escape features. Among those criteria is the ability to demonstrate a polygonal geometry to the inferred ice-wedge casts in plan view (Worsley, 1996): clearly, meeting such criteria on the basis of core studies is not possible. Notwithstanding these caveats, the feature described above from the Unayzah B member in well 4, occurring in close proximity to the pre-Unayzah unconformity, and in association with other features at the same general stratigraphic level that are ascribed to deposition within a glacial environmental setting (see discussions below), is considered to be a reasonable candidate for infill of periglacial fractured ground. This is particularly so given the lack of dewatering features that might suggest upward flow of fluids through the infill detritus.

**Stratabound, Internally Deformed Deposits (Push Moraines)**

**Description**

The lower Unayzah in well 7 was cored from its upper contact with the Unayzah A member, to below the top of the Unayzah C member, and the described section is reproduced in Figure 9. In the lower part of this interval, the lower Unayzah in well 7 was cored from its upper contact with the Unayzah A member, to below the top of the Unayzah C member, and the described section is reproduced in Figure 9. In the lower part of this interval.

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**Figure 9:** Continuous core log from well 7, showing the uppermost lower Unayzah in that well, from its contact with the overlying Unayzah A member, to the highest beds of the Unayzah C member. Note: Cm indicates the locations of the proven occurrence of the ‘Cm equivalent palynofloral assemblage’ (J. Filatoff, written communication, 2004).
(namely the Unayzah B member, between 3 ft and 85 ft), two clearly identifiable sections are seen that are characterized internally by severe structural dislocation. Significantly, each of these intervals is bounded by in situ undisturbed sediment.

The lower of these is 15.5 ft (4.65 m) thick and occurs between 26.5–42 ft in Figure 9. It commences with a brown fine-grained sandstone that displays numerous low-angle shear planes (Figure 10a). This passes up into purple to green-purple variegated, argillaceous sandstones that are fine- to very fine-grained, but also contain an abundance of dispersed grains of coarse- and very coarse-grained sand as well as granules, pebbles and rare small cobbles (Figure 10b). This sediment is intensely disrupted and sheared throughout, with localized pods and streaks of coarse debris interfolded with finer-grained sediment. High-angle (subvertical), slicken-sided thrust planes are prominent.

The stratigraphically higher deformed unit in well 7 is seen between 55–68 ft (Figure 9). In its lower part, it comprises about 7 ft (2.1 m) of medium- to coarse-grained sandstone that contains abundant intraformational clasts, and is well-laminated. Those laminations have been dislocated and overthrust at a high-angle relative to each other (Figures 10c and 10d). Overlying these sheared sandstones is about 6 ft (1.8 m) of micaceous siltstone that contains abundant dispersed grains of fine- to coarse-grained sand. That siltstone also is characterized by numerous high-angle shear planes.

This uppermost, deformed interval occurs 55 ft (16.5 m) above the upper contact of the Unayzah C member in this well. Palynological samples from within it have yielded the only examples of the “Cm palynoflora assemblage” identified from core (J. Filatoff, written communication, 2004) (Figure 9). Specifically, in this case, the assemblage comprises middle Silurian acritarchs, chitinozoans and spores; spores of middle and latest Devonian age; middle to late Tournaisian (early Carboniferous) spores; and spores and monosaccate pollen of post-Visean Carboniferous age. It is thus very slightly different from the “Cm palynoflora assemblage” as it was first described (see earlier discussion) and so in this well (well 7) it will be referred to as a “Cm equivalent palynoflora assemblage”. Since the samples were taken from core (as opposed to cuttings), the monosaccate pollen is confirmed to be an in situ element of the assemblage (J. Filatoff, written communication, 2004).

Interpretation

It has been noted above that these two intervals of severely deformed rocks are stratabound by undeformed sediments that can be demonstrated to be glaciogenic in origin (see below). It can be concluded therefore that they represent material that was deformed at, or very shortly after the time of deposition. They are interpreted as the product of glacial deformation, and specifically are identified as the preserved remnants of glacial push moraines.

Bennett (2001) has described how push moraines display a wide range of different morphologies at a range of scales from a few meters to features that extend for several kilometers. Specifically, Boulton et al. (1999) identified four broad categories of push moraines associated with increasing compressive stress. The style of deformation commonly involves either fans of imbricate thrusts, or superimposed sub-horizontal nappes produced by overthrusting (Figure 11). The smallest of these are no more than 16.4 ft (5 m) high (Figure 11a). They can be found in both terrestrial and subaqueous environments (Boulton, 1986; Boulton et al., 1999; Bennett, 2001). Their composition depends on the material available within the proglacial zone, but commonly consists of a mix of subglacial diamicton and a veneer of supraglacial clasts. Regarding the deformation features evident in such moraine ridges, it is significant that Kruger (1994) described the presence of several listric thrust faults and other small deformation structures within a push moraine in front of Slettjokull, Iceland.

With regard to the Unayzah B member in well 7, the deformed units do not exceed 15.5 ft (4.65 m) in thickness. Furthermore their composition (very poorly sorted sediment, i.e. diamicite, as well as the allochthonous “Cm equivalent palynoflora assemblage”), in addition to the noted occurrence of shear planes that pass downwards through the core from a high angle to a low angle (i.e. listric), all suggest that within that well, there are preserved the remains of two minor push moraines. This is further supported by their stratal associations with unequivocal glacial deposits (see below). The relationship of these moraine deposits to the overall glacial setting within the Unayzah B member is discussed in a later section.
Figure 10: Core photographs from well 7 showing features observed in the glacially tectonised facies of the Unayzah B member.
(a) Low-angle shear planes (S) truncating a variety of sedimentary laminations in sandstone (see Figure 9, 28 ft).
(b) Poorly sorted pebbly sandstone (diamictite) displaying a strongly sheared fabric (see Figure 9, 32 ft).
(c) Interval of sandstone exhibiting high angle, reverse faulted (thrust) dislocations (see Figure 9, 62 ft).
(d) Sandstone displaying overfolded laminations, cut by high angle normal fault (see Figure 9, 58 ft).
In the cores from wells 2 and 3 (Figure 1a), the Unayzah B member is seen directly to overlie rocks of early Paleozoic age (i.e. the Unayzah C member is not present in those wells). It is 40 ft (12 m) thick in well 2, and 65 ft (19.5 m) thick in well 3. In each well it consists of very poorly sorted, fine- to coarse-grained sandstones that contain rare, dispersed pebbles, and are characterized by an abundance of small-scale faults and low-angle shear planes (Figure 12). In neither well is this deformation visible in the subcropping formations. This extensive intra-formational deformation of the Unayzah B member in these wells is attributed to the action of ice, but the greater thicknesses of sediment involved suggest that in these cases greater or more permanent masses of ice may have been involved. This is discussed further in a later section.

Massive, Very Poorly Sorted Pebbly Siltstones (Diamictite)

Description
The term diamictite is used here to describe sedimentary rocks that are essentially argillaceous siltstones or very fine-grained sandstones, but within which there is an abundance of dispersed (‘floating’) coarser-grained detritus. They are very commonly observed within the Unayzah B member in the Saudi Arabian subsurface, and occur in wells 1, 2, 3, 4, 5, 7, 10 and 12. In some cases, they are severely deformed (e.g. wells 2, 3 and 7: see previous discussion; Figures 10b and 12) as a result of being incorporated in push moraines. They are generally grey-green in colour, but in places they can also be reddish-brown (e.g. wells 1 and 3). In the present study, the diamictites range in thickness from about 6 ft (1.8 m) in well 10 (Figure 13a, 44.0–50.5 ft) to 14 ft (4.2 m) in well 12 (Figure 13b, 7–20.5 ft), to over 200 ft (60 m) in well 5 (Figure 13c). In the latter well, they are grey-green in colour, and for the most part massive, only displaying any stratal fabric within the lowermost few feet (but see below). They are extremely poorly sorted, comprising a ‘host rock’ of very fine-grained, argillaceous sandstone within which occurs an abundance of well-rounded to subangular, dispersed grains of medium to very coarse quartz sand (Figure 14a), as well as up to 5% coarser material including granules and pebbles of granite (Figure 14b), quartz, feldspar, black chert, grey siltstone, sandstone and mudstone. Rare examples of cobble-sized detritus of fine-grained sandstone are also observed (Figure 14c). The lowermost five feet (1.5 m) of diamictite in the core in well 5 shows a pronounced, laminar fabric (cm scale) (Figure 13c, 4–9 ft). It overlies a thin grey mudstone, which itself caps a thin
sandstone, one foot (0.3 m) thick, that appears brecciated and displays elongate, angular ‘clasts’ and locally highly contorted (folded) bedding (Figure 13c, 3-4 ft; Figure 14d).

