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Interpretation of Late Ordovician glaciogenic reservoirs from 3-D seismic data: an example from the Murzuq Basin, Libya

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Abstract – Understanding the recessional behaviour of ancient pre-Cenozoic ice sheets based on seismic reflection studies is generally difficult through scarcity of data. In North Africa, however, hydrocarbon exploration has produced high quality seismic reflection datasets that permit an analysis of the morphology and internal sedimentary architecture of incisions of Late Ordovician age related to the Hirnantian glaciation. Analysis of a high-resolution 3-D seismic dataset covering a small area in western Libya (the N Murzuq Basin) reveals a sharply defined, WNW–ESE-oriented palaeo-escarpment, with a higher (cliff-forming) western margin and a lower (basin-forming) eastern margin. The palaeo-escarpment defines the western flank of a sub-basin extending up to 60 km in width, known as the Awbari Trough. The escarpment and the trough are interpreted as the morphological expression of a major unconformity dividing pre-glacial sediments below from Late Ordovician (?Hirnantian) glacially related sediments above. Two hypotheses are considered for the origins of both the escarpment and the Awbari Trough: (1) as a tectonic feature such as a half graben that was active during sedimentation and (2) a glacially related palaeotopography, with the latter interpretation preferred, owing to the lack of evidence for syn-sedimentary fault activity. The width of the Awbari Trough compares to the large-scale cross-shelf troughs in modern high latitude settings, such as the Barents Shelf, produced by ice streams. The Awbari Trough was progressively filled in by gravity flow deposits throughout the course of the glaciation, until the initial incision became filled in with sediments during an overall glacial retreat phase and ceased to influence sedimentation patterns. Glacial re-advance across the basin produced a second unconformity observed in seismic data. Above this unconformity, meltwater processes incised a shallow ($\sim$ 20 m) and wide ($\sim$ 5 km) subglacial tunnel valley. Stabilization of the ice front prior to its ultimate retreat resulted in the deposition of a delta complex prior to the Early Silurian transgression.

Keywords: glacial, seismic, Libya, Ordovician, Hirnantian.

1. Introduction

The use of 3-D seismic datasets to study the architecture of glacial sediments, and hence the evolution and demise of past ice sheets, is potentially very powerful. Analyses of ship-borne 3-D data from the Barents Shelf have revealed multiple unconformities in Quaternary deposits, many of which bear grooves, scratches and glacial lineations (e.g. Rafaelsen *et al.* 2002; Ottesen *et al.* 2002). These studies have, therefore, revealed that it is possible to image the record of glacial flow processes of the Pleistocene of the Northern Hemisphere through the analysis of seismic data. Likewise, seismic reflection data collected from the North Sea have revealed the presence of extensive networks of ‘tunnel valleys’ (or rinnentaler) that are interpreted to record the channelization of meltwater beneath Quaternary ice sheets as they retreated (Wingfield, 1990). Consequently, there is no reason why the use of seismic reflection studies to study the processes of ice advance and retreat should not extend to much older glaciations.

The record of the Late Ordovician glaciation extends across North Africa. In the Murzuq Basin, SW Libya (Fig. 1), glaciclastic sedimentary rocks of Late Ordovician age are a major hydrocarbon reservoir. These are frequently sand-prone, though heterogeneous, and are economically important because they lie immediately below organically enriched Lower Silurian ‘hot shale’, which is the main hydrocarbon source rock in this basin (Davidson *et al.* 2000). As a result of hydrocarbon exploration, seismic data coverage of the northern part of the Murzuq Basin is good. However, data quality is usually low (e.g. Smart, 2000), largely as a consequence of the difficulties in seismic acquisition in areas covered by sand seas or traversed by major topographic escarpments.

In Libya, as well as in wider North Africa, a considerable amount of work has been done over recent years to unravel the sedimentary record of the Late Ordovician glaciation (e.g. Ghienne *et al.* 2003; El-ghali, 2005; Le Heron *et al.* 2004, 2006; Le Heron & Craig, 2008). The prime academic motivation for study has been to reconstruct the ice sheet (Le Heron & Craig, 2008), but ultimately the main driver has been economic. As Late Ordovician glaciogenic reservoirs continue to be important in Libya, as well as in eastern Algeria (e.g. Hirst *et al.* 2002), it is increasingly important to integrate outcrop studies with subsurface data, and vice versa.

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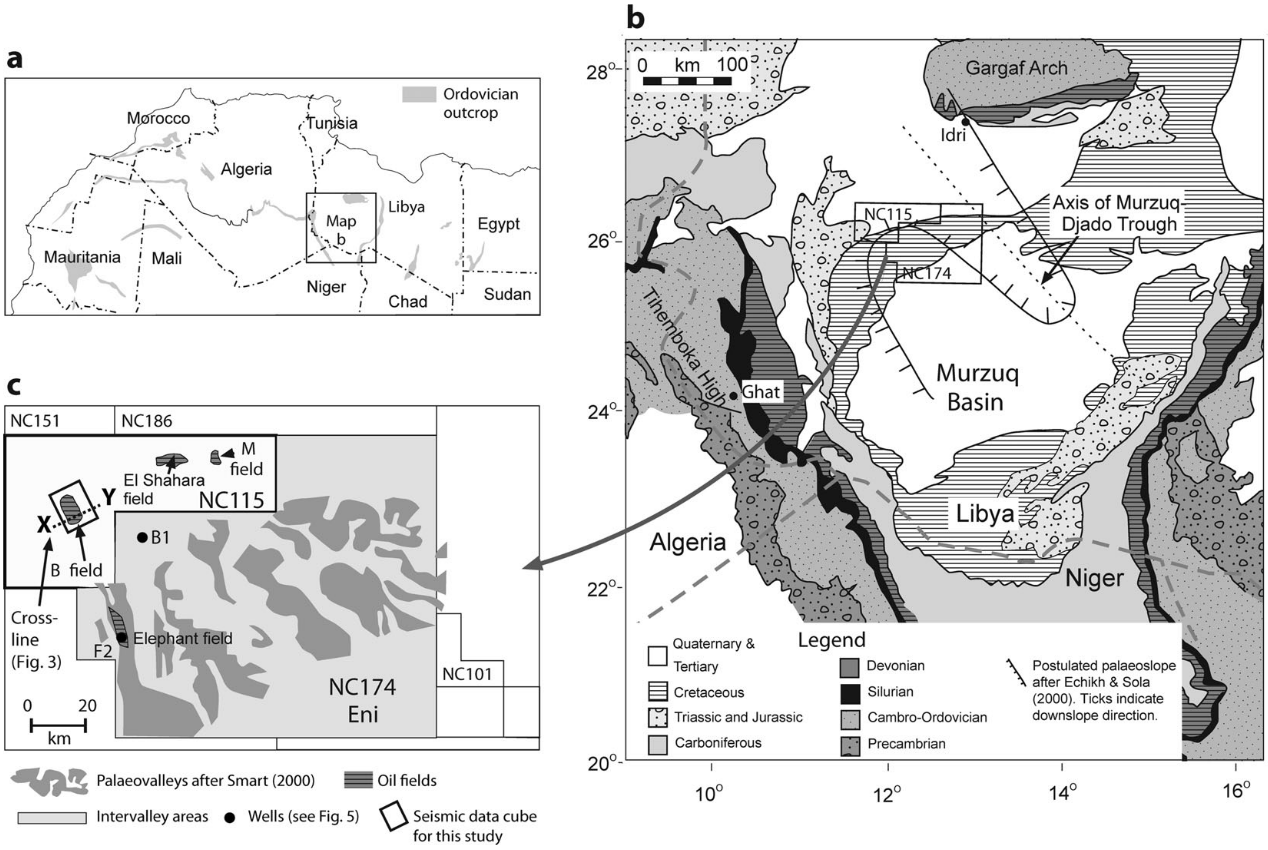

Figure 1. (a) Location map of the Murzuq Basin in the context of North Africa. Outcrops of Ordovician strata, including uppermost Ordovician strata correlative to those examined on seismic data in the present study, are shown in grey. (b) Geological sketch map of the Murzuq Basin, SW Libya, showing the main basin flanking outcrops where Late Ordovician glacially related strata are exposed, and the location of concession NC115 containing the seismic dataset presented in this paper. The two generations of sinuous and anastomosing tunnel valleys mapped by Smart (2000) from 2-D seismic data from the NC174 concession are also shown. (c) Location of subsurface data contained in this paper. Structural elements of the basin (axis of the Murzuq-Djado Trough and Cambro-Ordovician palaeohigh) are after Echikh & Sola (2000).

