Sedimentary architecture of Upper Ordovician tunnel valleys, Gargaf Arch, Libya: Implications for the genesis of a hydrocarbon reservoir

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ABSTRACT
In the Murzuq Basin, southwest Libya, as elsewhere in North Africa, Upper Ordovician glaciogenic rocks represent an important hydrocarbon reservoir. In this basin, anastomosing, potentially sand-filled palaeovalley networks within the Upper Ordovician succession have been described from seismic data that provide promising prospects for exploration. However, little is known about the origin and architecture of the palaeovalley-fills. On the Gargaf Arch, an outcrop analogue for these structures occurs and is comparable in scale to the valley networks described in the subsurface. This palaeovalley system is 30 km long with two 4 km-wide tributaries, cut into ice-distal glaciomarine mudrocks and diamictites and filled with ice-proximal sandstones and subordinate shales. It was created by subglacial meltwater erosion and glacial loading of a soft substrate during ice sheet advance. The initial stage of valley-fill involved the deposition of coarse-grained sands and conglomeratic ice-proximal, submarine outwash, as localised mass flows. The main stage of fill was characterised by axially (northerly) prograding, underflow-dominated fan lobes deposited in water depths of up to 80 m. A comparison with coeval valley systems in Mauritania, Algeria, Saudi Arabia and Jordan is provided that highlights the variable regional character of palaeovalley-fills and the influence that water-depth had on architecture.

INTRODUCTION
In North Africa and Arabia, the Upper Ordovician glaciogenic succession preserves palaeovalleys that represent an attractive target for hydrocarbon exploration (e.g. Hirst et al., 2002). A subglacial origin as tunnel valleys is inferred for some of these structures but the style of their sedimentary fill varies considerably from area to area (cf. Ghienne and Deynoux, 1998; Hirst et al., 2002). In the Murzuq Basin, southwest Libya, Upper Ordovician glaciogenic sandstones are an important hydrocarbon reservoir (Davidson et al., 2000; Echikh and Sola, 2000) and on seismic data, thick anatomising, channel networks have been identified within these rocks by Smart (2000) (Figure 1). The morphology of these structures is similar to that of subglacial tunnel valley networks that drained Quaternary ice sheets (e.g. Brennand and Shaw, 1994).

On the Gargaf Arch at the present-day northern margin of the Murzuq Basin, a palaeovalley complex is preserved in outcrop (Figures 1b, c, d). The sedimentological evolution and architecture of this valley-fill is described here to provide a model for predicting the potential sedimentary architecture in the subsurface of the Murzuq Basin. Possible modes of origin of the palaeovalley complex are discussed and a comparison with coeval palaeovalleys in Mauritania, Algeria, Saudi Arabia and Jordan is provided (Beuf et al., 1971; Vaslet, 1990; Abed et al., 1993; Powell et al., 1994; Ghienne and Deynoux, 1998; Hirst et al., 2002).

GEOLOGICAL SETTING
In the Murzuq Basin, Precambrian structures generated during the Pan-African Orogeny, created a series of NW-SE palaeogeographic highs and lows (Klitzsch, 1981). During the early Palaeozoic, the area represented by the present-day Murzuq Basin formed part of West Gondwana (Boote et al., 1998) (Figure 1a). The western margin of the Gargaf Arch occupied the eastern edge of the Murzuq-Djado Trough (Figure 1b).
Figure 1: (a) Late Ordovician palaeogeographic reconstruction of West Gondwana, showing the approximate extent of a grounded ice sheet and the position of the ancient South Pole (after Scotese et al., 1999; Sutcliffe et al., 2000b). Blue arrows indicate direction of ice sheet advance.

(b) Location and geological sketch-map of the Murzuq Basin, showing the location of the study area, the distribution of seismically defined palaeovalleys (after Smart, 2000) and the area where oil fields occur in the Mamuniyat Formation.
During the Cambrian to Late Ordovician, the continental shelf was subject to a marine transgression that resulted in the widespread deposition of thick sand-dominated shallow-marine successions (Boote et al., 1998; Carr, 2002). In the Late Ordovician, the North African margin of Gondwana drifted over the South Pole, and this influenced global climate change and promoted the growth of an ice sheet covering up to 65° of palaeolatitude (Scotese et al., 1999) (Figure 1a). The resulting glaciation caused the second largest mass extinction in Earth's history, a eustatic fall of up to 60 m and a significant increase in sediment supply to glacierised continental shelves (Brenchley et al., 1994; 1995; Sutcliffe et al., 2000a,b, 2001).

The glaciation was of short duration and almost entirely restricted to the *extraordinarius* Zone of the Hirnantian stage, which was of <0.5 My in duration (Sutcliffe et al., 2000b) (Figure 2b). During this interval, the global climate was significantly influenced by the Earths' orbital eccentricity cycles (0.1 My in duration; Williams, 1991), which also had an important control on the Quaternary ice-sheet volumes (Imbrie et al., 1992). In Upper Ordovician successions, evidence for two main cycles of full glaciation is widespread, supported by two major sea-level excursions on the global eustatic curve (Sutcliffe et al., 2000b) (Figure 2b). Therefore, glaciation was probably limited to a period of 0.2 My according to Sutcliffe et al. (2000b). However, four cycles of glaciation have also been proposed from field-based studies in Mauritania (Ghienne, 2003).