Interpretation
Interpretation of these deposits almost inevitably invites controversy. In the Unayzah B member of central Arabia, both Senalp and Al-Duaiji (1995) and Aktas et al. (2000) have interpreted red-colored, matrix-supported conglomerates (i.e. diamictites) as subaerial debris flows deposited, respectively, within canyons or upon alluvial fans. However, Senalp and Al-Duaiji (2001) illustrated very poorly sorted, matrix-supported conglomerates from their informally defined Jawb formation, and interpreted them as glacial diamictites. Massive diamictites similar to those described above from well 5 have been documented from the coeval Al Khlata Formation in Oman (Levell et al., 1988) and interpreted as tillites. However, those authors also acknowledged that non-glacial diamictites might occur, for example as debris flows related to meltwater deltas. Aitken et al. (2004) have more recently concluded that tillites sensu stricto do not occur within the Al Khlata Formation, and that the diamictites are instead entirely either debris flows or rain-out in origin. Visser (1982) has described upper Carboniferous glacial deposits of the Dwyka Formation in South Africa as containing a variety of types of diamictite that he interpreted as basal tillites, proximal and distal waterlain tillites and reworked tillites. Moncrieff and Hambrey (1990) studied similar rocks, identifying tillites, waterlain tillites and debris flow facies within the Proterozoic glaciogenic Tillite Group of Greenland. Those authors conceded that ‘there are numerous cases in which the interpretation remains open to question’. They did suggest, however, that inhomogeneities inherent to subglacial and waterlain tillites might be destroyed during debris flowage, leading to a much more homogeneous deposit (Moncrieff and Hambrey, 1990).
The origin of the very thick, apparently massive and homogeneous diamictite at well 5 might be best interpreted by consideration of those sediments immediately underlying it. The lowermost few feet of the diamictite have been described as displaying a well-developed laminar fabric (Figure 13c, 4–9 ft). Furthermore the ‘brecciated’ sandstone that is present near the base of the cored interval in this well (Figure 13c, 3–4 ft; Figure 14d) is of relevance. The brecciation and folding observed in this deposit is not considered to be due to erosive, ‘rip up’ processes. Rather, close examination suggests that this disruption is more due to post-depositional, explosive fluidization forces contained within the sandstone bed. It is likely that the ‘brecciated’ sandstone, having been deposited as a sublacustrine, gravity-flow sand, was then rapidly buried beneath a thin glacio-lacustrine siltstone. This thin siltstone horizon acted as an effective seal to the sandstone, preventing normal dewatering and creating an overpressured environment within it. Subsequently, instability at the lake margins triggered remobilization of a very large quantity of poorly sorted sediment, and this flowed very rapidly as a single large debris flow to the lake bottom. The well-laminated nature of the lowermost few feet within the diamictite indicates the development of a pronounced traction carpet within the lower levels of the flow. The impact of this homogenised debris flow deposit upon the substrate
initiated internal explosive disruption within the overpressured sandstone, and blanketed the lake floor as the 'massive diamictite' observed in the well 5 core.

In well 10, a massive diamictite deposit, 6 ft (1.8m) thick, (Figure 13a, 44.0-50.5 ft) is located at the base of an interval of siltstones and claystones that are interpreted below as lacustrine deposits. It therefore seems reasonable to interpret that diamictite also as a lake bottom debris flow deposit. Similarly, in well 12 a massive diamictite, 14 ft (4.2m) thick, occurs beneath an interval of stratified diamictite (Figure 13b, 7-21 ft) and is therefore interpreted as a sublacustrine debris flow deposit.

**Interstratified Pebbly Siltstones and Laminated Mudstones: Stratified Diamictite**

**Description**

Representatives of this distinctive facies have been recorded in core from well 4 (Figure 8, 19–20 ft), well 7 (Figure 9, 68–85 ft), and well 12 (Figure 13b, 20.5–28 ft). It occurs in composite units up to 17 ft (5.1 m) thick. It is heterolithic in character, and comprises units up to 6 inches (15 cm) thick of very fine-grained sediment (silty mudstone) interstratified with thin beds (mm- to dm-scale) of poorly sorted pebbly siltstone material. In well 7 the fine-grained sediment comprises grey (or locally red), extremely fissile claystone that is itself interlaminated on a scale of a few millimeters to a few centimeters with grey, argillaceous silty mudstone (Figure 15a). Dispersed grains of coarse to very
coarse sand are only very rarely observed. Palynological analyses of these laminated mudrocks have thus far failed to demonstrate that they possess any marine affinities (J. Filatoff, personal communication, 2004). In well 12 these silty mudstone sediments are also associated with very fine-grained sandstones that display sets of well-developed current ripple cross-lamination (Figure 15b). These contain dispersed granule- and small pebble-sized clasts of very poorly sorted sediment.

Associated with the laminated mudrocks are interbeds of poorly sorted sandy to pebbly mudstone, ranging in thickness from a few millimetres to about 15 cm, and occurring as discrete types. Type 1 beds (Figure 15c) are 0.5 to 10 cm in thickness, and may display crude internal partings. They have indistinct upper and lower boundaries. They consist of silty mudstone within which occur abundant dispersed grains of very fine- to very coarse-grained sand, as well as rare dispersed granule-sized clasts of quartz, granite and rare feldspar. Significantly, they also commonly contain distinctive pelletoid clasts of material that is itself very poorly sorted (diamictitic) in nature. These lithic clasts range in size from a few millimeters (Figures 15b and 15d) to 15 cm (Figure 15e), and in places show diffuse or ‘ragged’ edges (Figure 15e). They are commonly flattened and elongated parallel to bedding. In well 12 a very large lithic clast of this type is associated with deformed bedding (Figure 15e). Type 2 beds are seen in wells 4, 7 and 12. They are 2–12 inches (5 to 30 cm) thick, with sharp upper and lower boundaries (Figure 15f). They comprise very poorly sorted debris ranging in grain size from medium sand to small pebbles. Those clasts do not display any preferred orientation within their host beds, wherever they are identified.

**Interpretation**

The very regular alternation of the laminated claystone and silty mudstone lithologies suggests a possible seasonal influence on their sedimentation. In this context, the word ‘seasonal’ is used to imply fluctuating climatic conditions: there is no evidence to specify the duration of periods of seasonal similarity. Mackiewicz et al. (1984) described interlaminated glaciomarine sands, silts and muds from Muir Inlet in Alaska, and attributed their origins to meltwater streams discharging at subglacial and ice-marginal positions to form overflows, interflows and underflows. Ice-rafted sediment was also identified (Mackiewicz et al., 1984). In the Unayzah B deposits described above, the thin siltstone laminae can be attributed either to warmer weather (‘summer’) suspension fallout in a glacio-lacustrine environment, or to deposition by low density turbidity currents. The finer-grained, extremely fissile claystones more likely represent settling of very fine-grained clay-sized material from the lacustrine water column during periods of otherwise restricted sediment input to the lake (e.g. ‘winter’). Whether or not these inferred seasonal variations represented annual (i.e. ‘varved’) fluctuations per se is not possible to determine (see above). Similar laminated mudrocks with an inferred seasonal origin have been described from many other ancient glacial deposits, including the Al Khlata Formation of Oman (Levell et al., 1988) and the Dwyka Formation of South Africa (Visser, 1982).

The identification of Type 1 and Type 2 diamictites within these rhythmically laminated silty mudstone deposits is crucial to the overall interpretation of a glacial setting for this facies. In the Type 1 beds described above, the character of the diamictite, particularly the diffuse nature of the bed boundaries, is suggestive of rainout through the water column of debris derived from floating icebergs on the surface of the water body, probably during warm season meltout. The identification of pelletoid lithic clasts is of particular importance. Ovenshine (1970) observed similar phenomena in a modern setting at Glacier Bay, Alaska. He concluded that such pellets derive from the freeing of sediment masses from between clear ice crystals by melting of the enclosing ice. Individual pellets are soft and plastic when wet, and friable when dry, but in both states they maintain a palpable coherence (Ovenshine, 1970). The same author recognized similar lithic clasts in the glacial Proterozoic Gowganda Formation of Canada. There, they were flattened and elongate to the bedding direction, and in addition they were seen in thin section to exhibit diffuse margins, very similar to the character of the clasts described above from the Unayzah B member. Both of these observations are strongly suggestive that the pelletoid lithic clasts were to some extent unconsolidated when deposited. Furthermore, it has been suggested (Ovenshine, 1970) that, inasmuch as till pellets can be recognized in ancient rocks, they uniquely identify the existence of glacier ice very near to the environment of deposition. Till pellets have been identified in ancient glaciogenic sediments from Greenland (Moncrieff and Hambrey, 1990), South Africa (Visser, 1982) and Oman (Levell, et al., 1988). In contrast to the Type 1 deposits
Figure 15: Core photographs showing features related to the stratified diamictite facies within the Unayzah B member.

(a) Example of the finely alternating, very fine-grained claystones and silty mudstones (laminites) that comprise the ‘background’ sedimentation to the stratified diamictites. Note the delicate, very fine (mm scale) lamination in the rock (well 7).

(b) Very-fine-grained, ripple cross laminated sandstone with anomalous granule and small pebble-sized clasts of diamictitic material (till pellets) (arrowed). These larger clasts are interpreted as dropstones (well 12).

(c) Fine-grained glaciolacustrine laminites with thin (2 cm) bed of (Type 1) very poorly sorted diamictite (just above the arrow). Note the extreme fissility in the lower part of the laminites subfacies (well 7).

(d) Type 1 stratified diamictite showing sub-centimeter scale interbedding of (1) very fine-grained sandstone, and (2) poorly sorted diamictite with discrete, small pebble-sized clasts of diamictitic material (till pellets) (arrowed) (well 12). See text for discussion.

(e) Cobble-sized clast of diamictitic material (till pellet) in Type 1 stratified diamictite from well 12. Note the irregular, diffuse edges to the till pellet.

(f) Type 2 stratified diamictite from well 12. Note the sharp, loaded lower contact with flame structure (arrowed), and the sharp upper contact, suggesting a debris flow origin for this bed.
discussed above, the Type 2 diamictites have sharp, loaded, lower bed boundaries (Figure 15f); it thus seems more likely that they represent deposition by debris flows in a sublacustrine setting.

Thus, it appears that the stratified diamictite facies that occurs within the Unayzah B stratal unit represents a subaqueous (probably sublacustrine, based on the negative palynological evidence), glacially influenced depositional setting, within which highly regular, ‘seasonal’ deposition of very fine-grained sediment took place. Overprinted on that depositional pattern was the seasonal rainout of material derived from floating ice, including liberated lithic ‘till pellets’, as well as periodic influx by sublacustrine debris flows.