In this paper, we use seismic reflection datasets to understand aspects of Late Ordovician glacial processes in North Africa. In what can be regarded as a ‘test case’ for these data, we focus upon a 3-D seismic dataset collected from the northern part of the Murzuq Basin, to the north of the giant Elephant oil field (Fig. 1). Our analysis involves evaluating the internal architecture of Late Ordovician glacially related strata covered by the dataset, and reconstructing palaeo-ice sheet processes.

2. Stratigraphic framework

In the N Murzuq Basin, Cambro-Ordovician strata of the Gargaf Group rest unconformably upon conglomerates and sandy redbeds of the Mourizidie Formation (Jacqué, 1962) (Fig. 1). The Gargaf Group is split into four lithostratigraphic units, each of which have their type sections in the western Gargaf Arch. In ascending stratigraphic order, these formations are the Hassouna Formation, the Haouaz Formation, the Melaz Shuqran Formation and the Mamuniyat Formation (Fig. 2). This latter formation defines the topmost part of the Ordovician succession. The type sections were formally established in the accompanying field notes to 1:250 000 scale geological maps (Idrí and Qarāt al Marār sheets: Pařízek, Klen & Rohlich, 1984; Gundobin, 1985). An additional stratigraphic unit earlier known as the Ash Shabiyat Formation (Bellini & Massa, 1980) is now considered to form a lower unit within the Haouaz Formation (Ramos *et al.* 2006). No body fossils have been recovered from the Haouaz Formation, although it was suggested to be Llandeilo to Tremadoc (Lower to Upper Ordovician) age (Pařízek *et al.* 1984; Gundobin, 1985). Recent fieldwork on the Gargaf Arch demonstrates that pre-Hirnantian sandstones of the Haouaz Formation were deposited in tidally influenced marginal marine environments (Ramos *et al.* 2006).

The topmost part of the Gargaf Group is considered to be Hirnantian in age on the basis of atypical *Hirnantia* brachiopod fauna (Sutcliffe *et al.* 2001) found as a coquina within the Melaz Shuqran Formation. This formation is considered to represent the earliest record of glaciomarine sedimentation to have affected the Murzuq Basin in Late Ordovician times (e.g. Sutcliffe *et al.* 2001; Le Heron *et al.* 2006). The Melaz Shuqran rests disconformably upon the Haouaz Formation on the Gargaf Arch (Ramos *et al.* 2006; Le Heron *et al.* 2006). By comparison, on the Tihemboka

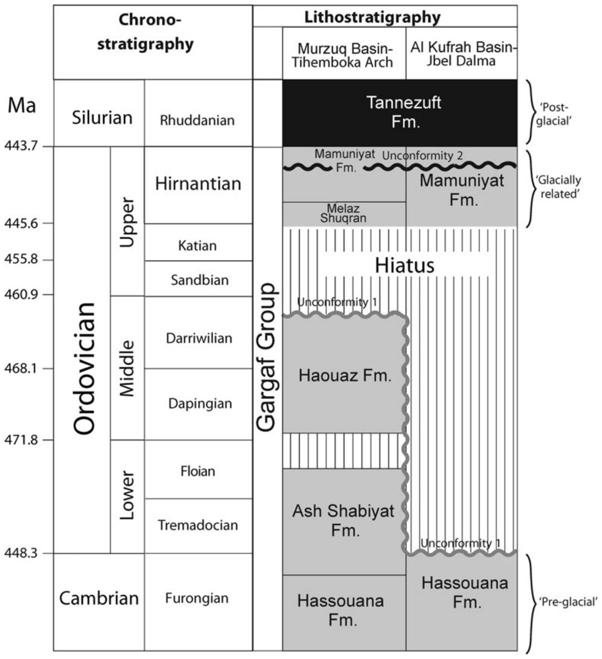

Figure 2. Stratigraphic column for the Lower Palaeozoic succession of southern Libya. The chronostratigraphy column, shown to the left of the chart, incorporates the most recently established stage names after the Subcommission on Ordovician Stratigraphy (2008). Hiatuses are shown in grey vertical dashed lines. Two principal unconformities are shown: the first occurs at the base of the Melaz Shuqran Formation, whereas the second separates this formation from the overlying Mamuniyat Formation. Together, these two formations represent the sedimentary record of Late Ordovician glaciation in the Murzuq Basin, which, on the basis of atypical brachiod fauna, have yielded a Hirnantian age from the Melaz Shuqran Formation (Sutcliffe *et al.* 2001).

Arch at the western basin margin, a more angular unconformity characterizes the contact between the Haouaz Formation and overlying glaciogenic rocks (e.g. El-ghali, 2005; Le Heron *et al.* 2006) which is particularly well expressed in neighbouring Iherir and Dider, SE Algeria (Hirst *et al.* 2002; Eschard *et al.* 2005). The unconformity separating the Haouaz from the Melaz Shuqran Formation is interpreted as composite in origin, recording the combined effects of isostatic loading during ice sheet advance and subglacial erosion (Sutcliffe *et al.* 2000; El-ghali, 2005; Le Heron *et al.* 2006).

Lithologically, the Melaz Shuqran Formation comprises clast-poor, sandy diamictites, siltstones and subordinate sandstones organized into a coarsening-upward succession that is interpreted to record the re-advance of ice sheets across the platform (cf. El-ghali, 2005; Le Heron *et al.* 2006). It is characterized by significant lateral thickness variations that result largely from truncation by palaeovalleys defining the unconformity at the base of the overlying Mamuniyat Formation (e.g. Ghienne *et al.* 2003; Le Heron & Craig, 2008). The Mamuniyat Formation is divided into three informal lithostratigraphic units or members: the lowermost is dominated by sandstone and conglomerate, the intermediate unit bears close lithological similarities to the Melaz Shuqran Formation, and the third is dominated by fine-grained shallow marine sandstone (Le Heron *et al.* 2006). Each of these informal units is bounded by unconformities which control the thickness and distribution of each unit. These unconformities vary in character from representing significant relief/palaeovalley incisions (e.g. Ghienne *et al.* 2003; Le Heron *et al.* 2004; Le Heron & Craig, 2008) to disconformities (Le Heron *et al.* 2006). The Mamuniyat Formation is overlain by shale of the Tannezuft Formation, which on the Gargaf Arch is assigned an Aeronian (Early Silurian) age (Lüning *et al.* 2000, p. 170) (Fig. 2).

Analysis of Hirnantian sediments, including the Melaz Shuqran and Mamuniyat formations, across North Africa highlights a strong influence of glaciation on sedimentation patterns (e.g. Sutcliffe *et al.* 2000, 2001; Hirst *et al.* 2002; Ghienne *et al.* 2003, 2007; Le Heron & Craig, 2008). Based on outcrop research, both small-scale, glacially generated structures such as striations (Deynoux & Ghienne, 2004; Le Heron *et al.* 2005) and the largest-scale palaeovalleys (e.g. Ghienne *et al.* 2003; Le Heron *et al.* 2004; Moreau *et al.* 2005) are restricted to the Late Ordovician glacial succession. As these features are notably absent from the Haouaz Formation, it is therefore regarded as a pre-glacial succession.