**UPPER ORDOVICIAN STRATIGRAPHY**

In the Murzuq Basin, Upper Ordovician glaciogenic rocks comprise the Melaz Shuqran and Mamuniyat formations (Figure 2a). Informal stratigraphic subdivisions have been proposed by various authors (Blanpied et al., 2000; McDougall and Martin, 2000; Sutcliffe et al., 2000b). However, these rocks display extreme lateral and vertical facies changes, limiting the value of lithostratigraphic interpretation and inhibiting the establishment of formal members for the Mamuniyat Formation.
Previously, two phases of glacial advance and retreat have been interpreted in Libya (Sutcliffe et al., 2000b). However, this Late Ordovician ice sheet, like its Quaternary equivalents, may have been susceptible to higher-order re-advances. On the Gargaf Arch, Blanpied et al. (2000) recognised five unconformities that were used to define four unconformity-bound units (Figures 2a, 2c). The Melaz Shuqrar Formation (Unit 1) onlaps an angular unconformity (UC1) developed on the pre-glacial Haouaz Formation (Figures 2a, 2c) and comprises mud-dominated facies with coarsening upward motifs. This formation has previously been interpreted to represent deposition of prograding ice-distal sedimentary fans (Sutcliffe et al., 2000b).

The lower Mamuniyat Formation (Unit 2) comprises km-scale, locally developed coarsening-upward, fan-like bodies of trough cross-bedded sandstones that are locally deformed into syn-sedimentary belts of imbricate thrusts and folds (4 km long and 1 km wide). In this unit, these fans are overlain, or laterally replaced by, m-thick, sheets of planar to hummocky cross-stratified sandstones. This unit is interpreted to represent glaciotectonically thrust ice-contact fans, later reworked in a stormy shelf environment (Sutcliffe et al., 2000b). It is interpreted to indicate periods of more ice-proximal glaciomarine sedimentation and corresponds with a transition from an ice-contact architectural element to a glaciomarine shelf architectural element (Sutcliffe et al., 2000b).

The middle Mamuniyat Formation (Unit 3) is lithologically similar to the Melaz Shuqrar Formation, corresponds to a glaciomarine shelf architectural element and was probably deposited during a glacial re-advance (Sutcliffe et al., 2000b). The Gargaf Arch palaeovalley was incised into these deposits and in intervalley settings, large rootless synclines are truncated by a flat unconformity (Figure 2c).
The upper Mamuniyat Formation (Unit 4) is heterogeneous and comprises the Gargaf Arch palaeovalley-fill described in this paper and local half-graben depocentres filled with shallow marine sandstones. The half-graben developed near the top of Unit 4 and are associated with the products of large-scale mass movement, syn-sedimentary slides and gravitational instability (Glover et al., 2000). These half-graben fills of Unit 4 correspond to the postglacial isostatic rebound architectural element of Sutcliffe et al. (2000b).

McDougall and Martin (2000) proposed that the evolution of the Melaz Shuqran (Unit 1) and Mamuniyat formations (Units 2, 3 and 4) was only influenced by relative sea level change. However, their depositional model does not account for the glacial erosion events, which are clearly evident across the region. The stratigraphical model proposed by Blanpied et al. (2000) recognised the role of ice sheets, and isostatic unloading, on deposition but did not incorporate the influence of ice-proximal glaciomarine processes. Ice-proximal deposits and processes have been identified across the Murzuq Basin and should be included in the sedimentary models for these rocks. On this basis, a sedimentary model, characterised by successive oscillations of an ice sheet, is preferred with additional glacioisostatic responses.

**VALLEY MORPHOLOGY AND STRUCTURE**

The Gargaf Arch palaeovalley is recognised on satellite (LANDSAT) imagery and is located in a region characterised by subhorizontal bedding dips (Figures 1c, 1d). It was first recognised by Ghienne et al. (2000) in a poster presentation at the GEO 2000 conference, Bahrain. The palaeovalley is ‘Y’ shaped and a minimum of 30 km in length (Figures 1c, 1d). Two parallel-sided, relatively straight, tributary channels (4 km wide) join northwards at a confluence and beyond this point the valley-width increases. Along both the western and eastern tributaries, the palaeovalley margins are defined by beds dipping at 18-25° towards the axis (a structural downbend; Figure 3). These beds are onlapped by an undeformed, horizontal fill (Unit 4).
Figure 4: Facies in the vicinity of the Gargaf Arch palaeovalley. (a) Interbedded micaceous siltstones and shales in the mudrock and diamictites facies association. (b) Planar cross-stratified sandstones in the current rippled to planar laminated sandstone facies association. (c) Scattered mud rip-up clasts are typically randomly dispersed or crudely stratified in the massive to cross-bedded conglomerate facies association. Photos d to h show the range of facies preserved in the planar to...
SEDIMENTOLOGICAL EVOLUTION OF THE PALAEOVALLEY

The sedimentological evolution of the Gargaf Arch palaeovalley is subdivided into pre- and post-incision successions. Distinctive facies associations occur in each.