Non-Stratified Pebbly Siltstone: Rainout Diamictite

**Description**

In well 8 the Unayzah B member directly overlies the supra-Unayzah C unconformity, where it is represented by a 2 ft (60 cm) thick diamictite (Figure 5b, 58–60 ft). The rock is mud-supported, very poorly sorted and displays no internal stratification. It contains abundant dispersed grains of fine- to very coarse-grained sand as well as rare dispersed granules and small pebbles of quartz and sedimentary rock fragments. In one case, a small pebble, 1-cm-long, is seen near the top of the bed with its long axis oriented perpendicular to bedding (Figure 16a). In the lower part of this diamictite bed, indistinct mottling is observed that is suggestive of bioturbation. Similar mottled diamictites are seen in well 7 (Figure 16b), that pass upwards with a ‘sharp gradation’ into finer-grained mudrock displaying more pronounced fissility, with only very rare, ‘floating’ grains of sand.

**Interpretation**

Visser (1982) has described a number of different types of glacial diamictites from the Carboniferous Karoo sediments of South Africa. Among those, he identified rocks that contain large clasts with their long axes perpendicular to bedding. He interpreted that feature as supporting an origin by melt-out from floating ice. The diamictite recorded from the Unayzah B member in well 8, although very different in scale, is similarly interpreted as a water-lain deposit consequent on rainout from melting icebergs in a glacial lake. The alternation of similar types of diamictite in well 7 with clast-poor, fissile mudrocks may indicate a seasonal nature to the deposition of the diamictite. This is supported by the recognition of probable bioturbation in those rocks. Thus, during relatively warm periods, coarse-grained detritus was released from melting ice floes in a glacio-lacustrine setting; having settled upon the lake bottom the sediment was inhabited and bioturbated by organisms that were more suited to the relatively mild environmental conditions. When harsher conditions prevailed, sediment rainout was reduced to a minimum, faunal activity virtually ceased and sedimentation was reduced to suspension settling of very fine-grained silts and muds.

Multistorey Graded Sandstones: Glacio-lacustrine Gravity Flow Deposits

**Description**

In well 9, a 50 ft (15 m) thick mudstone (uncored, but which yielded the original, distinctive ‘Cm palynoflora assemblage’: see earlier discussion) lies directly upon sandstones of the Unayzah C member (Figure 17a), and is abruptly overlain by a 230 ft (69 m) thick interval of distinctive, fine- to very fine-grained sandstones. The sandstones occur in beds that are 1–5 ft (0.3–1.5 m) thick, have sharp, commonly erosional, basal contacts and in many cases are clearly graded (Figure 17a). They display an abundance of fluid escape structures, dominated by elutriation pillars and dish structures (Figure 18a). From the cored interval, it is clear that these sandstones are organized into (at least) two upward-thinning and fining bedset packages, 35 and 55 ft (10.5 and 16.5 m) thick, respectively (Figure 17a).

In well 10, there occurs a sequence of moderately sorted, medium- to coarse-grained, graded sandstones that similarly display sharp, erosional basal contacts (Figure 13a, 0–25 ft). One of those sandstone beds contains an angular, cobble-sized sandstone clast in its uppermost part (Figure 13a, 17 ft; Figure 18b). Sharp-based, graded beds of medium- to coarse-grained sandstone have also been recognised in the Unayzah B member in well 12 (Figure 13b, 29–41 ft; 17c) and well 7 (Figure 9, 13–26 ft).
ft). Their depositional profile is similar to that described for wells 9 and 10. In well 13, there occurs directly upon the upper contact of the Unayzah C member a thin, grey/green siltstone that contains rare pebble- and cobble-sized clasts (Figure 17b, 28 ft) occurring either in isolation, or in small, mounded accumulations. This is overlain by 42 ft (12.6 m) of sharp-based, graded sandstones and pebbly sandstones (Figure 17b, 29–70 ft). The lower 25 ft (7.5 m) of that interval display upward-fining bedsets that are 4 to 9 ft (1.2 to 2.7 m) thick. They comprise sharp-based beds of medium-grained sandstone, characterized by planar laminae of medium-grained sand, that alternate with laminae rich in bed-parallel mudstone clasts (Figures 17b and 18d). Within each bedset, these strongly laminated beds pass upwards into an interval of thinner bedded graded sandstones (Figure 17b). The uppermost 18 ft (5.4 m) of this cored interval in well 13 is dominated by thin (1 to 25 cm) beds of sharp-based, graded, fine- to very fine-grained sandstones (Figure 17b, 52–70 ft). These may display an abundance of small, dispersed mudchips, or well developed climbing ripple lamination.

**Interpretation**

The graded sandstones described above from well 9 display all the characteristics of rapidly deposited, highly fluidized sediment gravity flows. The organization of the beds into thick, upward-fining and upward-thinning packages (Figure 17a) suggests a significant sublacustrine fan deposit, upon which broadly channelized depositional lobes were formed. The relatively coarse-grained, graded sandstones in well 10 are similarly interpreted as gravity flow deposits associated with a subaqueous fan. The large angular clast described from the upper surface of one of those sandstones is interpreted as a dropstone melting out of floating ice on the lake surface, and falling on to the upper surface of the gravity flow deposit on the lake floor beneath. In well 13, the siltstones with rare pebbles and cobbles that directly overlie the Unayzah C sandstones are interpreted as glacial lake sediments with dispersed dropstones. The immediately overlying graded sandstones that display mudclast-rich planar laminations represent very high energy gravity flow deposits. The organization of these rocks
Figure 17: (a) Core log from well 9, showing thick development of multiple beds of highly fluidised sediment gravity flows (as indicated by abundance of dish structure). Note how the beds are arranged in thick ‘packages’ that show a general upward thinning and fining trend. This suggests a level of architectural organisation upon a sublacustrine fan. Note also how this thick interval of gravity flow sandstones sits directly upon an interval (uncored) that has a high gamma-ray log signature, and which yielded the original samples of the ‘Cm palynoflora’ (see Owens et al., 2000). (b) Core log from well 13, showing smaller scale, upward thinning and fining packages in the Unayzah B member of high-density, mudclast-rich gravity-flow deposits (between 31 and 70 ft). Note also the thin interval of sandy siltstone containing floating pebbles (dropstones) located abruptly on top of the Unayzah C member (at 28 ft).
into upward-fining and thinning bedsets, as well as the evidence for very high energy deposition suggests that these deposits were laid down in channels in a proximal setting upon a sublacustrine fan. The uppermost, thinner-bedded and finer-grained graded sandstones of this depositional sequence in well 13 are more ‘distal’ in character, and are suggestive of an overall ‘transgressive’ depositional setting, possibly related to a progressive deepening of the glacial lake. The graded sandstones identified in wells 7 and 12 are similarly interpreted as the product of turbidity currents, related to outwash processes on sublacustrine ice-proximal fans.

### Ripple Cross-Laminated Sandstone: Sublacustrine Glacial Outwash

#### Description

This distinctive depositional facies has only been observed in core in well 10, where it consists of a single deposit, 20 ft (6 m) thick (Figure 13a, 25–45 ft). It occurs directly above the interval of graded, sublacustrine gravity flow sandstones discussed above (Figure 13a, 0–25 ft), and is overlain by a massive diamicite (Figure 13a, 45–50.5 ft). It comprises fine- to very fine-grained sandstone, characterized by multiple, thin (1–3 cm) lamina sets of climbing ripple-drift cross-lamination. These occur in three packages, ranging in thickness from 3 ft (0.9 m) to 11 ft (3.3 m) (Figure 13a). In the lower two packages, the lamina sets display a low angle of climb (less than 5 degrees), and only lee-side laminae are preserved (i.e. there are no preserved stoss-side laminae) (Figure 19a). As such, they are ascribed to Jopling and Walker’s (1968) Type A ripple-drift cross-lamination. Both of the lamina set packages grade sharply to a thin (5–10 cm) interval of dark grey, silty mudstone (Figure 19b). The uppermost lamina set of ripple-drift cross-lamination (Figure 13a, 42–45 ft) is characterized more by laminae that show complete preservation of stoss-side laminae as well as lee-side laminae, and wherein the angle of climb is much steeper compared with the Type A lamina sets (Figure 19c). These beds are more representative of Jopling and Walker’s (1968) Type B ripple-drift cross-lamination.

#### Interpretation

The dominance in well 10 of Type A ripple-drift cross-lamination (Jopling and Walker, 1968) within the lower two cosets of cross-laminated sandstones (each of which grade ultimately into silty mudstone) indicates sustained bedload transport of sediment that was superseded in each case by suspension fallout of fines in a lower energy setting. The Type B ripple-drift cross-lamination that characterizes the uppermost coset of cross-laminated sandstone suggests that the bedload transport rate of these deposits was significantly reduced in favor of deposition from increased fallout from suspension. Gustavson et al. (1975) have discussed the occurrence of various types of ripple-drift cross-lamination in a variety of glacially related deposits from the Quaternary of Canada. They have demonstrated how the ripple-drift lamina sets predominate as ‘summer layer’ deposits, and alternate with (or grade into) finer-grained ‘winter layer’ mudrocks. This was observed on glacio-lacustrine delta slopes, as well as in association with sublacustrine kame deltas laid down at the terminus of englacial tunnels on the bottom of glacial lakes (Gustavson et al., 1975). Rust and Romanelli (1975), working with Quaternary subaqueous esker fan outwash similarly suggested that graded, rippled units represent ‘proximal varves’, and therefore carry an implication of seasonality in their depositional history. These observations are highly relevant to the facies associations described above from the Unayzah B member in well 10.

It was noted above how the ripple-drift cross-laminated sandstones in well 10 lie directly on top of an interval of graded gravity flow sandstones (Figure 13a), wherein at least one example of a probable glacial dropstone (Figure 18b) has been observed. As has been discussed earlier, those gravity flow deposits most likely represent a subaqueous outwash fan on the bottom of a glacial lake. These graded cosets of ripple-drift cross-laminated sediment that occur directly on top of these sublacustrine fan sandstones are very similar to the subaqueous outwash deposits described by Rust and Romanelli (1975) and Gustavson et al. (1975). Their association with sublacustrine fan deposits laid down in a glacial lake supports an interpretation that they were therefore similarly deposited as subaqueous, glacio-lacustrine outwash. These distinctive rippled sandstones in well 10 are overlain by a six feet (1.8m) thick massive diamicite (Figure 13a, 45.0–50.5 ft), interpreted earlier to be a lake bottom debris flow deposit. That in turn is overlain by 19 feet (5.7m) of mudrock that is interpreted (below) to be a lacustrine deposit. The evidence thus points strongly to the ripple cross-laminated sandstones having...
been laid down as outwash debris on the bottom of a glacial lake. Significantly the noted occurrence of laminated mudrocks over ripple-drift cross-laminated sands in their Pleistocene examples led Gustavson et al. (1975) similarly to infer a sublacustrine origin for those sands (as opposed to a lake-marginal delta).