3. Previous work

3.a. Seismic reflection studies in North Africa

Studies of pre-Cenozoic glacial deposits using seismic reflection data are extremely few. In Libya, Smart (2000) mapped incisions of Late Ordovician age from 2-D seismic data in the N Murzuq Basin (Fig. 1). His mapping identified a lowermost set of incisions that were generally broad (> 25 km), long and NNW–SSE oriented. The basal surface of these incisions was interpreted as an unconformity defining the base of the Late Ordovician (Hirnantian) glacial succession. In the present paper, this unconformity is expressed as an Intra-Ordovician reflector within the Lower Palaeozoic succession (Fig. 3). Two further sets of anastomosing palaeovalleys in identical orientations were identified in the overlying sediments, which in turn were found to be overlain by well-dated lowermost Silurian shale (Smart, 2000). In this work, no detailed interpretations were offered for the origin of these palaeovalleys. However, their anasotomosing character (Fig. 1) is analogous with subglacial meltwater channels or tunnel valleys that were produced during Quaternary deglaciation of Germany (Ehlers, 1981) and the North Sea (e.g. Wingfield, 1990). Spectacular palaeovalley incisions are now being imaged from seismic data across wide areas of Libya, and multi-kilometre wide palaeovalleys, some bearing striations at their bases, are recognized at outcrop on the Gargaf Arch that cut down into the pre-glacial Haouaz Formation (Fig. 4a, b). Such

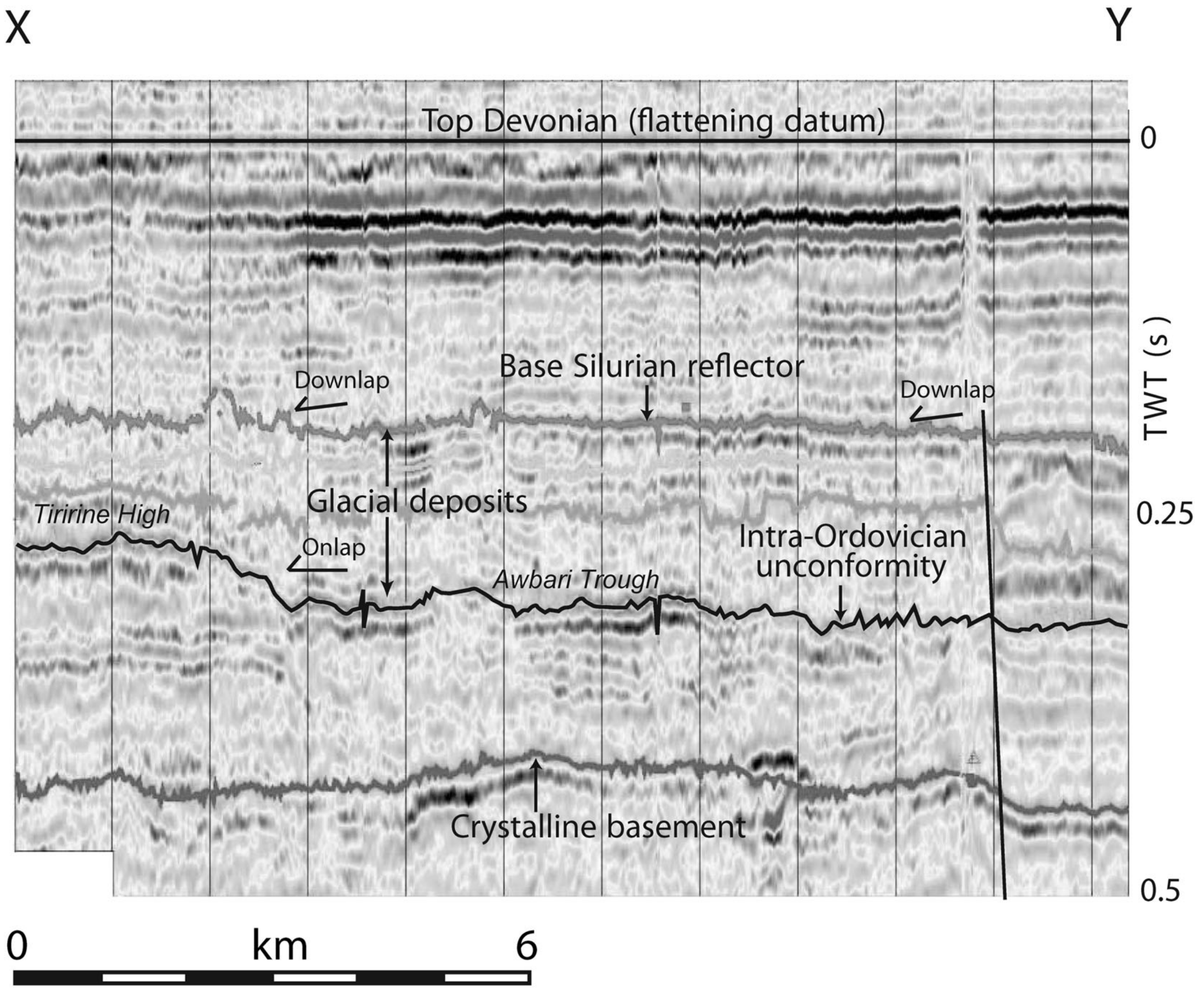

Figure 3. Seismic cross-line across the B-field, NC115, in the N Murzuq Basin; see Figure 1c for location. Seismic sections have been flattened to the top Devonian. Note the lateral continuity of reflectors and their general sub-horizontal character. Unconformities 1 and 2 (UC1, UC2) are regionally extensive and can be traced across the B-field. Note the onlap of reflectors onto UC1, and the occurrence of a large fault to the right of the seismic line which does not penetrate the base Silurian.

palaeovalleys have received much attention in recent years as 'prospect-scale' analogues to incisions in the subsurface of SW Libya. To date, however, no detailed studies based on seismic data have been forthcoming which might provide direct linkage between research advances made at outcrop, and subsurface (exploration) data. One reason for this may be the commercial sensitivity of the data itself, although the quality of the seismic data (particularly where collected over sand seas) is sometimes poor. A systematic analysis of the morphology and fill of seismically defined palaeovalleys is therefore overdue.

3.b. Core-based studies of Late Ordovician glacially related deposits

Hydrocarbon exploration has resulted in the recovery of core material of Late Ordovician glacially related deposits from the N Murzuq Basin. The core materials provide an important link with sedimentological data derived from outcrop on the Gargaf Arch, and which can be readily integrated with seismic reflection data. Data from both the B1 well and F2 well (locations shown on Fig. 1c), which penetrated the Melaz Shuqran and Mamuniyat formations, respectively, were published by El-ghali (2005). Logs from both of these wells are reproduced herein on Figure 5. Both wells were drilled in the NC174 concession rather than NC115 (Fig. 1).

In the B1 well, the Melaz Shuqran Formation comprises a > 30 m thick succession (Fig. 5a). The contact/unconformity with the Haouaz Formation is not observed on these data. Likewise, previously published interpretations of seismic sections through NC115 have only inferred the contact, as a result of the poor quality of seismic reflection data (e.g. fig. 3 of Aziz, 2000). The Melaz Shuqran Formation comprises stacked fining-upward successions of massive and parallel laminated sandstone 1–2 m thick, separated by 1–3 m of mudrocks (Fig. 5a). Additionally, in his consideration of these deposits as part of a delta facies association, El-ghali (2005) described the presence

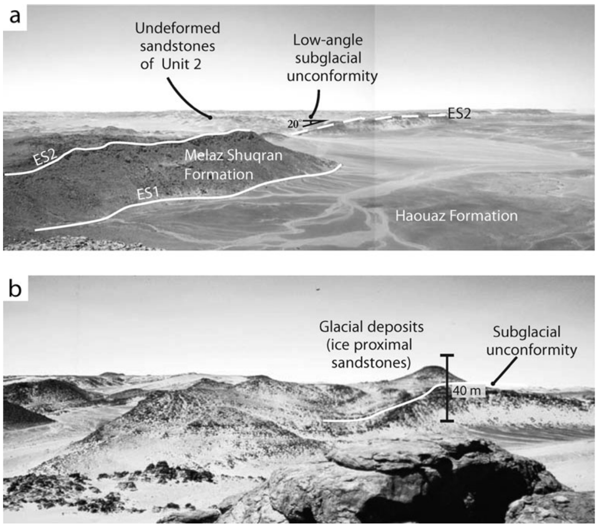

Figure 4. Examples of Late Ordovician glacial palaeovalleys from southern Libya. (a) Eastern flank of a large palaeovalley observed at outcrop on the Gargaf Arch, developed within glacial deposits resting unconformably upon the Haouaz Formation. (b) Detail of deformation along the strike of the palaeovalley shown in (a), illustrating the potential for disruption of sediments as a result of glacial/glaciotectonic processes.

of trough cross-stratification, wave ripples and mud drapes which are 'also recognized in the drill cores'. Despite this, these features were not illustrated in a facies analysis of the core (fig. 5C of El-ghali, 2005).