Pre-incision deposits
Adjacent to the tributaries of the palaeovalley, the pre-incision deposits are characterised by two main facies associations. Stratigraphically, these rocks correspond to Unit 3 of Blanpied et al. (2000) (Figure 2c).

Mudrock and diamictite facies association
These deposits define the lower part of a coarsening-upward motif that comprises massive to bedded, micaceous, siltstones and shales or thinly bedded to laminated clast-poor silty diamictites with rare granules (Figures 2b, 4a, 5e).

The siltstone and shales are interpreted to represent the hemipelagic settling of muds. However, the interpretation of the silty diamictites is more equivocal. Two depositional mechanisms are plausible, which include debris flows or the deposition of iceberg-rafted debris. In modern glaciomarine shelf settings, such as the Barents Sea (Elverhøi et al., 1989), comparable diamictites are produced through iceberg-rafting. A similar origin is proposed for the silty diamictites, which is also supported by the occurrence of thin stratification. These rocks are interpreted to represent ice-distal settings.

Current rippled to planar laminated sandstone facies association
This facies is dominated by sandstones that subtly coarsen-upward (Figures 5e, 5g). Sandstones are moderately to well-sorted, commonly planar laminated and very fine to medium grained. Primary current lineation occurs in the medium grained deposits but is absent from the finer grained planar laminated sandstones. Stacked, subcritical climbing ripples also occur, interbedded with thin structureless beds. In the coarsening-upward motif at Section G, a transition from fine-grained, planar laminated, to current rippled, to low-angle (<5°) cross-stratified sandstones is preserved (Figures 4b, 5g). In Section E, a transition from current rippled to medium grained, planar laminated sandstones with primary current lineation is recorded (Figure 5e).

The common preservation of current/climbing ripples and cross-bedding supports deposition from traction currents. In Section G, the upward transition from fine-grained planar laminated sandstones (without primary current lineations) to low-angle cross stratification implies an upward increase in energy levels and the development of larger bedforms. A similar interpretation can be adopted for Section E where the uppermost medium-grained, planar laminated sandstones reflect deposition from unconfined, high energy flows. Therefore, this facies association is interpreted to represent the basinward progradation of a glaciomarine sandbody. The juxtaposition of current rippled to planar laminated sandstones on top of the mudrock and diamictite facies association is interpreted to represent a transition from an ice-distal, iceberg-influenced outer shelf toward an inner shelf setting, potentially affected by meltwater-derived underflows.

Striated surfaces
At the margins of the palaeovalley, near to the confluence of the two tributaries, a bedding surface within the current rippled to planar laminated sandstone facies association preserves striations (Figures 3, 6). The surface consists of subparallel ridges and grooves (striations), with cross-cutting relationships, that display a relief of up to 1 cm (Figure 6). They strike N-S and are therefore parallel to the margins of the palaeovalley (Figure 5d).

undulose bedded sandstone facies association. (d) and (e) show channelised, massive sandstones cut into and surrounded by sheet-like finer grained sandstones. In (f), an overall coarsening-up is noted, and this is interpreted to reflect the progradation of an underflow-dominated fan lobe (see Figure 9). (g) antidunes in underflow-sandstones interpreted to have migrated up-current (to the south), opposite to the main transport direction (to the north). (h) Large-scale undulose bedding, interpreted to reflect deposition from oscillatory or combined flows during high-latitude storms.
Figure 5: Correlation panel across the tributaries of the Gargaf Arch palaeovalley (see Figure 1d for location of measured sections). This diagram shows the extent of loading and incision at the base of the palaeovalley-fill and the approximate stratigraphic relationships of the different facies associations.
These striated surfaces are interpreted to form beneath an advancing ice sheet. Beuf et al. (1971) proposed that they formed by abrasion, and this interpretation is supported by the rare occurrences of cross-cutting striations (Figure 6). Stacked striated surfaces with a common orientation at each level are also recognised elsewhere in the basin (Abugares and Ramaekers, 1993; Sutcliffe et al., 2000a, b). The stacked nature of these latter surfaces has been interpreted to reflect the transmission of shear throughout the sediment column (Sutcliffe et al., 2000a, b). Therefore, it is possible that the striations may result from a combination of abrasion and shearing within the sediment column. However, both these models support the genesis of the striations beneath an ice sheet.

**Post-incision deposits**

Stratigraphically, the valley-filling sandstones of the Gargaf Arch palaeovalley correlate with Unit 4 of Blanpied et al. (2000) elsewhere on the Gargaf Arch (Figures 2b, 5). Two facies associations can be recognised within the valley fills.

**Massive to cross-bedded conglomerate facies association**

These deposits consist of locally preserved, poorly-sorted, coarse-grained sandstones to granular conglomerates that occur immediately above the unconformity defining the base of the palaeovalley (Figures 5d, 5f). The thickness of these deposits is variable but can be up to 40 m thick (Figure 5f). They occur near the confluence of the tributaries (Figure 5d), in their axial regions (Figure 5f) and along their outer margins (Figure 5a).