**Mudrock Facies: Distal Glacio-lacustrine Deposits**

**Description**

In well 10, there occurs an interval of dark grey mudrock, 19 ft (5.7 m) thick that directly overlies the six feet (1.8 m) thick diamictite described previously (see Figure 13a, 50.5–69.5 ft). The lowermost 10 ft (3 m) comprise a series of stacked, thin (cm-scale) muddy siltstone beds that are distinguished from each other in most cases only by very thin (mm-scale) claystone partings. Only rarely is it possible to identify features such as sharp, loaded bases with associated flame structures (Figure 19d) in these sediments. This lower unit fines upwards gradationally into decreasingly silt-prone, dark grey mudrock (Figure 13a, 60.0–69.5 ft). The uppermost 4 cm is a pale grey claystone.

**Interpretation**

The thick mudrock unit described above from well 10 comprises a lower interval of sharp-based siltstones that display the characteristics of very fine-grained gravity flow deposits (‘distal turbidites’); this passes upwards gradually into finer-grained, featureless mudstone. The latter is interpreted to represent suspension fall-out deposits in a large standing body of water. The association with directly subjacent sediment that passes upwards from dropstone-bearing gravity flow sandstones into ripple-drift cross-laminated sands and a moderately thick very poorly sorted (diamictitic) debris flow deposit (Figure 13a) implies that this overall sequence represents deposition of various types of sublacustrine glacial outwash in an overall ‘transgressive’ setting. That is to say, the lake became progressively deeper through time, as represented by the association of increasingly ‘distal’ sediment in the vertical profile.

It is clear that many of the other depositional facies thus far recognized from within the Unayzah B member represent deposition within glacially influenced lakes. For example, the stratified diamictites described from well 7 are intimately associated with laminated mudrocks that are ascribed to seasonal ‘cold climate’ deposition in a glacio-lacustrine setting. Similarly, the various occurrences of gravity flow sandstones described earlier have been interpreted as having been laid down in glacial lakes. This is true in well 10, as discussed above, as well as in well 13, where such sandstones directly overlie pebble- and cobble-bearing grey/green siltstones at the base of the Unayzah B member in that well (Figure 17b, 28 ft). Those siltstones have been interpreted as lacustrine deposits containing a number of dispersed glacial dropstones.

**Fluvial Sandstones**

**Description**

In well 8 there is an interval of sandstones that is about 30 ft (9 m) thick (Figure 20a, 29.5–60 ft), and which occurs about 18 ft (5.4 m) above the top of the Unayzah B member. The sandstones are fine- to medium-grained, and moderately sorted with subrounded to well-rounded grains. They occur in stacked beds, each ranging in thickness from 2 to 4 ft (0.6–1.2 m). The beds have sharp, erosional basal contacts, commonly with associated mudclast horizons (Figure 21a). The sandstones display low-angle trough cross-lamination (Figure 21a), which in places passes upwards into finer-grained sandstone showing ripple cross-lamination. At the top of this sandstone unit there occurs a red/pink variegated, poorly sorted, fine- to coarse-grained sandstone. It is severely disrupted, showing only very faint relict cross bedding, and fines upwards into a series of trough cross-bedded sandstones (Figure 20a, 51-60 ft).

**Interpretation**

This multi-storey unit of upward-fining, cross-bedded sandstones is interpreted as being fluvial in origin, comprising stacked channel deposits laid down in a low sinuosity to braided fluvial setting.
Figure 18: Core photographs showing examples of the sublacustrine gravity-flow facies from the Unayzah B.

(a) Sandstone from well 9 showing very well developed fluidisation features including dish structures and water-escape pillars.

(b) Core from well 10 (see Figure 13a, 17 ft) showing a cobble-sized sandstone clast in the upper part of a sediment gravity flow deposit. Note how the clast disrupts the bedding beneath, and how the overlying laminations are draped over it, strongly suggesting that this outsize clast is a dropstone.

(c) Gravity-flow deposits observed in well 12. Note the abrupt grain size variations, and subtle grading in the upper parts to the thin intervening siltstone laminae.

(d) Sharp-based, mudclast-rich, well-laminated and graded beds from the Unayzah B member in well 13.
Aeolian Sandstones

Description
This distinctive facies is recognised in wells 6 and 7. In well 6 it is 23 ft (6.9 m) thick, and occurs 13 ft (3.9 m) above the contact with the Unayzah C member (Figure 20b, 23–46 ft). The lower 17 ft (5.1 m) comprises beds of fine- to medium-grained sandstone, 2–4 ft (0.6–1.2 m) thick wherein the grains are

Figure 19: Core photographs of ripple-drift cross-laminated sandstones (see Figure 13a, 25-45 ft), and silty mudrock, from well 10.
(a) Low-angle climbing laminasets with only lee-side preservation of laminae (Type A of Jopling and Walker, 1968).
(b) Similar Type A laminasets in lower part of the photograph, grading upwards into dark, silty mudstone deposit.
(c) Climbing ripple-drift cross-lamination showing high angle of climb, and preservation of both stoss side and lee side laminae (Type B of Jopling and Walker, 1968).
(d) Silty mudrock deposits from well 10 (see Figure 13a, 50-60 ft). Note thin, darker inter-laminations, showing sharp contacts and flame structures (arrowed) near middle of photograph.
well-rounded and well to very well-sorted, and commonly frosted. The beds are characterized by very low-angle to flat, grain size-segregated laminations showing local inverse grading on a millimetre scale. In places they pass upwards into fine-grained sandstones that display well-developed adhesion ripple cross-laminations (Figure 21b). Locally, the sandstone beds are separated by thin (cm scale) dark grey siltstones (Figure 21b).

The uppermost 5 ft (1.5 m) of this sandstone interval in well 6 (Figure 20b, 41–46 ft) is a sharp-based, fine- to medium-grained sandstone. It consists of well sorted, well-rounded and frosted grains displaying high-angle, grain size segregated, cross laminations. In places, those cross laminations exhibit small-scale displacement indicative of synsedimentary faulting (Figure 20b, 42–43 ft; Figure 20: Core logs from wells 8, 6 and 7. These rocks supersede Unayzah B member glaciogenic sediments and comprise red siltstone (pink), and fluvial (orange) and aeolian (yellow) sandstones, terminated in places by paleosol (brown). See text for detailed discussion.)
Figure 21c). In the highest part of this bed the laminations are obscured, and disrupted by vertically oriented features that are interpreted as rootlets, and which are overlain by a 4 ft (1.2 m) thick deposit of the paleosol facies (qv) (Figure 20b, 46–50 ft).

Figure 21: Core photographs illustrating different sandstone facies within the red-beds associated with the Unayzah B.

(a) Sandstone in core from well 8 showing low-angle cross bedding in the lower fourth of the photograph, truncated by an angular scour surface (arrowed) that is overlain by a mudclast horizon. These rocks are interpreted as fluvial sandstones.

(b) Sandstones from well 6, showing well developed low angle to flat lamination, with the subtle development of adhesion ripple lamination in the upper fourth of the picture. Note also the thin beds of grey siltstone at the bottom and middle of the photograph. These rocks are typical of aeolian sand sheet deposits, passing up into damp, sandy interdune conditions as a result of fluctuating (rising) water table.

(c) Sandstones, also from well 6, showing high angle cross lamination indicative of aeolian dune cross bedding. Note the synsedimentary faulted laminations in the upper half of the picture, and the mottling in the lower part, suggestive of slumping. See text for discussion.

(d) Cross-bedded sandstone from well 7 (Figure 20c, 5 ft), showing similar mottling indicative of slumping, and a pronounced small lens of anomalously coarse (granule-sized) detritus (arrowed). See text for discussion.
Interpretation

The flat-laminated sandstone beds have the depositional characteristics of aeolian sand sheet deposits, such as have been well documented by Fryberger et al. (1979). The beds showing adhesion ripples represent damper, sandy interdune-like conditions, and the thin siltstone interlaminations are indicative of short-lived, shallow bodies of standing water (ponds) in an aeolian dominated environment. The arrangement of these subfacies relative to each other in the core suggests a cyclicity related to fluctuations in the paleo-water table.

The overlying cross-bedded sandstone is interpreted from its textural characteristics to be an aeolian dune deposit. The synsedimentary laminar dislocations may simply be the result of gravitational collapse on the dune slip face. However, it is possible that they relate to readjustment in response to melting of bodies of ice or snow that were trapped during dune migration, such as has been described from modern cold climate aeolianites by Ahlbrandt and Andrews (1978), and ancient analogues by Williams et al. (1985). The termination of this aeolian phase in well 6 is represented by the rooting that occurs at the top of the interpreted dune deposit.