For El-ghali (2005), a prograding delta complex was the preferred interpretation of the Melaz Shuqran Formation in the B1 well (Fig. 5, left). This was also consistent with earlier published interpretations of Repsol/Remsa, based largely on proprietary work (Aziz, 2000). Here, however, we challenge that interpretation by pointing out (1) the absence of evidence of an overall coarsening-upward profile indicating the progradation of a delta system, (2) the absence of sedimentary structures generated by tractive processes within the cored section and the predominance of massive sandstone beds instead, and (3) the organization of the Melaz Shuqran into well-developed fining-upward cycles. Dealing with each of these points in turn, deltaic successions consist of a predictable vertical transition of lithofacies reflecting

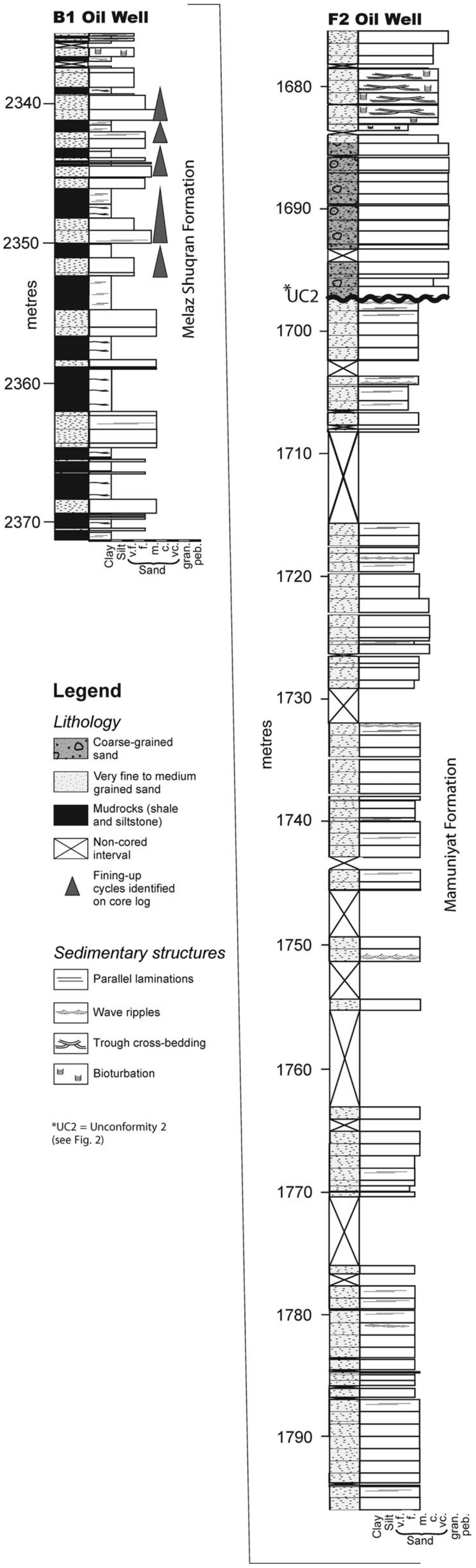

Figure 5. Sedimentary logs from the subsurface of the N Murzuq Basin that correspond to the interval of seismic data covered in this paper. The paucity of public domain data available for this area leaves the data open to different interpretations (see text for these alternatives). The deposits in the F2 well lie to the south of those in the B1 well (see Fig. 1 for exact locations). In the F2 well, a significant unconformity is identified toward the top of the glacially related succession, dividing fine-grained sandstones below from pebbly sandstones and granular conglomerates above. This horizon is interpreted as the second significant unconformity idenitified in the 3-D data cube. Such a major lithological change above an unconformity is likely to deliver a strong reflector which can be identified in NC115. Logs modified after the originals published in El-ghali (2005).

the relative importance of competing river, wave and tidal processes as the delta progrades into deeper water (Bhattacharya & Walker, 1992). Such predictable transitions are absent from the B1 core. Second, for a deltaic succession, traction deposits such as stacked sets of climbing ripples characterize many medial to proximal mouth bar deposits in river-dominated delta settings (e.g. Bhattacharya & Giosan, 2003), whereas in wave-influenced deltas, structures such as hummocky or swaley cross-strata (Cheel & Leckie, 1993) and/or wave ripples should be expected. Finally, in tidally dominated systems, features such as herringbone cross-bedding and clay drapes on foresets are common, while cyclicity (e.g. tidal bundles) provides further evidence for tidal depositional processes (Klein, 1970). Given that, in the B1 core at least, these features are absent, an alternative interpretation must be sought. The predominance of massive sandstone beds arranged into fining-upward cycles is more likely to indicate deposition by gravity flows, potentially turbidites (Gani, 2004). Therefore, the sedimentological characteristics of the B1 well compare closely with glacio-turbidites that have been investigated in detail near Wadi Analalin on the Tihemboka Arch (Le Heron *et al.* 2006).

The contact with the overlying Mamuniyat Formation was not illustrated by El-ghali (2005). In well F2-NC174 (Fig. 5, right), the lower and middle parts of the Mamuniyat Formation consist of a monotonous succession of fine-grained sandstones ~ 80 m thick, that are typically massively bedded, with rare parallel lamination and possible wave ripples. These deposits are capped disconformably to unconformably by 25 m of coarse-grained sandstone to granular conglomerate, bearing rip-up clasts of underlying sandstone and trough cross-bedding and bioturbation towards the top. El-ghali (2005) proposed a foreshore interpretation for the lower monotonous sandstones, although this may be questionable, due again to (1) the prevalence of massive beds that are poor in sedimentary structure and (2) the stratigraphic position of these deposits below the considerably coarser deposits. In line with the interpretations for the Melaz Shuqran Formation offered above, it is suggested that the Mamuniyat Formation records comparatively more proximal gravity flow processes, producing stacked turbidites. Therefore, the Melaz Shuqran Formation (Fig. 5, left) through to the lower and middle parts of the Mamuniyat Formation (Fig. 5, right) are suggested to represent part of a subaqueous (marine) fan complex.

The topmost, coarse-grained sandstone unit (Fig. 5, right, 1697–1677 m) lies sharply on underlying deposits. The dramatic increase in grain size, coupled with a subtle change in dip azimuth (Aziz, 2000), indicates that the surface at the base of the coarse-grained sandstone unit corresponds to a subtle angular unconformity. In wells across the NC115 concession, reported thicknesses of these topmost deposits range from 15 to 45 m (Aziz, 2000). These deposits were considered part of a Gilbert delta by Aziz (2000). Almost identical, coarse-grained sandstones to granular conglomerates with extensive bioturbation (*Thalassanoides*) of a very similar thickness (< 40 m) are recorded from the topmost unit of the Mamuniyat Formation north of Ghat on the Tihemboka Arch (Le Heron *et al.* 2006). Resting above a glacially cut unconformity, these deposits were interpreted as ice-proximal deposits reworked during ice sheet retreat (Le Heron *et al.* 2006).