In this facies association, bed bases are erosional, incising up to 4 m into the underlying deposits. The overlying sandstones and conglomerates are massive to stratified, have a sheet-like to channelised geometry and can be traced for tens of metres. Some massive beds grade upwards into planar laminated or climbing ripple cross-laminated sandstones. The latter structures are common on top of channelised units. In the massive sandstones, mud rip-up clasts tend to be randomly arranged but locally they crudely define bedding. Large-scale planar to trough cross-bedded units are commonly interbedded with, or grade laterally and vertically into, the massive sandstones (e.g. Figure 5a) and
in rare instances are defined at their base by intraformational lags of fine-grained sandstone pebbles. Dewatering structures are common and include elutriation pipes and dish-and-pillar structures.

The graded character of the massive and dewatered conglomeratic sandstones is interpreted to reflect rapid deposition from granule-rich, high-density, turbulent underflows. This interpretation is also supported by the crude stratification of mud rip-up clasts. Deposition from debris flows can be rejected because of the common preservation of planar laminated and current rippled sandstones, which suggest deposition from traction currents. During deposition, the strength of turbulent underflows was variable with lower energy, more dilute flows resulting in the deposition of the finer-grained, channelised and normally graded sandstones with current rippled upper surfaces. Therefore, it is assumed that much of the massive to cross-bedded conglomerate facies association represents deposition from local, high-energy turbulent underflows that displayed significant variability in energy levels over time.

In these underflow-dominated successions, the development of large-scale planar to trough cross-bedded sandstones is somewhat enigmatic, but implies the development and migration of large-scale 2-D and 3-D dune-like bedforms. Elsewhere on the Gargaf Arch, unconformities interpreted as subglacial erosion surfaces are overlain by locally developed ice-contact fans deposited from meltwater jets/plumes (Sutcliffe et al., 2000b). The coarse-grained nature of these deposits and their locally developed nature closely resemble sediments deposited in modern ice-contact settings.

Deposition in glaciomarine ice-contact settings is strongly influenced by the release of sediment-laden, high-pressure, high-energy subglacial meltwater jets (Powell and Molina, 1989; Powell, 1990) (Figure 7). On their release into a marine setting, these freshwater flows move along the sea bed for a distance before they become buoyant in response to a density contrast between the fresh water and the ambient seawater (Powell, 1990). Away from a glacier, the highest energy meltwater jets (characterised by hyperconcentrated flows) become more dilute and erode channels into older deposits before finally becoming buoyant (Figure 7). At the point of flow-detachment, large volumes of sediment collapse from these plumes to generate a large barchanoid bedform (Powell, 1990). The rainout of sediment from these buoyant plumes generates high-energy sand-dominated underflows. Deposition from ice-proximal meltwater flows is capable of generating the large-scale 3-D bedforms and the channelised to unconfined massive sandstones beds.

**Planar to undulose bedded sandstone facies association**

These deposits are dominated by moderate to well-sorted, fine-to coarse-grained sandstones with subordinate mudrocks (Figures 5a, 5b, 5c, 8h, 8i, 8j). In these rocks, vertical and lateral variations in grain size are limited, although 10-12 m thick coarsening-upward successions are preserved (Figures 5a, 5b, 5c, 8h, 8i, 8j) that tend to have finer grain sizes than the massive to cross-bedded conglomerate facies association (Figures 8f-j).
This facies association is characterised by the intercalation of massive sandstone channel-fills (20-30 m in width, 2-5 m in thickness; Figures 4d, 4e) with thinly bedded, laterally extensive, sheet-like finer grained sandstones (Figures 4d, 4e, 4f). Sedimentary structures include planar laminae, primary current lineations, convolute lamination, rare antidunes (Figure 4g), current ripples and large-scale undulose bedding (Figure 4h). The latter structures comprise large, symmetrical megaripples (hummocks and swales) up to 14 m apart, with subparallel laminae, which maintain a constant thickness. However, the low-angle truncation of laminae defines the base of lamina-sets. These structures are larger in scale than swaley or hummocky cross-stratification (e.g. Harms et al., 1975; Cheel and Leckie, 1993).

The preservation of channelised massive sandstones is interpreted to represent deposition from relatively confined, sand-dominated, high-density underflows. The finer grain size of these rocks, when compared with the massive to cross-bedded conglomerates, suggests deposition as a more distal underflow. The intercalation of these channelised sandstones with thinly bedded sheet-like planar laminated sandstones (with current lineation) implies sedimentation from high-energy, unconfined flows under upper flow regimes. The rare subordinate mudrocks are interpreted to represent the hemipelagic settling of fines.
The sedimentological interpretation of the large-scale undulose bedding is equivocal. Hirst et al. (2002) described similar structures within an Upper Ordovician palaeovalley of southeast Algeria and interpreted them as upstream-migrating antidunes deposited from turbidity currents. However, this interpretation is rejected for the undulose bedding because of the symmetrical and subparallel nature of the laminae, which imply the aggradation of a bedform rather than its migration. Comparable structures have been described from the Precambrian of India where they were interpreted as an intermediate bedform between trough cross-beds and swaley cross-stratification generated under storm conditions from combined or oscillatory flows (Datta et al., 1999). By analogy, the large-scale undulose bedding in the Gargaf Arch palaeovalley sandstones is interpreted to represent deposition from oscillatory or combined flow during high-latitude storms.