 Deposits similar to the aeolian sandstone facies described above from well 6 have been recognised also in well 7 (Figure 20c, 53–72 ft). There, they are represented by about 17 ft (5.1 m) of flat-laminated sandstones of the aeolian sand sheet subfacies, with minor interbeds of the damp, sandy interdune subfacies. Those rocks occur directly overlying about 17 ft (5.1 m) of sandstones that show evidence of a more water-lain origin, such as well-developed climbing ripple cross-lamination (Figure 20c, 33–41 ft), and thus are more suggestive of deposition by sheet floods in a fluvial environment. Figure 20c shows that in well 7, this combined interval of alluvial, overlain by aeolian sandstones, is underlain by about 26 ft (7.8 m) of red, very fine-grained sandstones and siltstones. These rest upon a sandstone, two feet (0.6 m) thick, that is also considered to be aeolian in origin (Figure 20c, 5–7 ft). It displays high-angle cross laminations that in places are highly diffuse. They contain local nested concentrations of subrounded to subangular, granule-sized grains (Figure 21d). This sandstone exhibits an extremely sharp, pebble-strewn basal contact with the subjacent, grey glacio-lacustrine mudstone deposits. The latter display severe disruption in the form of cracking and shearing, and the aeolian sands above are seen to deeply penetrate the dislocations (Figure 22a). Given the glacial origin of the lacustrine mudstones, these dislocations are believed to result from frost action in a very cold climate. This interpretation, as well as the textural immaturity of the aeolian sandstone, leads to the tentative conclusion that the aeolian sandstone is also a cold climate deposit.

Red Sandy Siltstones: Floodbasin Deposits

Description

In many cored wells the rocks of the Unayzah B member are overlain by sandy siltstones and silty, very fine-grained sandstones that are generally red in colour, ranging from reddish brown to reddish purple (and locally red/green variegated) (Figure 22b). These have been recognized in well 7 (see above; Figure 20c, 7–33 ft). However, the thickest development of these rocks in core (70 ft, or 21 m) is seen in well 8 (Figure 20a, 60–80 ft and above; Figure 22b). Melvin et al. (2005a) presented the complete core log through these sediments, including their contact with the overlying Unayzah A member. There appears to be a cyclical development in well 8 (Figure 20a, 60-80 ft) wherein red sandy siltstones, displaying only very diffuse bedding characteristics suggestive of highly liquefied sediment, alternate with red, silty, very fine-grained sandstones. The latter rocks may show indistinct crinkly lamination, or very thin (cm-scale) beds with current ripple lamination (Figure 22b). These beds very commonly have abrupt upper contacts that are punctuated by thin downward-tapering cracks which in many places are infilled with grains of coarser sand. They are interpreted as desiccation cracks.

Interpretation

These fine-grained sediments were clearly deposited in a very low energy environment. The widespread red coloration indicates a highly oxidising setting, and they are interpreted from these characteristics, as well as associated facies, to have been deposited in a terrestrial environment.
dominated by low energy floodbasin conditions. Specifically, the cyclicity that is evident from the cores suggests deposition within shallow lakes that were regularly completely infilled to the point of exposure and desiccation.

**Paleosols**

**Description**
The uppermost part of the lower Unayzah is not everywhere represented by extensive development of the red silty sandstones described above. For example, in well 7 (Figure 20c, 72–76 ft), much thinner deposits are instead encountered that are only 4 ft (1.2 m) in thickness, and are red or red/purple/grey variegated in color. They are tightly cemented with silica, and consist of argillaceous, very fine-grained sandstones that contain an abundance of dispersed (floating) grains of medium- to coarse-grained sand. They are characterized by well-developed root traces (up to 30 cm long), cutans and other indicators of pedogenic development (Figures 20c and 22c). These rocks occur directly above the aeolian sediments described above from this well. Similar sediment is identified overlying the aeolian facies recognized in well 6 (Figure 20b, 46–49.5 ft).

**Interpretation**
These variegated, texturally immature rocks are interpreted as paleosols. In most places where they are recognized, they represent the stratigraphically highest-occurring facies within the lower Unayzah.

**STRATIGRAPHIC ARCHITECTURE OF THE LOWER UNAYZAH FORMATION**

**Unayzah C Member**
The foregoing discussion has described how the lower Unayzah is made up of two major units, namely a lowermost Unayzah C member and an overlying series comprising the Unayzah B member, and associated silty red-beds that contain varying amounts of terrestrial sandstone deposits. In places, the Unayzah C member is absent; where present, it displays highly variable thickness, and is everywhere found resting directly upon the middle Carboniferous pre-Unayzah unconformity (Figure 7). Its wireline log signature is reasonably consistent, generally displaying a very clean, low gamma-ray response with randomly occurring, thin spikes of much higher API value (Figure 3). Core studies detailed above show that the Unayzah C member comprises very quartz rich sandstones with minor pebble and cobble conglomerates that display many features characteristic of deposition upon a laterally unconstrained fluvial braidplain.

A very significant and distinguishing feature of this stratal unit is the occurrence within it of discrete zones that display intense, low-angle shear dislocation. In many places those zones are manifest on gamma-ray logs as intervals dominated by thin, high gamma-ray spikes. They also commonly display a distinctive, chaotic signature on image logs, which facilitates their identification in uncored wells. These shear zones are generally separated by thick sections of relatively undeformed rock. Also common within the Unayzah C member are irregular, stylolitized laminae that in many places are associated with high-angle fractures. The occurrence of all these post-depositional features is
limited in all the wells investigated to the Unayzah C member. This observation, as well as other corroborating stratigraphic evidence discussed previously, points strongly to the top Unayzah C surface being a significant unconformity. The distribution of the Unayzah C among the studied wells in the subsurface of east-central Saudi Arabia, and the unconformable nature of its lower and upper contacts is illustrated in Figure 7.

**Unayzah B Member and Associated Red-beds**

As opposed to the generally consistent log signature of the Unayzah C member, the log character of the Unayzah B member is highly variable. In effect, it can be used to only very limited extent for the purposes of identification and correlation of this stratal unit and its bounding surfaces in the subsurface. It is clear from the core studies discussed above that the Unayzah B member consists of a number of lithologies representing a large number of different depositional facies, and hence a disparate variety of depositional environments. Furthermore, it appears that in most of the wells examined in this study, the Unayzah B member is overlain by the persistent occurrence either of red, very shallow lacustrine siltstones and very fine-grained sandstones laid down in a terrestrial, alluvial floodbasin setting, or of similarly red-colored silty sandstones that are more characteristic of a paleosol environment. Even in uncored wells, these facies are suggested by wireline log character and ditch cuttings. The end of lower Unayzah deposition thus appears to have been characterized by low-energy to non-depositional conditions. This would suggest that the landscape at that time was extremely low-lying, or in geological terms, essentially flat. Therefore, in order to understand the distribution of the various lower Unayzah members and their component facies in a stratigraphic context, a stratigraphic section was constructed through the study wells using the top of the lower Unayzah as a datum (Figure 23).

It is clear from Figure 23a that the lower Unayzah above the Unayzah C member displays significant thickness variation across the study area and that in some locations (e.g. well 11) it is missing entirely. Where this interval is relatively thick, the lowermost parts are dominated by facies of the Unayzah B member that are indicative of glacio-lacustrine settings. Thus, for example, in well 9 the basal Unayzah B deposits are represented by about 50 ft (15 m) of mudrock (not cored, but inferred from the gamma-ray log), from within which the distinctive, and allogenic “Cm palynoflora assemblage” has been recovered (Owens et al., 2000) (see earlier discussion). Overlying these mudrocks is a 230-ft-thick interval of sandstones (Figure 17a) that were interpreted above as sublacustrine fan deposits. It is likely that the basal mudrock interval also represents resedimented detritus (?)debris flow) on the lake bottom, considering the nature of its palynomorph assemblage. Significantly, Owens et al. (2000) stated that their organic residues suggested “rapid deposition into a body of water with little current activity”. Sandy sublacustrine sediment gravity flows (turbidites) with local dropstones are also recognized in the lowest parts of the Unayzah B member in well 10 (Figures 13a and 23b) and well 13 (Figure 17b, 29–70 ft). In Figure 23b, the Unayzah B member in well 5 is much thicker than elsewhere, and appears to be almost wholly composed of diamicite, interpreted earlier as lake-bottom debris flows. In well 7, the Unayzah B member contains two discrete units of glacially tectonized push-moraine material that also yields palynological debris of the “Cm equivalent palynoflora assemblage” (Figure 9). These deformed units are interstratified with a variety of sediments interpreted to be subaquous, proglacial outwash deposits, including sublacustrine turbidites, massive diamicite and glacio-lacustrine stratified diamicites, as has been discussed earlier (Figure 9).

In the west of the study area, at wells 2 and 3, the Unayzah B member is represented only by intervals of severely deformed sediment (Figure 12). That deformation has been interpreted in an earlier section to be due to the action of ice. In these two wells, the deformed sediments are considerably thicker than the push moraine deposits seen in well 7, and unconformably overlie much older (early Paleozoic) rocks (i.e. the Unayzah C member is absent in these locations). They are overlain by sandstones that can be assigned to the late Permian, Basal Khuff Clastics (see Figure 2), i.e. the Unayzah A member is also absent in these wells. Therefore, the upper boundary of the Unayzah B member in each of these two wells is also unconformable (the pre-Khuff unconformity) (Figure 23a).

As discussed earlier, in the Unayzah B member in well 7, the highest part of the 83 ft (24.9 m) of glaciogenic deposits comprises glacio-lacustrine stratified diamicites (Figures 9 and 14c). They are abruptly superseded by 2 ft (0.6 m) of aeolian sandstone. The contact between these facies is
Figure 23: Stratigraphic sections across the study area (see Figure 1a), showing facies relations within and between the Unayzah B and the newly identified, un-named middle Unayzah member. In wells where this sediment package is thick, the lowermost parts of the section are dominated by glaciogenic deposits (Unayzah B member). These are overlain in those wells by non-glacial, terrestrial floodbasin deposits of the un-named middle Unayzah member. Where the overall sediment package is generally thin (e.g. well-6), it comprises only the latter depositional facies. Note the effects of the pre-Khuff unconformity in wells 2, 3 and 4. See text for full discussion.
extremely sharp, and is characterized by sand-filled cracks (Figure 22a; Figure 9, 85 ft). The aeolian sandstone is overlain by 26 ft (7.8 m) of red-brown, sandy floodbasin siltstones (Figure 9, 87–113 ft) that are followed abruptly by about 37 ft (11.1 m) of fluvial and aeolian sandstones, terminating in a well-developed paleosol. That paleosol marks the end of lower Unayzah deposition in that well (Figures 20c and 23a).