In addition to providing new interpretations for published core data, the previous section has highlighted how outcrop observations can be linked directly to subsurface core descriptions to provide a close linkage between the two datasets, hence more confidently enabling the extension of sedimentary models for better studied outcrop sections into the subsurface. These sedimentary models provide a context with which to interpret seismic reflection data from glacially related deposits in the N Murzuq Basin.

4. Seismic data analysis

4.a. Seismic stratigraphy

In seismic section, the sedimentary rocks of the N Murzuq Basin are characterized by parallel and shallow dipping reflectors that are mostly laterally continuous (Fig. 3). The base of the sedimentary succession is marked by a strong, high amplitude, negative phase reflection (the ‘basement pick’; Fig. 3). Onlap of this reflector, which locally shows a polarity reversal from a negative (trough) to a positive (peak), is exhibited by overlying reflectors. Though unpenetrated by wells in the N Murzuq Basin, this reflector probably compares to the Infra-Cambrian unconformity separating metamorphosed Infracambrian flysch deposits from unmetamorphosed Cambrian sandstones in SE Algeria (Beuf *et al.* 1971).

Upper Ordovician unconformity 1 (UC1) is picked along a strong, negative phase reflector generally 90–160 ms two way travel time (TWT) above the basement pick (Fig. 3). This reflector defines a coherent, traceable event over much of the study area, although it diminishes in strength to the east and south and near the edges of the data cube, as a result of a decrease in the ‘fold’ of the seismic data. Because UC1 is the most significant discontinuity above the basement pick, and underlying reflectors exhibit toplap against it, this unconformity is interpreted to define the base of the Hirnantian glacially related sediment package (that is, the base of the Melaz Shuqran Formation). The overlying upper Ordovician unconformity 2 (UC2) is thus interpreted as an intra-formational unconformity within the glacially related succession, and corresponds either to the base of the Mamuniyat Formation or to the base of one of the informally defined members within it (e.g. le Heron *et al.* 2006). This surface was picked along a widespread negative phase reflection between 30 and 80 ms above UC1. The base Silurian is identified by a negative phase reflection that varies significantly in amplitude, above which reflections downlap at a very low angle (Fig. 3). The Top Devonian reflector is coherent, of consistent amplitude, easy to trace across the block, and characterized by a negative phase reflector (Fig. 3). Confirmation of the stratigraphic affinity of these reflectors is facilitated by good well control across the NC115 and NC174 concessions (Aziz, 2000; Smart, 2000).

The limited visual information available from cross-lines through the seismic data cube (Fig. 3) focuses our attention on the generation and interpretation of high-resolution time-slices, isochore and isochron maps (Figs 6–9). In 3-D seismic data, data bins of equal value are joined to give contours known as isochores. These values can be used to illustrate the topography of glacially related (intra-Ordovician) and post-glacial (base Silurian) unconformities, albeit with a subsequent tectonic overprint. The effects of subsequent tectonic overprint have been minimalized by flattening the isochores to a top Devonian datum, which has been chosen as it is a regionally extensive flooding surface (e.g. Adamson *et al.* 2000). Isochron data, by comparison, give the 'time thickness' of a data interval, such as between two unconformities, to provide information on the stratigraphic thickness between these two surfaces. Combining maps showing time-slice, isochore and isochron data, it is possible to gain detailed insight into the evolution of glacial sedimentary systems in the Late Ordovician in plan view.

4.b. Time-slice data: description

The time-slice data available range from 272 ms TWT (deepest and oldest) to 232 ms TWT (shallowest and youngest), and these are shown with corresponding interpretations on Figure 6. These data cover an approximate stratigraphic interval from UC1 (base Melaz Shuqran Formation) to just below the base Silurian. Each of the slices was cut through a data cube flattened to the top Devonian. In these datasets, red and orange hues are positive reflections and grey and blacks negative, whereas zero crossovers are white. Features discussed below, and their corresponding interpretations, are shown on Figure 6.

At 272 ms TWT (Fig. 6a, b), a well-defined, sinuous and sharp WNW–ESE-trending feature is identified between negative reflections to the west and positive reflections to the east. In the south and southeast of the dataset, well-defined negative reflections occur. On the 264 ms TWT time-slice (Fig. 6c, d), these reflections are absent. By 256 ms TWT (Fig. 6e, f), a series of poorly defined, NW–SE-trending channels appear. These channels attain 3 km long and 50–100 m wide, and occur in association with an area characterized by a strong, positive reflection. At 248 ms TWT (Fig. 6g, h), this strong positive reflection attains approximately 48 km^2 in area, and the channel network extends up to 8 km in length. By 240 ms TWT (Fig. 6i, j), the palaeovalley margin in the western part of the dataset has become concealed, and in the far northeast of the data cube, lenticular patches of positive reflections occur that are elongate in a NW–SE direction. These lenses attain dimensions of only a few hundred metres. The final time-slice, at 232 ms TWT (Fig. 6k, l) shows a mature dendritic channel network, extending at least 10 km in length. Positive reflections define the channels.

4.c. Time-slice data: interpretation

A sequential interpretation of these data is provided below each of the time-slices on Figure 6. The sharply defined, WNW–ESE-oriented sinuous feature at 272 ms TWT (Fig. 6a, b) is interpreted as a buried palaeo-escarpment, with a higher (cliff-forming) western margin and a lower (basin-forming) eastern margin. In seismic cross-section (Fig. 3), the palaeo-escarpment can be seen to mark the boundary between the Tiririne High to the west and the Awbari Trough to the east. The escarpment and the trough are interpreted as the morphological expression of a major unconformity dividing pre-glacial sediments below from Late Ordovician (?Hirnantian) glacially related sediments above. Below, we consider two competing interpretations for the origins of the palaeo-escarpment: (1) a fault margin that was active during sedimentation and (2) a glacially related palaeotopography/palaeovalley margin.

On the Gargaf Arch, there is evidence for faults that were active during sedimentation, cross-cutting the Mamuniyat Formation at outcrop, and locally defining the flanks of palaeovalley incisions (Ghienne *et al.* 2003). Additionally, the upper part of the Mamuniyat Formation in the same area shows evidence for growth faulting within half graben (Le Heron *et al.* 2006). In fieldwork on the correlative deposits in Jordan, Turner, Mahklouf & Armstrong (2005) invoked re-activation of Precambrian basement structures to explain thickness variations in the Ammar Formation. In Jordan, the lateral distribution of a green, chloritic siltstone at the base of the succession shows significant lateral thickness variations and termination against faults. The faults were interpreted to have been hardened by permafrost activity and were considered to have formed parallel to the strike of the ice margin (fig. 14 of Turner, Mahklouf & Armstrong, 2005). On our data, in seismic cross-section (Fig. 3), there is no evidence for offset of reflectors either side of the palaeo-escarpment that might be suggestive of syn-sedimentary tectonics. The palaeo-escarpment is thus interpreted as the flank of a palaeovalley whose margin was not, in this case, fault defined. Furthermore, the westward onlap of reflections onto the palaeo-escarpment is consistent with a topographically subdued area lying to its east (Fig. 3), and demonstrates that it is not a data-processing artefact. As a similar escarpment is not observed in the eastern part of the data cube, we conclude that the palaeovalley is at least 8 km wide.