Away from the ice-contact deposits of the massive to cross-bedded conglomerates, the gradual northward decrease in grain size along the axis of the palaeovalley implies a southerly source for the turbidites and storm beds and the basinward reworking of older ice-contact deposits (Figure 8). This reworking possibly occurred in the later stages of glacial retreat. Furthermore, the development of coarsening-upward successions in this facies association implies the development of axially prograding sandbodies during the infilling of the palaeovalley. The planar to undulose bedded sandstone facies association is therefore interpreted to represent the deposition from confined to unconfined, relatively ice-distal underflows or high-latitude storms on northerly prograding sandbodies.

ARCHITECTURE OF PALAEovalLEY-FILL

Rocks with characteristic textures and trends in grain sizes dominate the facies associations of the Gargaf Arch palaeovalley. These characteristics represent an important control on the performance of rocks as hydrocarbon reservoirs (Davidson et al., 2000; Hirst et al., 2002). Therefore, an evaluation of large-scale architecture and the arrangement of facies associations within a palaeovalley will help to define models for fluid flow in the rocks as potential reservoirs.

Valley incision is observed to be about 60 m, which represents the residual thickness of ice-distal sediments (Unit 3) in the area between the two tributaries (Figure 5e). A significant north-dipping palaeotopography also occurs along the axis of this palaeovalley (Figure 8).

Ice-proximal outwash (the massive to cross-bedded conglomerate association) locally drapes the basal subglacial erosion surface at the valley-floor and characterises the initial stage of valley fill (Figures 9, 10a, 10b). The lateral extent of these deposits is limited to several hundreds of metres but the extent to which these deposits were eroded and reworked during the deposition of the main fill is not certain (Figure 10b).

Across the palaeovalley, the ice-distal underflows and storm beds of planar to undulose bedded sandstone facies association form the main stage of valley fill. These onlap the margins of the palaeovalley and the initial fill (Figures 5, 8, 9, 10b, 10c). The maximum thickness of the fill is 80 m. Hence, these sand-dominated deposits overtop the valley-margins by about 20 m.

Within the main fill, clinoform-like geometries are recognised (Figure 11), that are truncated by three discontinuities that dip at shallow angles toward the north (Figure 11). In cross-section, the uppermost discontinuity correlates to the uppermost coarsening upward succession of the planar to undulose bedded sandstone association (Figures 5a, 5b, 5c, 8h, 8i, 8j). These discontinuity-bound coarsening-upward units are interpreted to reflect the northwards progradation of a fan-like body along the axis of the palaeovalley (Figure 10c), that was probably sourced from glacier-related underflows or storm events. The abandonment and rejuvenated deposition of these fans resulted in the development of the discontinuities. During deposition, the water depth was probably a minimum of 80 m (i.e. the thickness of the valley-fill plus the 20 m thickness of sediments which overtop the margins).

Sedimentologically, the transition from ice-proximal mass flows (initial fill) to underflows and storm beds (main fill), records the retreat of an ice sheet (Figure 9). During retreat, the ice sheet would be expected to have stabilised on topographically higher parts of the sea floor known as pinning points.
These pinning points would have partly countered the effects of rising eustatic sea-level, resulting in a staggered glacial retreat. During this staggered manner of retreat, it is suggested that the various sandbodies of a valley fill will backstep, with landward examples of the initial fill representing the temporal seaward equivalents of the main fill. Therefore, the meltwater jets from ice-proximal settings may have acted as feeder systems for the more distal fan-lobes.

Comparison with intervalley settings

A comparison of the Mamuniyat Formation inside and outside the Gargaf Arch palaeovalley suggests that in both settings, locally developed, coarse-grained to conglomeratic ice-proximal deposits represent the initial stages of glacial retreat (Sutcliffe et al., 2000b) (Figures 2, 5, 8). Outside the valley, these deposits include ice-proximal debris flows and ice-contact fans or deltas, which may have accumulated near to palaeogeographic highs. The lack of ice-contact deltas in the valley-fill probably indicates a greater depth of water.

In intervalley settings, ice-contact rocks are overlain or replaced laterally by sheet-like bodies of sandstone, up to 10 m thick, that lack the prograding foresets of the main valley-fill (Figure 2). These sandsheets include hummocky cross-stratification and the large-scale undulose bedforms, which are interpreted to represent the effects of high-latitude storms on a sand-rich continental shelf. Similar storm beds occur within the palaeovalley-fill (Figure 5). Therefore, in the intervalley settings, the lack of accommodation space allowed the reworking of older sands by storms into laterally extensive sheet-like bodies. Sands in these intervalley settings were potentially derived from ice-contact fans or the reworking of sediment from an overfilled valley.
The deposits of intervalley settings are considered to have a similar origin to those of the palaeovalley-fills. However, the architectural motifs that develop in these settings are largely influenced by water-depth, accommodation space and the extent of sediment reworking during high-latitude storms.