In contrast to the above, where the lower Unayzah is relatively thin (e.g. Figure 23a, well 6), it consists predominantly of red, sandy floodbasin siltstones that rest directly upon the Unayzah C member. Those siltstones are overlain by aeolian deposits that terminate in a paleosol that is only 4 ft thick (Figures 20b and 23a). In well 8, only the lowermost 2 ft (0.6 m) of the lower Unayzah sequence that overlies the Unayzah C comprises glaciogenic, rainout diamicrite. Those deposits are assigned to the Unayzah B member. Above that occurs a thin sandstone of probable fluvial origin that passes upwards into 10 ft (3 m) of red, floodbasin siltstones. Those are overlain by 30 ft (9 m) of fluvial sandstones, followed by about 65 ft (19.5 m) of red sandy siltstones and silty very fine-grained sandstones that were deposited in a fluvio-lacustrine (floodbasin) environment (Figures 20a and 23a).

It thus appears that that part of the lower Unayzah which overlies the Unayzah C member can itself be subdivided into two stratal units, each with its own distinctive depositional characteristics. The lower of these units is the Unayzah B member per se (sensu Ferguson and Chambers, 1991), and is intrinsically highly variable in thickness (Figure 23), and discontinuous in its distribution. It comprises depositional facies that reflect a close association with glacial processes, including ice-contact deposits such as push moraines, and subaqueous, glacial outwash facies. The latter include ice-proximal, glacio-lacustrine gravity flows of several types, as well as relatively ice-distal ripple-drift cross-laminated sandstones, glacio-lacustrine mudrocks and rainout deposits that derived originally from glacio-lacustrine ice floes. In this study, the Unayzah B has been identified in wells 1, 2, 3, 7, 8, 9, 12 and 13.

The upper of the two units recognised above is herein identified as an ‘un-named middle Unayzah member’ of the lower Unayzah. It is more continuous than the Unayzah B member, and comprises fine-grained red-bed facies, and sandstones that in general represent continental fluvial and/or cold climate, aeolian, terrestrial depositional settings. The boundary between the Unayzah B member and the un-named middle Unayzah member therefore represents an abrupt shift from glacio-lacustrine sedimentation to cold climate terrestrial sedimentation, and marks a shift from discontinuous facies belts to more continuous rock units (Figure 23). It appears therefore that it represents a disconformable surface. In several places, the uppermost deposits of the un-named middle Unayzah member are represented by well-developed paleosols. These are suggestive of an extended period of non-deposition, which in turn implies that the boundary between the un-named middle Unayzah member and the overlying Unayzah A member is also a disconformity of some significance. This supports the suggestion by Melvin and Heine (2004) that the onset of Unayzah A member deposition heralded a significant shift in climatic conditions (to increased aridity) in this part of the Gondwanan continent in early Permian times. This view appears to be supported also by palynological evidence presented by Stephenson et al. (2003). It is important to recognise that these paleosols at the top of the un-named middle Unayzah member are not in any way related to the widespread paleosols that occur at stratigraphically much higher levels within the Unayzah Formation. Those younger soil horizons occur at, and tend to characterise the rocks at the top of the Unayzah A member, immediately below and above the pre-Khuff unconformity (Melvin et al., 2005b). Their nature and distribution will be the subject of a future paper.

**STRATIGRAPHIC COMPARISONS WITH OMAN**

Stephenson et al. (2003) have recently erected a palynological zonation scheme that attempts to establish biostratigraphic correlations between the various component stratal units of the Unayzah Formation (and the basal Khuff Formation) in Saudi Arabia, and the Al Khlata and Gharif formations of Oman (Figure 2). The lithostratigraphy of the Permian-Carboniferous of Oman has been significantly advanced with the recent publication of detailed studies of both the Al Khlata and Gharif formations (Osterloff et al., 2004a, b). However, in Saudi Arabia any coherent understanding of the lithostratigraphy of the Unayzah has been limited thus far by the extreme variations in thickness.
of the formation, as well as the extreme variability (and consequent ambiguity) in the character of the conventional wireline logs throughout the formation. The present core-based study has clarified many of the reasons for this variability in wireline log response. These are principally due to the diverse number of depositional facies, particularly within the Unayzah B member, as well as the recognition of a number of widespread depositional disconformities within the Unayzah Formation as a whole. For example, similar facies variations are also observed within the Unayzah A member that historically have created significant problems in log-based lithostratigraphic correlation in that stratal unit (Melvin and Heine, 2004).

From all of the foregoing discussion, it is now clear that the lower Unayzah can be subdivided into a number of stratal units (i.e. the Unayzah B and C members, as well as the newly defined, unnamed middle Unayzah member) that are separated by surfaces of some stratigraphic significance. Consideration of those stratal units in relation to the biozones identified by Stephenson et al. (2003), and the various lithostratigraphic units identified in the Al Khłata and Gharîf formations in Oman by Osterloff et al. (2004a, b), suggests that some degree of correlation can be achieved between the Permo-Carboniferous rocks of Saudi Arabia and Oman.

The lowermost bounding surface of the Unayzah Formation is the pre-Unayzah unconformity. This is the erosion surface that was created following the middle Carboniferous tectonic events within the Arabian Plate, and which was significantly enhanced during early glacial advance phases of the late Paleozoic Gondwanan glaciation. The Unayzah C, where present, rests directly upon the pre-Unayzah unconformity. Extreme thickness variations reflect considerable paleotopography upon the unconformity surface, interpreted here primarily to be an indication of the severity of erosion by the Gondwanan ice sheets. Sparse palynological data suggest a late Carboniferous (late Moscovian-Gzhelian = late Westphalian-Stephanian) age for the Unayzah C member, and it has been assigned to palynological Zone OSPZ1 (Stephenson et al., 2003). The rocks are mineralogically mature, and represent deposition upon extensive, laterally unconstrained fluvial braidplains. Both the age determination and the nature of the depositional facies suggest a close comparison of the Unayzah C member with the lower part of the lower Al Khłata in Oman. Specifically, these rocks are considered equivalent to Al Khłata Depositional Sequence DS C30 and the lower part of DS CP of Osterloff et al. (2004a) (Figure 2).

The Unayzah B sits unconformably upon the top Unayzah C surface, or, if the Unayzah C member is absent, upon older Paleozoic rocks beneath the pre-Unayzah unconformity (e.g. wells 2 and 3, Figure 23a). It is early Permian (Asselian-Sakmarian) in age (Stephenson and Filatoff, 2000a; Stephenson et al., 2003; Stephenson, 2004) and is characterized by palynomorph assemblages of Zone OSPZ2 (Stephenson et al., 2003). It is represented by a great diversity of glaciogenic depositional facies (described above), ranging from glacially tectonized push-moraine deposits and ice-proximal sublacustrine turbidite fans and debris flows, to more ice-distal stratified diamictites and glacio-lacustrine mudrocks with dropstones. These characteristics suggest that the Unayzah B member is coeval with the upper part of the Al Khłata Formation in Oman. Specifically, it is considered equivalent to the upper part of Depositional Sequence DS CP, as well as DS P6 and DS P8, as defined by Osterloff et al. (2004a) (Figure 2). In particular, the stratified diamictites that occur at the top of the Unayzah B member in well 7 (Figure 9, 68–85 ft), and the glacio-lacustrine mudstone described above from well 10 (Figure 13a, 50.5–69.5 ft) are most probably equivalent to Al Khłata Depositional Sequence DS P8 of Osterloff et al. (2004a), which represents the Rahab Shale Member of the Al Khłata Formation of Levell et al. (1988) (Figure 2).

The contact between the Unayzah B member and the un-named middle Unayzah member is best displayed in core in well 7. There, it is seen to be extremely sharp (Figure 9, 85 ft; Figure 22a), and separates glacio-lacustrine mudrocks beneath from terrestrial floodbasin deposits above. This represents a significant basinward shift in depositional facies, and thus is considered to represent a significant stratigraphic surface, most likely a regional disconformity at the top of the Unayzah B member. Its geological significance is discussed in the following section. The terrestrial floodbasin deposits of the un-named middle Unayzah member are dominated by red-colored, fine-grained sediment that is heavily oxidized, and consequently notoriously barren of any biostratigraphic indicators. Dating of this member is thus extremely difficult to accomplish. However, the underlying dark coloured mudrocks at the top of the Unayzah B member have been equated to the Rahab Shale.
Member in Oman (see above). Stephenson et al. (2003) have shown how in Oman the Rahab Shale is overlain by the Lower Gharif Member, which is characterized by the Zone OSPZ3 assemblage. The same authors have suggested that in Saudi Arabia the Lower Gharif Member (or its equivalent) appears to be absent, and there is instead a hiatus separating the Unayzah B from the Unayzah A member (Stephenson et al., 2003, their Figure 2). More recently however, Stephenson (written communication, 2006) has acknowledged that in Saudi Arabia the OSPZ3 Zone might alternatively be placed “against some barren section”. Thus, the palynological evidence for the stratigraphic distinctions considered above may not be clear-cut. Their fuller understanding necessarily first requires a brief consideration of the Unayzah A.

The specific nature of the Unayzah A member is complex, and beyond the scope of the present study. It will be discussed fully in a forthcoming paper. In general, however, it has been reported as representing a significant change in climate relative to the underlying members of the lower Unayzah. Consequently, its lower contact has been interpreted to be a sequence boundary (Melvin and Heine, 2004). Furthermore, Melvin and Heine (2004) and Melvin et al. (2005a, b) have described the Unayzah A member as comprising sediments that were deposited in an arid environment dominated by aeolian and ephemeral fluvial facies. Specifically, Melvin et al. (2005a) have illustrated the relationship in core between the un-named middle Unayzah member of this paper and the Unayzah A member. The distinction is subtle, given that the contact between these rock units in some cases separates two accumulations of red siltstone facies (Melvin et al., 2005a, p. 248). However the sedimentological evidence exists to distinguish the two, and to identify the climate change referred to above. It is also known that in many wells in the Saudi Arabian subsurface the uppermost parts of the Unayzah A member, as well as the lowermost parts of the overlying Basal Khuff Clastics (see Figure 2) are characterized by well-developed paleosols (Melvin et al., 2005b).