Time-slices 272 to 232 record the development, filling and overspilling of a Late Ordovician palaeotopography. In time-slices 272 and 264, the margins

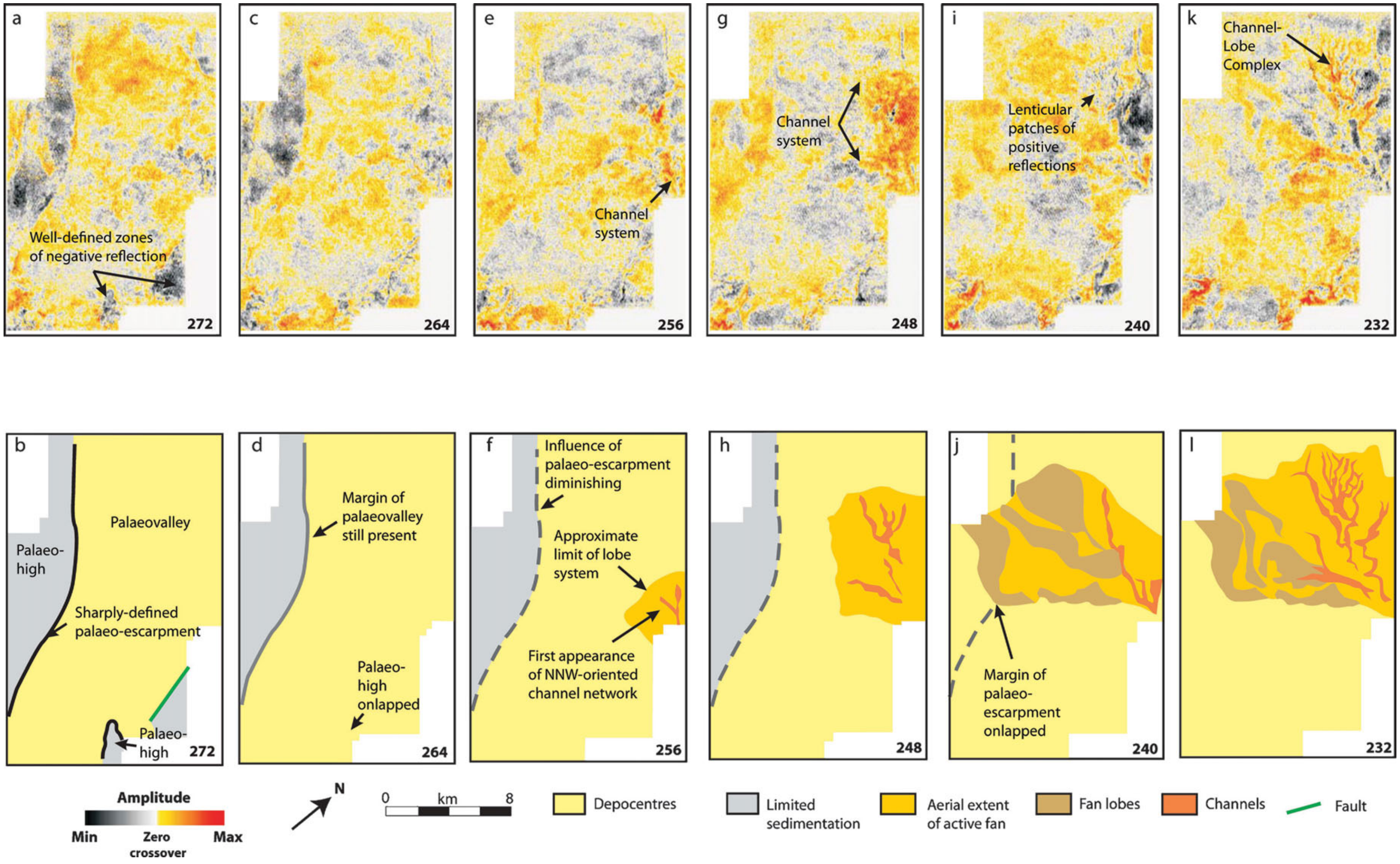

Figure 6. Time-slice data (top row: a, c, e, g, i, k) with corresponding interpretations immediately beneath each time-slice (bottom row: b, d, f, h, j, l) from the B-field, NC115. From left to right, each of the images corresponds to successively ‘higher’ time-slices, corresponding to progressively younger stratigraphic intervals. The data shown here range from 272 to 232 ms TWT. See text for interpretation of successive time-slices.

of this palaeovalley are well defined (Fig. 6a–d). The areas of strong negative reflections on time-slice 272 are interpreted as topographically raised areas, the disappearance of which on successive time-slices indicates onlap and concealment by later sediments. The presence of active sedimentary depositional lobes is implied by the occurrence of bulbous areas of high-amplitude, positive reflections (Fig. 6i–l), whereas the progressive development of a dendritic channel network between time-slices 256 and 232 indicates the NW progradation of this fan system (Fig. 6e–l). As the channel-lobe system progrades across the palaeovalley margin on later time-slices (Fig. 6i, j), evidence is provided of the decreasing influence of palaeotopography upon the geometry of sedimentary systems over time.

4.d. Isochore data: description

Isochore data show that for both unconformities 1 and 2 (Fig. 7), a large NE–SW-oriented fault traverses the data cube towards the east. This feature is also present (though less well defined) in the base Silurian time-thickness data (Fig. 7). The palaeo-escarpment at the westward limit of the data cube is also apparent along the base of the glacially related sediments (UC1; Fig. 7a). It is not apparent, however, along either UC2 or the base Silurian reflector (Fig. 7b, c). UC1 is generally shallower (1220 ms TWT) to the western side of the block and deeper ($\sim$ 1270 ms TWT) on its eastern side.

4.e. Isochore data: interpretation

The isochore data support the evidence from time-slices of an important palaeo-escarpment, interpreted to define the western flank of a palaeovalley in the Awbai Trough (Figs 7, 8). Moreover, the poor definition of this feature in the isochore for UC2 (Fig. 7b) also supports the idea of a diminishing influence on sedimentation over time. Taking the difference in time-thickness values between UC1 and the base Silurian (110–160 ms TWT in the interpreted palaeovalley versus 70–95 ms TWT outside of it), the sediment thickness differences across the interpreted palaeovalley can be calculated as follows:

$$\frac{\mathrm{D} = \mathrm{V}_0\mathrm{TWT}}{2} \qquad (1)$$

where D is the thickness of the interval being measured, V_0 is the velocity through which P-waves propagate, and TWT is the two-way travel time. Taking a very conservative seismic velocity through Ordovician strata of $\sim 4000\ \mathrm{m\,s^{-1}}$ (cf. Tod *et al.* 2007), 1 ms TWT approximates to 2 m thickness. Therefore, sediment thicknesses within the palaeovalley range from about 220 to 320 m, whereas those outside the palaeovalley attain only 140–190 m thickness.

4.f. Isochron data: description

Isochron data calculated for the total thickness of the glacially related succession (that is, between UC1 and the base Silurian; Fig. 8) show significant differences in time thickness across the palaeovalley margin. To its west, time thicknesses measure 70–95 ms TWT, but to its east, time thicknesses of 110–160 ms TWT are noted. A ‘time thin’ also occurs to the southeast of the block, corresponding to the palaeohigh interpreted from the time-slice data (Fig. 6a). No significant time thickness differences occur across the large faults mentioned above. Isochron data calculated for the upper part of the glacially related succession (UC2 minus base Silurian) show much more subtle time-thickness differences across the palaeovalley margin (Fig. 9). The time thickness of this interval varies approximately 30–60 ms TWT. In the northern part of the data cube, a 5 km wide, parallel-sided W–E-oriented channel-like feature is identified which cross-cuts the underlying palaeovalley margin (Fig. 9).

4.g. Isochron data: interpretation

The ‘time thin’ apparent on the total upper Ordovician isochron data at the south of the data cube confirms the palaeohigh interpretation on the time-slice data (cf. Figs 6a, b, 8). The gradual decrease in time thickness toward the south of the palaeovalley may reflect comparatively less incision towards the south of the block, with progressive down-cutting to the north.