IMPLICATIONS FOR RESERVOIR ARCHITECTURE

The sedimentary architecture described above has several implications for the evaluation of potential hydrocarbon fluid flow within Upper Ordovician palaeovalleys. At the base of the palaeovalleys, the coarser grained initial fill forms locally developed sandbodies whose connectivity is limited (Figure 9). Their coarse-grained nature, and the absence of clays, from these rocks suggests that they will have good reservoir potential (Davidson et al., 2000). At the base of a correlative palaeovalley in the Tiguentourine field, Algeria, analogous conglomeratic ice-proximal sandbodies have a permeability of up to 1,000 mD (Hirst et al., 2002).

On the Gargaf Arch, the main palaeovalley fill comprises stacked coarsening-upward successions of prograding fan-like bodies that were deposited from underflows and storms (Figure 9). Immediately above the bounding discontinuities of these fans, the mud-dominated nature of sandstones suggests that these rocks will impede fluid flow (Davidson et al., 2000) and form a metre thick, planar baffle that dips at a low angle down the axis of the palaeovalley. In the upper parts of these lobes, the development of thicker and cleaner sandstones suggests that reservoir potential will improve upwards. This interpretation is also supported by the correlative analogues from the Tiguentourine field, Algeria, where mud-dominated sandstones, deposited from density currents, have significantly lower permeabilities (<1 mD) than their sand-rich counter parts (tens to hundreds mD) (Hirst et al., 2002).

In the upper part of these fan-lobes, sandbody connectivity should be good, although the transmissibility of fluids between adjacent clinoforms is not certain. Therefore, the main fill of a palaeovalley is characterised...
by seaward dipping, alternating metre to tens of metre-thick units of poor and moderate reservoir quality (Figure 8). It is suggested that this architecture will tend to direct fluid flow upwards or downwards through the palaeovalley.

In the Upper Ordovician palaeovalley of the Tiguentourine field, mud and sand-dominated diamictites have negligible reservoir quality (<1 mD) and occur immediately above the ice-proximal initial fill (Hirst et al., 2002). These deposits are assumed to represent ice-distal processes and are potentially developed in the distal part of a palaeovalley. Thus, away from the retreating ice front, comparable diamictites may form a significant barrier between the good quality reservoirs of the initial fill and moderate quality reservoirs of the main fill. This potential barrier will pinch-out in a landward direction.

**ORIGIN OF PALAEOVALLEYS**

During glaciation, the increased storage of water in ice sheets results in mean sea-level fall, incision of the continental shelf by fluvial processes and the development of incised valleys (Van Wagoner et al., 1990). An incised valley origin for the formation of the Gargaf Arch palaeovalley can be rejected because this model fails to account for structural downbending at the valley margins (Figure 3) and the evidence for subglacial shearing at the valley-floor (i.e. glacial striations; Figure 6).

On modern glacierised continental shelves, anastomosing networks of subglacial tunnel valleys develop that undergo abrupt changes in depth (O’Cofaigh, 1996). This morphology is comparable to palaeovalley networks recognised in seismic section from the Murzuq Basin, suggesting that tunnel valleys provide an analogue for the Gargaf Arch palaeovalley described in this paper and for those in the subsurface. Tunnel valleys reach several km in width, <500 m deep, tens of kilometres in length and act as a conduit for high-pressure, subglacial meltwater flows (Brennand and Shaw, 1994). Examples of tunnel valleys that cut down into consolidated/hard rock substrates have been reported from both the Quaternary (Harris et al., 1998) and Late Palaeozoic records (Eyles and de Broekert, 2001). However, most Quaternary examples cut into unconsolidated substrates (e.g. Wingfield, 1990; Brennand and Shaw, 1994). The precise origins for tunnel valleys is uncertain as reviewed by O’Cofaigh (1996), and the three main models are summarised below.

In the first model, the loading of a soft, deformable substrate by an overlying ice sheet results in the movement of sediment into a subglacial meltwater conduit (Boulton and Hindmarsh, 1987) (Figure 12a). The removal of this sediment by subglacial meltwaters creates topography at the ice-sediment interface that is subsequently enhanced and widened by glacial loading. The high hydraulic head...
Figure 12: Models for the formation of tunnel valleys. (a) Ice-sheet loading model (Boulton and Hindmarsh, 1987). (b) Time-transgressive model (Wingfield, 1990). Collapse of meltwater ice tunnels and landward migration of plunge-pools. (c) Catastrophic meltwater release after ice sheet retreats from a permafrost seal to a soft unconsolidated bed (Piotrowski, 1994).
Upper Ordovician tunnel valleys, Gargaf Arch, Libya

Table 1: Characteristics of the Upper Ordovician tunnel valley-fills of West Gondwana.