The oxidized, continental nature of the Unayzah A member has resulted in notoriously poor recovery from most palynological samples. However, Stephenson and Filatoff (2000b) have described a palynological assemblage, which they identify as the in-house Saudi Aramco P3 Biozone. Those specimens were recovered from Unayzah A depositional facies in a small number of limited well sections in central Saudi Arabia. Stephenson et al. (2003, p. 483) have tentatively correlated that assemblage with their OSPZ3b and OSPZ4 zones. From the above summary, the combined accumulation of data, namely: (1) the palynological assemblage (albeit very limited in content and distribution); (2) a lower contact interpreted to be a sequence boundary (i.e. an unconformity); and (3) the continental nature of the facies, including an abundance of paleosols, all suggests that the Unayzah A member may be tentatively correlated with the Middle Gharif Member in Oman. This supports the suggested biostratigraphic correlation of Stephenson et al. (2003).

The above discussion is important in relation to the present paper, since it gives a regional stratigraphic context to the new, hitherto unrecognized stratigraphic unit within the Unayzah Formation in the subsurface of Saudi Arabia, namely the un-named middle Unayzah member. That unit lies between the Unayzah B member (equivalent in its upper part to the Rahab Shale in Oman, as discussed above), and the Unayzah A member (tentatively considered above to be equivalent to the Middle Gharif Member in Oman). The un-named middle Unayzah member lies between the Unayzah B and the Unayzah A member; the Lower Gharif Member lies between the Rahab Shale and the Middle Gharif Member in Oman. It is thus proposed that there is some equivalence between the un-named middle Unayzah member, and the Lower Gharif Member (specifically, Depositional Sequence DS P10: Osterloff et al., 2004b) in Oman. Angiolini et al. (2006) have shown from paleontological (fusulinid) evidence that the Haushi limestone of the uppermost Lower Gharif is Sakmarian (as opposed to Artinskian) in age. Associated terrestrially-sourced palynomorph data confirmed that the OSPZ3c sub-biozone (Stephenson et al., 2003) in Oman is therefore also Sakmarian in age (Angiolini et al., 2006). Clearly the implication is that the barren, un-named middle Unayzah member in Saudi Arabia may also be Sakmarian in age. It is acknowledged that there is no facies equivalence in this proposed correlation (Depositional Sequence DS P10 is generally marine: Osterloff et al., 2004b). However, in sequence stratigraphic terms the uppermost part of the Lower Gharif Member, namely the Haushi limestone, has been interpreted as a Highstand Systems Tract (Osterloff et al., 2004b). The paleosols that in places characterize the top of the un-named middle Unayzah member (described above) may represent the terrestrial lateral equivalent deposits of that Highstand Systems Tract. More work remains to be done to clarify the details of this interval in the Permian of the Arabian Plate. The above gross correlations...
between the lower Unayzah (Unayzah B and C members, and the new, un-named middle Unayzah member) of Saudi Arabia and the Al Khlata Formation and Lower Gharif Member in Oman are represented in Figure 2.

**DISCUSSION**

It was stated in the introductory section of this paper that one of the primary purposes of the study was to identify whether or not the lower Unayzah Formation in the subsurface of Saudi Arabia could be demonstrated to have had a glacial origin, given its age equivalence with rocks elsewhere on the Arabian Plate that display such characteristics. From the preceding description and discussion of the various depositional facies recognized in core, it is clear that the Unayzah B was laid down in a glacial setting. It remains to consider the relationships of the lower Unayzah Formation as a whole (i.e. the Unayzah C member, as well as the Unayzah B member and the un-named middle Unayzah member) in the context of the late Paleozoic glaciation that affected much of the Gondwanan continent at the time.

Caputo and Crowell (1985) have discussed how glacial centers migrated across the Gondwanan continent throughout the Paleozoic Era. They have described how, during the late Paleozoic Era, many ice caps and ice sheets came and went across Gondwana, beginning in the west, culminating in southern Africa during the late Carboniferous, continuing strongly in India and Australia in the Permian and dying out in eastern Australia and in Antarctica in early late Permian time. Studies of the sequence stratigraphy of Upper Mississippian carbonate ramp deposits in the Illinois Basin by Smith and Read (2000) have provided indirect evidence that the late Paleozoic Gondwanan glaciation commenced rapidly, and possibly as early as during the late Visean.

Contemporary glacial events on the Arabian Plate were confirmed by Helal (1965), McClure (1980) and Braakman et al. (1982), who provided evidence for a late Paleozoic glaciation in Saudi Arabia and Oman. Recent paleotectonic reconstruction studies by Stampfl and Borel (2004) show the northernmost extent of the Gondwanan ice sheet in middle Stephanian (Kazimovian) times confined to the southern part of the Arabian Peninsula (Figure 1b). Al-Husseini (2004) considers that the late Paleozoic Gondwanan glaciation on the Arabian Plate may have commenced in the middle Carboniferous (late Visean-early Namurian) and persisted for 30–45 million years until the early Permian (Sakmarian). Considerable uncertainty exists regarding the specific timing of the onset of the glaciation in Arabia, not least because of the possibility of a number of phases of glacial advance and retreat within its overall duration, and the consequent likelihood that older glaciogenic deposits may very well have been removed as a result of extensive reworking during later glacial advances. Osterloff et al. (2004a) have noted how the various depositional sequences that they identified in the Al Khlata Formation in Oman were deposited during many tens of millions of years, and that each one “represents only a fraction of the deposits of a single or a set of glaciation periods, including several ice sheet advances and their accompanying interstadials and interglacials”. The same authors have observed how the Permian-Carboniferous ice age lasted about fifteen times longer than the Pleistocene ice age in the northern hemisphere. Since during the Pleistocene ice age, the interglacial periods represented only about 10% of the duration of the total ice age, they have assumed that that proportion was similar for the late Paleozoic glacial event in Arabia (Osterloff et al., 2004a).

Significantly, the start of the Permian-Carboniferous glaciation in Arabia is close to the estimated age of the middle Carboniferous compressional tectonic event (Serpukovian-Bashkirian = Namurian-early Westphalian, 327-311 Ma) (Al-Husseini, 2004). It was that tectonic event that resulted in the pre-Unayzah unconformity, widely recognised in the subsurface of eastern central Saudi Arabia. The oldest sediments to be deposited upon the pre-Unayzah unconformity were the quartz-rich sandstones of the Unayzah C member. Earlier attempts to date the Unayzah C member have relied on its association with the “Cm palynofloral assemblage”. However, the present study shows that the Cm assemblage is a palynofacies dominated by reworked taxa and associated more with glacially influenced resedimentation within the Unayzah B (see Figures 7, 9 and 23). This implies that the Unayzah C member is actually somewhat older than has previously been thought, and may indeed have been deposited at a very early time consequent upon the formation of the pre-Unayzah unconformity. It is further implicit from this conclusion that deposition of the Unayzah C member commenced at a very early stage of the late Paleozoic glaciation.
Descriptions of the sediments that characterize the Unayzah C member have been presented above (Figures 5-6), and it was noted how their depositional features are characteristic of stacked, braided stream channel sandstones and conglomerates, within which occur rare, thin siltstone horizons. It is clear that these fluvial sediments have a very widespread distribution throughout the subsurface across the study area (Figure 7). Similar very extensive sands and gravels are identified within post-glacial outwash deposits associated with the several phases of retreat of the Pleistocene ice sheets in northern Europe. It is inferred that the Unayzah C coarse-grained sandstones and conglomerates analogously represent extensive fluvio-glacial outwash deposits associated with retreat phases of the late Paleozoic Gondwanan ice sheets.

Of significance with regard to the north European Pleistocene outwash deposits is the occurrence of an extensive line of associated end-moraine complexes known as the Rehburg Line (Figure 24), which extends over 500 kilometers from the North Sea in the west to Hanover, Germany in the east (Bennett, 2001). This marks the approximate extent of glacier ice during the Rehburg Phase (Drenthe advance) of the Saalian Glaciation (Van der Wateren, 1995). Several push moraine complexes have been documented along the Rehburg Line (Van der Wateren, 1985, 1987, 1994), wherein their architecture consists of a number of subhorizontal nappes that have been displaced horizontally (in some cases as much as 6 km), producing forms that are typically 15–25 meters thick, with aspect ratios of between 1:20 and 1:100 (cf Figure 11b). These nappes are bounded above and below by a number of shear zones (Bennett, 2001). The description of the Unayzah C member presented above has highlighted in a number of cored wells the recognition of significant shear zones, between which the rock is much less deformed (sheared). This evidence, considered in conjunction with the earlier conclusion that the top of the Unayzah C member represents an unconformity of some magnitude, suggests the following model for the evolution of the Unayzah C member.