The identification of a wide channel feature in the upper part of the glacially related sediments (Fig. 9) is notable because this structure does not appear at any level on the time-slice data (Fig. 6a–l). A time-slice across a totally flat lithological unit of consistent thickness and tabular geometry within the data cube would be expected to return a laterally continuous seismic peak or a trough. In contrast, a time-slice across a dipping or folded lithological unit in the data cube would be expected to return a combination of peaks and troughs in response to the changes in acoustic impedance across the unit. Using equation (1), thicknesses of $\sim$ 120 m for the channel sediments can be estimated, as compared to $\sim$ 100 m outside of the channel; these values are suggestive of a broad, shallow channel. On slightly diachronous time-slice data, it is not surprising that such a shallow channel would not be detected.

To the south of the data cube, in concession NC174, high-angle reverse faults occur, striking NNW–SSE to NNE–SSW, and one of these is the main structure on which the giant Elephant field is located (Davidson *et al.* 2000). These are thought to have been initiated as normal faults during the late Ordovician, and are suggested to have influenced subsequent facies trends parallel to them, before being reactivated during Alpine compression (Davidson *et al.* 2000). To the south of the data cube, the C1–NC174 structure is an example of a

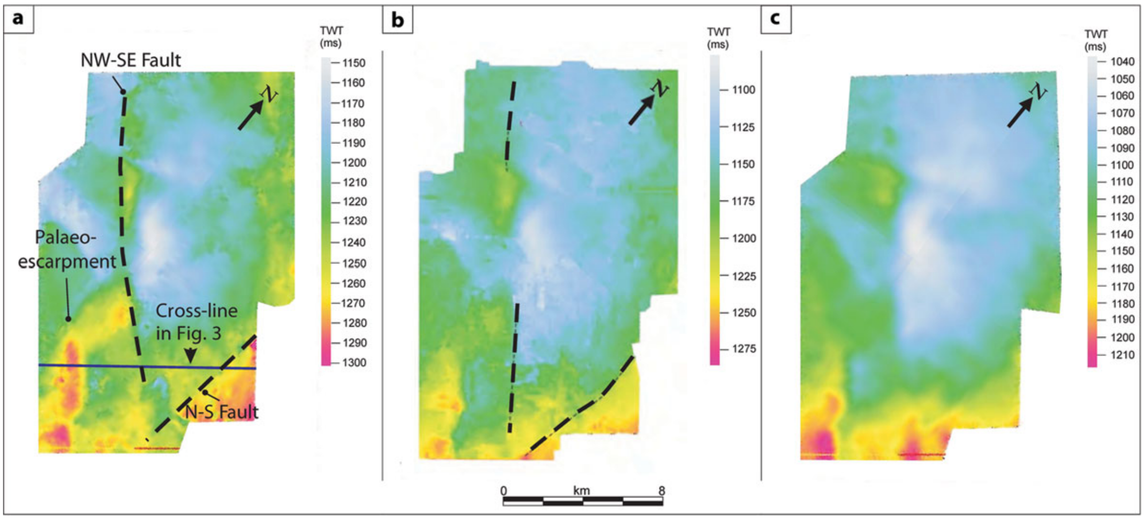

Figure 7. Two way travel time (TWT) isochore data to emphasize unconformities at the base of, within and above the glacially related sediment package. (a) Isochore data for Unconformity 1, interpreted to mark the base of the Late Ordovician glacial succession. (b) Unconformity 2, an intra-formational discontinuity within the glacially related sediments. (c) Isochores showing the morphology of the unconformity marking the top of the glacially related sediments/ base of the Silurian shale.

fault that was active during deposition (Smart, 2000). However, there is no indication that faults affected the progradation direction of the fan complex (Fig. 6a–l), and neither is there evidence of a link between faults and the orientation of the shallow channel (Fig. 9). Therefore, our data do not strongly support the idea of syn-glacial tectonics affecting sedimentation in this part of the N Murzuq Basin.

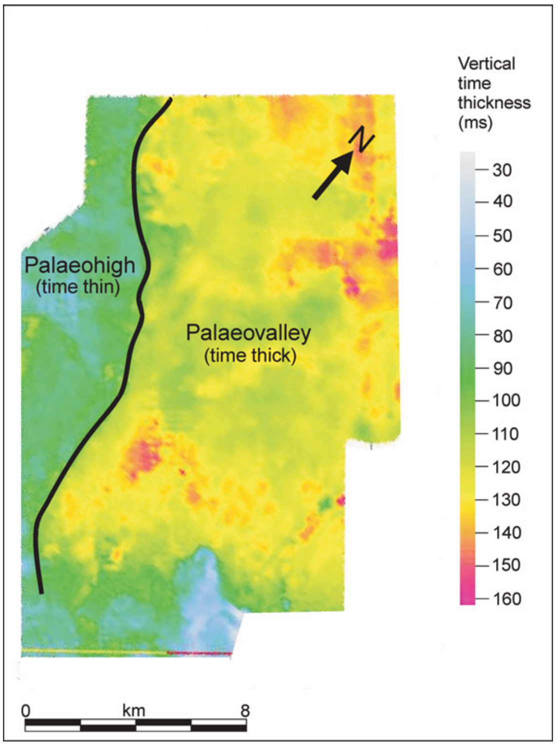

Figure 8. Isochron data for the whole thickness of upper Ordovician strata across the B-field, calculated by subtracting the base Silurian event from the base upper Ordovician unconformity (UC1). These isochron data thus represent the two-way time thickness of the sedimentary package defined at the base by UC1 and above by the lower Silurian reflector. They clearly illustrate the presence of a major palaeovalley in the data cube.

5. Discussion

The three datasets presented in this paper, namely time-slices, isochores and isochrons, each have different roles in interpreting Hirnantian glacial depositional

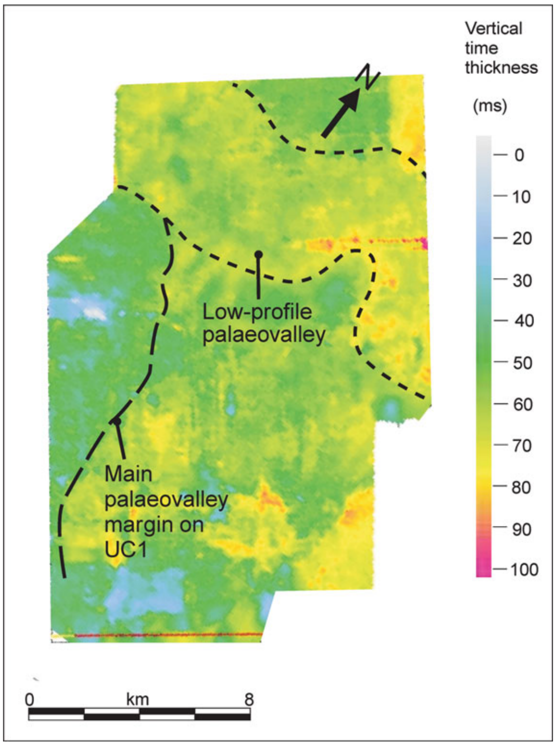

Figure 9. Isochron data for the uppermost glacially related sediment package. These data were calculated by subtracting UC2 from UC1.

processes and hence interpreting palaeo-ice sheet behaviour from 3-D seismic data. To summarize, time-slices enable us to deduce the stepwise evolution of these ancient glacial depositional systems through time (Fig. 6). The influence of each of the glacial unconformities at the base of the succession on sedimentation patterns can be inferred through isochore data (Fig. 7). These include an unconformity interpreted to define the base of the glacial succession (UC1: base of the Melaz Shuqran Formation), within the succession (UC2: interpreted to mark the base of the Mamuniyat Formation), as well as the unconformity at the top of the Mamuniyat Formation representing the transition into the Tannezuft Formation (Fig. 7c) The isochron data, meanwhile, may be used to lend further support for the interpretation of these unconformities, in addition to providing information on the persistence of topography over time through a record of thickness changes across that topography (Figs 8, 9).