| Setting          | Cross-section profile | Planview architecture | Incised substrate | Architecture          | Striations |
|------------------|-----------------------|-----------------------|-------------------|-----------------------|------------|
| MAURITANIA        | Sinuous and isolated | Wide depressions       | Both consolidated and unconsolidated | Coarse-grained sediments (glacioluval outwash) | Not observed at margins, but present in early fill |
| ALGERIA (therit)  | Sinuous, isolated     | Anastomosing           | Both consolidated and unconsolidated | Sheet-like diamictics, and medium-grained ssts, interlaminated with of channeling the diamictics. | Present in early fill |
| SAUDI ARABIA      | Sinuous, isolated     | Anastomosing           | Both consolidated and unconsolidated | Locally developed "lillites" with evidence for subaqueous deposition. | Not observed |
| JORDAN (Abed et al., 1993; Powell et al., 1994) | Sinuous and isolated | Palaeovalley confluence isolated | Consolidated        | Pebbley to cobbly diamictic with structureless sst. | Present at floor of valley near margins and in fill |
| GARGAF ARCH, LIBYA (this paper) | Sinuous and isolated | Palaeovalley confluence isolated | Unconsolidated | Main stage of fill deposits medium to coarse-grained sandstone, interpreted as glaciouluvial or glaciomarine deposits. | Present at floor of valley near margins and in fill |

In the second model, a plunge pool is created beneath an ice sheet by the sporadic flow of high-energy meltwater, which generates sufficient discharge to promote erosive scouring (Wingfield, 1990; Figure 12b). During successive events, these plunge pools migrate landward, resulting in the development of a tunnel valley. In this model, tunnel valley formation is time-transgressive (O’Cofaigh, 1996), but requires the catastrophic incision of a tunnel valley by a massive subglacial meltwater event (Piotrowski, 1994).

In the third model, an ice-dammed lake builds up near the glacier terminus but meltwater drainage is impeded by the presence of a permafrost layer in front of the ice sheet (Figure 12c). With progressive melting, the lake increases in size, and the frozen toe of the ice sheet is breached releasing meltwaters catastrophically (Figure 12c), creating a tunnel valley (Piotrowski, 1994). Therefore, both the second and third models require the discharge of large volumes of meltwater.

On the Gargaf Arch, the first model for the formation of tunnel valleys is considered the most appropriate because an episode of ice-sheet loading can account for the structural downbending at the palaeovalley margins (Figure 3) and the development of striated surfaces within the palaeovalley fill (Figures 3, 5). On the Gargaf Arch, the formation of these features is difficult to reconcile with the catastrophic release of meltwaters beneath an ice sheet implied by models 2 and 3. Furthermore, model 2 requires a terrestrial glacial setting (braiidplains) and model 3 permafrost (probably requiring subaerial exposure). No terrestrial glacial facies are interpreted in the vicinity of the Gargaf Arch palaeovalley. However, models 2 and 3 are considered to be viable mechanisms for the incision of Upper Ordovician tunnel valleys in consolidated/hard rock substrate areas.
Figure 13b: Palaeogeographical model for the characteristics, architecture and genesis of upper Ordovician tunnel valley-fills.

COMPARISON WITH COEVAL NORTH AFRICAN AND JORDANIAN/ARABIAN PALAEOVALLEYS

Features interpreted to represent outcrops of Upper Ordovician palaeovalleys have been reported from Mauritanian, southern Algeria, Saudi Arabia and Jordan (Beuf et al., 1969, 1971; Bennacef et al., 1971; Deynoux et al., 1972; Vaslet, 1989, 1990; Powell et al., 1994; Ghienne and Deynoux, 1998). Analogous structures have also been reported from the subsurface of Algeria, Libya and Saudi Arabia (Aoudeh and Al-Hajri, 1995; Smart, 2000; Hirst et al., 2002).
Palaeovalleys are cut into both indurated (preglacial) and unconsolidated Upper Ordovician deposits (Figure 13a). The depth of incision is generally >100 m and variations in the character of the fill are recognised. Most workers suggest that the fill was deposited during deglaciation or marine transgression (Powell et al., 1994; Vaslet, 1990; Ghienne and Deynoux, 1998; Hirst et al., 2002). The orientations of palaeovalleys is interpreted to reflect the direction of palaeo-ice-flow, as in Quaternary examples, which in Saudi Arabia and North Africa, radiate away from the centres of glaciation (Beuf et al., 1971; Blanpied et al., 2000). In some regions, palaeovalleys parallel pre-existing tectonic trends (eg. Beuf et al., 1971; Ghienne and Deynoux, 1998), suggesting the exploitation of lines of weakness. Within the palaeovalleys, soft-sediment striations and glaciotectonic features (e.g. push-moraines) support the interpretation for valley-parallel ice-flow and confirm that these palaeovalleys record variations in the direction of ice-flow (Figure 5).

In the subsurface of the Murzuq Basin, two generations of palaeovalleys have been recognised in seismic section (Smart, 2000; Figure 1B). However, the resolution of the seismic data is insufficient to distinguish their internal architecture (Smart, 2000). These valleys vary between 100 m and several kilometres across, have steep sides and a flat bottom, form anastomosing networks in plan (Smart, 2000) and are comparable in shape and scale with Pleistocene subglacial tunnel valleys (e.g. Brennand and Shaw, 1994).