Following the middle Carboniferous tectonic event and the near-coincident inception of the late Paleozoic Gondwanan South Polar glaciation, the ice ultimately extended across the southern part of the Arabian Plate to the vicinity of wells 13 and 14 in this study. That is to say, it spread to paleolatitudes at least as far north as the present-day location of the Central Arabian Arch and therefore significantly farther north than has been previously documented (e.g. Stampfli and Borel, 2004, Figure 1b). This glacial event was long-lived, and possibly persisted for some 30–45 million years, from the middle Carboniferous (late Visean to early Namurian) to early Permian (Sakmarian) times (Al-Husseini, 2004). Therefore, it seems likely that it involved a number of separate phases of glacial advance and retreat, similar to those documented from the Pleistocene of the northern hemisphere, as noted by Osterloff et al. (2004a, p. 65). Each of those retreat phases resulted in substantial volumes of fluvioglacial outwash sands and gravels being deposited across the area upon laterally unconstrained alluvial braidplains. During subsequent re-advances, the ice sheet progressed across the fluvi-glacial outwash of each preceding retreat phase. In the process it formed a number of glacially induced, push-moraine nappes, similar to those documented along the Rehburg Line from the Pleistocene of the North European Plain (Figure 24). Ultimately, this process created a thick pile of subhorizontal, superimposed units of fluvio-glacial sands and gravels, separated by distinct shear zones. Those glacially deformed sediments comprise the Unayzah C member in the subsurface of eastern central Saudi Arabia. The top Unayzah C unconformity is considered to represent the sub-glacial surface at the time of the final advance of the late Paleozoic Gondwanan ice sheet.

Eventually, climatic conditions ameliorated and the Gondwanan ice sheet commenced its final retreat. That event marked the onset of Unayzah B deposition. As the ice retreated, the topographic lows that it had carved out were infilled with meltwater, forming glacial lakes. These received large volumes of sublacustrine glacial outwash material in the form of turbidity currents (e.g. wells 7, 9, 10, 12 and 13), and debris flows (massive diamictites) representing remobilized till deposits (e.g. wells 5, 10 and 12). In some cases this sublacustrine deposition was probably enhanced by ongoing tectonic activity. For example, well 9 is located very close to, and on the downthrown side of a western bounding fault at Ghawar field. In that well the Unayzah B member displays a particularly enhanced depositional thickness, most of which is accommodated by the sublacustrine gravity flow deposits described earlier (Figure 23a). It seems likely that at times of maximum advance, glacial erosion utilized crustal weakness in the area, resulting in over-deepened hollows that later became very deep glacial lakes during the time of retreat. Sustained deposition of glacially derived sublacustrine gravity flows would have been enhanced by continued seismic instability in the area.
The glacial retreat was phased, at least in some locations. Thus in well 7, two minor readvances took place, evidence for which is seen in the two small push-moraine deposits identified within the Unayzah B member (Figure 9). It is pertinent to note that, with regard to these inferred readvances, the sediment deposited below the first readvance (i.e. between 13 and 26 ft in Figure 9) comprised proglacial turbidites, laid down upon an ice-proximal sublacustrine fan. The sediment between the readvances (i.e. between 42 and 55 ft in Figure 9) consists of massive diamictite. However, the deposits that overlie the push-moraine deposits of the second, and final, readvance (between 68 and 85 ft, Figure 9) consist of well-stratified diamictites, comprising alternations of very fine-grained laminites and thin rainout diamictites. These are suggestive of a much more glacially distal setting. The overall gradual retreat of the ice from the location of well 7 is thus well-documented in the progressively more ice-distal nature of the sedimentary units that occur interstratified with the respective readvance deposits. Similarly, the sequence of facies recorded in well 10 (Figure 13a) has been discussed earlier in terms of how it represents increasingly ice-distal sedimentation, and progressive deepening of the lake in that location. It is instructive to note that in the stratigraphic section (Figure 23), relatively thick glacio-lacustrine deposits are seen in wells 7 and 9, and only very thin, rainout diamictite (Figure 16a) is observed in the intervening well 8 (Figure 23a). This suggests that the landscape during deposition of the Unayzah B member was characterized by numerous lakes, which were separated by silled barriers that were only finally overtopped at the time of maximum flood (melt out).

In the west of the study area, at wells 2 and 3, the Unayzah B member is represented only by glacially tectonized sediment, and sits directly upon the pre-Unayzah unconformity (Figures 12 and 23a). It is possible, given the greater thickness of glacially deformed material in this western area, that the ice remained longer in this part of the Arabian Plate during the deposition of the Unayzah B member. However, this remains open to conjecture, since any conformably overlying sediments are not now present, as a result of the pre-Khuff unconformity which truncates the Unayzah B member at these locations (Figure 23a).

All of the sediments discussed thus far in this section are assigned to the Unayzah B member. It is clear that, by the end of deposition of this member, the landscape was dominated by an abundance of glacial lakes, representing widespread flooding by meltwaters following terminal retreat of the

Figure 24: Map of the northwest European plain showing the Rehburg Line of push moraines (green), associated with phases of glacial advance from the Fenno-Scandian ice sheet (see inset). Modified after Bennett (2001).
Gondwanan ice sheet. The contact between the Unayzah B member and the un-named middle Unayzah member is extremely sharp (Figure 22a), and may display frost-wedged cracks. Furthermore the sediments that comprise the un-named middle Unayzah member are very different in character from the glacio-lacustrine deposits of the Unayzah B member. They lack a strongly glacial signature, and are instead more typical of a low-lying, terrestrial setting, being dominated by red, sandy siltstones. In places, fluvial and cold climate aeolian sandstones are identified, although these do not appear to have a widespread extent (Figure 23). It thus appears that the end of glacio-lacustrine deposition of the Unayzah B member was marked by a significant drainage event. It is possible, albeit speculative at this stage, that the area was terminally drained as a result of the melting of a major ice barrier, effectively signifying the end of the Gondwanan glaciation in Saudi Arabia. Pertinent to this suggestion is the observation by Martini and Brookfield (1995) of a similar very sharp demarcation between clay-rich glacio-lacustrine rhythmites and overlying sand-prone sediments in Pleistocene deposits at the Bowmanville Bluffs in Ontario, Canada. They proposed that the widespread occurrence of this sharp contact and the nature of the overlying successions suggested that it was “not related to local erosion, but rather it may be associated with a sudden drop in lake level caused by retreat of the glacier” (Martini and Brookfield, 1995).

Moncrieff and Hambrey (1990) described a late Proterozoic glaciogenic succession in Greenland, and similarly observed a wide variety of depositional facies. Those included, not only glaciogenic tillites, debris flows, various glaciomarine deposits and a variety of ice-rafted sediments, but also terrestrial deposits including aeolian sandstones and evaporites. The marked change from glaciogenic deposits to facies that were essentially devoid of any glacial signature was attributed by Moncrieff and Hambrey (1990) to the response of glaciomarine sedimentation to landward retreat of the ice. Thus, once the ice sheet has retreated on to land, it follows that no further ice-rafting can occur, and the only means of transporting sediment from the ablating ice front to the sea is by carrying it in meltwater streams. ‘Normal’, terrestrial depositional processes (such as fluvial and aeolian transport and deposition) predominate, and the close proximity of an ice front is disguised (Moncrieff and Hambrey, 1990). In the case of the Unayzah B member, there is no unequivocal evidence of a marine component to the glaciogenic sediments. However, the succession is clearly dominated by subaqueous (lacustrine) deposits having strongly glacial affinities, and these are abruptly succeeded by sediments that display terrestrial, and apparently non-glacial characteristics. A single, dramatic drainage event would have the same effect on the depositional record of these rocks as the landward migration of a marine ice shelf appears to have had in the Proterozoic of Greenland.

CONCLUSIONS

The detailed description and analysis of over 2,277 ft of core from the Lower Unayzah sandstones of eastern central Saudi Arabia has confirmed that the effects of the late Paleozoic Gondwanic glaciation extended significantly further north on to the Arabian Plate than has hitherto been interpreted. The glacially-derived sediments extended at least as far north as the southern margins of the Central Arabian Arch. Initiation of glaciation may have occurred as early as Serpukhovian to Moscovian (Namurian to Stephanian) times, and the effects appear to have persisted through to early Permian (Asselian to Sakmarian) times.

During (probably several) retreat phases of the ice sheets in late Carboniferous times, deposition occurred of the braided fluvial sandstones that characterize the Unayzah C member of the Saudi Arabian subsurface. These were deformed during intervening glacial readvances, which led to the formation of a number of stacked, low-angle thrusts, push moraine features. The sheets of glacially thrust material are separated by discrete shear zones. This glacial episode was long-lived, and resulted in considerable sub-glacial deformation of the Unayzah C sedimentary pile, and the establishment of an unconformity surface at the top of the Unayzah C member.

In early Permian times, the final retreat phase of the Gondwanian glacial event was underway. This led to deposition of the Unayzah B member. This member has a highly variable thickness and is characterized by a variety of glaciogenic depositional facies. These include strongly deformed intervals that are stratabound, and display the characteristics of relatively small push moraines. These deposits indicate that the retreat of the ice sheet was not uniform and involved at least two
minor episodes of glacial readvances. Other characteristic facies seen within the Unayzah B member include: (1) ice-proximal outwash material in the form of either resedimented ‘massive’ diamictite (debris flows) or highly fluidized, sandy sediment gravity flows with dropstones that were probably laid down upon ice-proximal fans; (2) more ice-distal deposits including stratified diamictites, ripple cross-laminated sublacustrine outwash sandstones, glacio-lacustrine rhythmites and glacio-lacustrine mudrocks; (3) minor evidence for periglacial frost wedging and infill. The top of the Unayzah B member is extremely sharp, and appears in places to be characterized by a frost-wedged surface in glacio-lacustrine mudstones. It is considered to represent a disconformity, separating the Unayzah B member from the new, un-named middle Unayzah member, and indicative of a significant drainage event within a landscape dominated by glacial lakes.

The un-named middle Unayzah member is newly recognised in this study. It is more widespread and laterally continuous then the Unayzah B member, and is characterized by red, very fine-grained sandstones and siltstones representative of terrestrial floodbasin deposits. Within these occur accumulations of fluvial and cold climate aeolian sandstones. However the latter appear to have only limited continuity within this member. The top of the un-named middle Unayzah member, and therefore the top of the lower Unayzah, in a number of places is identified as a relatively thin (4–6 ft; 1.2-1.8m) paleosol horizon. This is interpreted to represent a hiatus following the deposition of the un-named middle Unayzah member, and is therefore seen to be a disconformity between that member and the Unayzah A member.

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