The previous sections have shown that, on the time-slice data in particular, there is strong evidence for a palaeo-escarpment which is interpreted to define the western margin of a palaeovalley of unknown width. Despite studies suggesting that active tectonics played an important part during sedimentation to the south in the concession NC174 (Davidson *et al.* 2000), our dataset contains no evidence for a fault-bounded palaeovalley margin in this particular case. Furthermore, while faults are identified on the isochore data (Fig. 7), there is no evidence that they influenced patterns of sedimentation throughout the data cube. This finding comes despite unequivocal evidence for fault activity during deposition of the Mamuniyat Formation on the Gargaf Arch, noting that in some cases palaeovalleys may be fault-bounded (Ghienne *et al.* 2003). The time-slice data reveal that the palaeo-escarpment had a diminishing influence on sedimentation over time.

As noted previously, no ‘counterpart’ palaeo-escarpment is observed in the easternmost part of the data cube, suggesting that the palaeovalley is > 10 km wide. Constraints must be sought on its width before an interpretation is offered. In the M-field, approximately 60 km to the east, a clear NW–SE-trending palaeo-escarpment (or ‘buried hill’) is recognized on the top surface of the Haouaz Formation from proprietary well and seismic data (Aziz, 2000) (Fig. 9). This palaeo-escarpment exhibits onlap from the west by the Melaz Shuqran and Mamuniyat formations (Aziz, 2000), and marks the eastern extent of the Awbari Trough. Therefore, it is suggested that the palaeo-escarpment discussed in the current paper has a counterpart in the M-field, defining a palaeovalley of about 60 km width, that is, the width of the Awbari Trough.

Published data on Late Ordovician glacially related palaeovalleys indicate a range of dimensions that reflect the process by which they formed. Tunnel valleys, cut underneath ice sheets by meltwater at enhanced hydrostatic pressures, typically measure 1–6 km width across the North Africa/Middle East region (Beuf *et al.* 1971; Vaslet, 1990; Powell, Basim Khalil & Masri, 1994; Ghienne & Deynoux, 1998; Ghienne *et al.* 2003; Le Heron *et al.* 2004). In the Illizi Basin of neighbouring Algeria, these incisions are observed to cut approximately 300 m into underlying stratigraphy (Hirst *et al.* 2002). The widths and depths of these Late Ordovician tunnel valleys are almost identical to those associated with the Saalian ice retreat in the North Sea and imaged on seismic data (e.g. Lonergan, Maidment & Collier, 2006; Huuse & Lykke-Andersen, 2000) and to those at outcrop on the North European Plain (Ehlers, 1981). These analogues suggest that at up to 60 km width, the palaeovalley cut along UC1 is too large to have formed through the work of subglacial meltwater processes. Furthermore, the likely width of the palaeovalley also exceeds the dimensions of incisions on the shelf that may have been produced during sea-level fall during ice sheet growth: fluvial incised valleys rarely exceed a few kilometres in width (Catuneanu, 2006). However, this hypothesis is rejected when it is considered that sediment thicknesses within this incision locally exceed about 320 m. This would indicate accommodation space within an incision deeper than that possible by the maximum of ∼ 80 m of eustatic sea-level fall estimated from sections remote from the centre of glaciation (Meifod, Wales: Brenchley *et al.* 2006).

A third hypothesis is that the Awbari Trough palaeovalley cut along UC1 belongs to a much larger, regional-scale feature formed directly by ice rather than meltwater erosion. In the modern-day Barents Sea, the continental shelf is traversed by elongate and sinuous cross-shelf troughs. These features, which were cut by the passage of Pleistocene ice streams, are several tens of kilometres wide, hundreds of kilometres long, and oriented parallel to palaeo-ice sheet flow (Andreassen *et al.* 2004). At a width of 60 km, the Awbari Trough palaeovalley could correspond to such an incision. By analogy, at outcrop on the Tihemboka Arch, excellent evidence in support of palaeo-ice stream activity has been found (laterally continuous belts of glacial lineations: D. P. Le Heron, unpub. Ph.D. thesis, Univ. Wales Aberystwyth, 2004; Moreau *et al.* 2005; Ghienne *et al.* 2007), and subsequently elsewhere in Libya, in Jabal az-Zalmah at the northern flank of the Al Kufrah Basin (Le Heron & Craig, 2008). This evidence is based, among other criteria, on the recognition of belts of mega-scale glacial lineations that result from extreme attenuation of unconsolidated sediment beneath fast flowing ice. On the dataset presented in this paper, evidence for such mega-scale glacial lineations is lacking. Nevertheless, mega-scale glacial lineations have been mapped on high quality 3-D seismic data elsewhere in the Awbari Trough (J. Moreau, unpub. Ph.D. thesis, Université Louis Pasteur, Strasbourg, 2006). Hence, an origin for the Awbari Trough palaeovalley by ice stream incision is tentatively suggested.

The Awbari Trough palaeovalley may be a northward extension of palaeovalleys incised into the upper surface of the Haouaz Formation to the south in concession NC174 (Smart, 2000). Progressive infilling of the Awbari Trough palaeovalley is interpreted to have occurred throughout the Late Ordovician glaciation, as demonstrated by the successive time-slices that provide evidence of progressive concealment of the palaeo-escarpment (Fig. 6). Given our preferred reinterpretation of the core material from wells B1 and F2 NC174, it seems probable that deposition was primarily from turbidite deposits, culminating in the development of a fan system by the end of the glaciation. Available core data suggest that the base of this fan corresponds to Unconformity 2 (UC2) (Fig. 5). These latter coarse-grained fan sediments may compare directly to ice contact deposits following the last glacial cycle to affect the Murzuq Basin in the Ghat region (Le Heron *et al.* 2006), which may also have been reworked during isostatic rebound (El-ghali, 2005). However, from the data presented in this paper alone, it is uncertain whether the topsets were subaqueous (ice contact fan) or subaerial (ice contact delta). At its maximum extent, the fan covered approximately 100 km^2. Successive time-slices demonstrate that periodic switching/abandonment of fan lobes occurred, and that progressively, channels defined a meandering drainage pattern.

The sinuous, 5 km wide channel developed in the uppermost part of the upper Ordovician package (Fig. 8) was probably also cut along UC2, corresponding to the base of the Mamuniyat Formation. The morphology of this channel is much more suggestive of a shallow and wide tunnel valley, while when compared to the depths of incision usually associated with tunnel valleys (~ 100 m or more), tunnel valleys of only 10–25 m deep were cut locally during the Wisconsinan glacial retreat of the Laurentide ice sheet from east-central Minnesota, USA (Patterson, 1994). Hence, it is argued that this sinuous channel was cut during a relatively late phase of meltwater release from Late Ordovician ice sheets. It is possible that the sinuous channel connects southward with a network of base Mamuniyat or intra-Mamuniyat Formation palaeovalleys identified previously on 2-D seismic data in NC174 (Smart, 2000).

6. Summary

Our analysis of a cube of 3-D seismic data in the N Murzuq Basin allows important inferences to be drawn about the nature of glacially related incision processes purely on the basis of seismic data. The nature of the subglacial structures discussed here, namely a large palaeovalley developed on UC1 and a probable low aspect ratio tunnel valley developed on UC2, support the idea for deep glacially related incision in this area. These processes are likely to have accelerated sediment production rates, explaining the high sediment thickness values (up to 320 m) within the palaeovalley. It is probable that the main palaeovalley in the Awbari Trough was 60 km in width with its present margin defined by the M-field, NC115 (Aziz, 2000). The working model proposed here, based upon the dimensions of the structure, proposes that the Awbari Trough palaeovalley is analogous to a cross-shelf trough carved by a palaeo-ice stream. This general interpretation is supported by mapping of mega-scale lineations by previous authors (Moreau *et al.* 2007), but requires further investigation. The analysis of 3-D seismic datasets that image the deposits of pre-Cenozoic glaciations has considerable potential. As a means of bridging the link between outcrop observation and subsurface datasets, the 3-D seismic data clearly play an important role, and may provide a means of partly reconstructing the behaviour of ancient ice sheets.

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