At outcrop in Saudi Arabia, two generations of Upper Ordovician palaeovalleys are also recognised (Vaslet, 1989, 1990). The oldest palaeovalleys are filled with the Zarqa Formation, which is characterised by a succession of slumped and deformed mud to sand-dominated diamictites and fine-grained sandstones (Vaslet, 1989, 1990). Lithologically, these deposits compare with the Melaz Shuqran Formation (Unit 1) and Unit 3, into which the Gargaf Arch palaeovalley is incised (mudrock and diamictite facies association). The Zarqa Formation onlaps a preglacial topography (Vaslet, 1990) and is interpreted here to represent ice-distal facies deposited during glacial advance. It is suggested that the Zarqa Formation palaeovalley-fills do not provide an appropriate analogue for those of the Mamuniyat Formation, which was deposited during glacial retreat.

In Saudi Arabia, the Sarah Formation represents the fill of the second generation of palaeovalleys. The Sarah Formation palaeovalleys contain medium-grained cross-bedded sandstones that have been interpreted as glaciofluvial to glaciomarine outwash deposits (Vaslet, 1990). At the margins of these palaeovalleys, locally preserved pockets of graded diamictites show evidence for deposition under high-energy traction currents. Therefore, it is suggested that many of these rocks also represent ice-proximal subaqueous meltwater flows. The scale and sand-dominated fill of these younger palaeovalleys are comparable to those on the Gargaf Arch.

In Jordan, the architecture of upper Ordovician palaeovalleys is characterised by a lower slumped unit of pebbly to cobbly diamictites with common intra- and extraformational clasts and a valley-filling upper unit of medium- to coarse-grained trough cross-bedded sandstones (Abed et al., 1993; Powell et al., 1994) (Figure 13a). The latter deposits were interpreted to represent glaciofluvial outwash. There is uncertainty about the origin of the diamictites but sedimentologically, these deposits compare with ice-proximal, intraformational debris flows that are interpreted to represent hyperconcentrated meltwater flows at an ice front (Sutcliffe et al., 2000b) (Figure 7).

In Mauritania, the palaeovalleys are similar to those on the Gargaf Arch and comprise an initial fill of ice-proximal outwash that is overlain by a main fill of high-energy, glaciomarine sandstones (Ghienne and Deynoux, 1998; Hirst et al., 2002) (Figure 13a). However, in Mauritania, there is a change in the character of a palaeovalley-fill that reflects the palaeogeographic setting and proximity to the centre of glaciation. In the proximal regions of the Late Ordovician continental shelf, the glacier-related parts of a valley-fill are characterised by glaciofluvial outwash, probably deposited in non-marine settings (Figure 13b). These fills compare with those of Jordan and Saudi Arabia (Figure 13b).

In Algerian palaeovalleys described from the Tassili N’Ajiers region, fill style varies considerably (Beuf et al., 1971). The two tributaries of the Iherir palaeovalley are cut into pre-glacial Mid- to Upper Ordovician sandstones (Beuf et al., 1971). Comparative study of these structures to support the data given in this paper (D. Le Heron) suggests that pre-glacial rocks show structural downbending at
the margins of the Iherir palaeovalley that compares to dip geometries at the margins of the Gargaf Arch palaeovalley (Figure 3). In Algeria, the effects of palaeogeographic setting are also recognised because above an initial ice-proximal unit, a succession of mud and sand-dominated diamictites are preserved that are overlain by sand-dominated turbidites (Hirst et al., 2002). These diamictites probably represent deeper water deposition than within the Gargaf Arch palaeovalley (Figure 13b).

Across western Gondwana, Upper Ordovician tunnel valley fills can be subdivided into an initial and a main fill (Figure 10). The initial fill was influenced by ice-proximal meltwater flows and comprises a variety of locally preserved intraformational conglomerates to very coarse-grained, massive to large-scale trough cross-bedded sandstones. In contrast, the sedimentological motif of the main fill is influenced by palaeogeographic setting and water depth, with a variety of glaciomarine and non-marine fills recognised (Figure 13b). In deeper water settings, a transition from ice-distal diamictites to sand-dominated underflows may occur, whilst in proximal settings, glaciofluvial sandstones dominate the main fill. Therefore, variations in sandbody architecture along the length of a tunnel valley reflect the transition from marine to non-marine settings. These characteristics will affect fluid flow through these sandstones.

CONCLUSIONS

The Gargaf Arch palaeovalley is interpreted to have formed through the subglacial loading and incision of an underlying, mud-dominated, ice distal succession deposited during glacial advance. This palaeovalley was infilled during deglaciation by sand-dominated facies associations. The architecture of this fill is split into an initial fill of ice-proximal outwash that is overlain by valley filling high-density underflow fan-lobes (Figure 10). The progradation of these lobes occurred down the axes of the tunnel valley.

The architectural characterisation of Upper Ordovician tunnel valleys has important implications for petroleum exploration because it allows us to model the distribution of heterogeneities within the sand fairway. The nature of the fill varies in style depending upon the palaeogeographic setting (Figure 13b). In proximal settings, non-marine glaciofluvial sandstones overlie an initial fill of ice-proximal deposits. In deeper water settings, the initial, locally developed, ice-proximal deposits are overlain by a transition from ice-distal diamictites to sand-dominated underflow-fans.

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