Giant Sandwaves from the Late Ordovician of the Tassili N'Ager , Algeria

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ABSTRACT: Giant sandwaves are described from the Ordovician outcrops of the Tassili N'Ager (SE Algeria). The sandwaves have been examined in the field and mapped using remote sensing techniques (Landsat, SPOT 5 & Quickbird Data) they occur at the top of a Late Ordovician glacial sequence and unconformably overlie a sequence of pro – glacial sediments. They are in turn overlain by shelfal sediments of Lower Silurian age, mostly organic – rich, graptolitic shales that are a major petroleum source rock in Algeria & Libya. The sandwaves are developed in medium to coarse grained sand with occasional quartzose granules and are characterised by large scale, cross sets up to 4m in height with dips of 10 – 15 degrees. Simple, small, vertical burrows are occasionally present. In the outcrops visited cross sets are unidirectional with palaeo flow toward the east. In the Gara Nessaret area the sandwaves outcrop on a gently dipping bedding plane with an areal extent of some 300 square kilometres, minor normal faults break this surface and outliers of the Silurian shales locally obscure the Ordovician sediments but otherwise the sandwaves are superbly exposed. The sandwaves form an array of long (at least 4km) slightly sinuous, locally bifurcating forms the width of which varies along their length (from 90m to 160m). A typical crest to crest distance would be 150m and a typical trough width would be 60m. Aerial photographs and Quickbird images of exceptional outcrops reveal that the internal structure of the sandwaves is dominated by large scale troughs (up to 130m wide) . The coarse grained nature and large size of the bedforms suggests the existence of strong unidirectional currents in the eastern Tassili N'Ager at the end of the Ordovician. The interaction of tidal currents and post – glacial topography in the early stages of the Silurian transgression seems the most likely explanation of these spectacular features

1. INTRODUCTION

The Tassili N'Ager in south eastern Algeria expose a sedimentary succession that ranges in age from Cambrian to Devonian (Eschard etal, 2005). The Cambro – Ordovician section is dominated by sandstones and forms a major escarpment that fringes the basement core of a NE – trending, regional high known as the Tihemboka Arch. The north western limb of the arch dips gently at 1 degree and forms huge bedding plane outcrops in the upper part and top of the Ordovician sequence where it is capped by relatively soft, graptolitic and organic – rich, Silurian shales. A second major escarpment is formed by thick, paralic sandstone units of Late Silurian and Early Devonian age. In the subsurface of the Ghadames / Illizi Basin to the north of the outcrop belt (Figure 1) the Silurian shales have generated large volumes of petroleum some of which has been trapped in both Cambro – Ordovician and Silurian / Devonian sandstone reservoirs. In order to improve our understanding of the subsurface we have undertaken extensive studies of the outcrops using various remote sensing techniques augmented by focused geological fieldwork. We have used an extensive dataset of landsat images (resolution 15m), Spot 5 Panchromatic images (resolution 5m) and some Quickbird images (resolution 0.7m) to try and resolve the outcrop stratigraphy and complex internal geometries of the glacial sequence because this sequence is the main reservoir in the In Amenas Gas Development (BP/Statoil/Sonatrach).. The sandwave sequence that is the subject of this extended abstract is also a significant reservoir unit at In Amenas, but has only been penetrated in a few wells and as yet we do not have the ability to confidently predict where the unit will be found. Unfortunately this unit is typically less than 10m in thickness and beyond

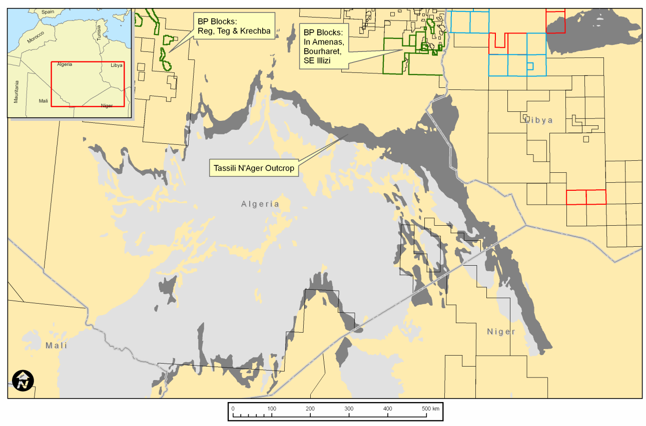

Figure 1. Location map showing Tassili N'Ager and BP blocks in the Ghadames / Illizi Basin

the resolution of our best, wide azimuth 3D seismic dataset (acquired in 2004). On the latter and older (2000) vintage 3D seismic data the most prominent seismic reflector is known as the 'Top Ordovician', this reflector is clearly on-lapped by reflectors within the early part of the overlying Silurian sequence suggesting that considerable 'topography' of several 10's of metres was associated with the 'Top Ordovician' surface. It seems likely that in the subsurface of the Ghadames / Illizi Basin the sandwave sequence overlies the 'Top Ordovician' seismic reflector though this is not proven. In the Tassili N'Ager outcrops there is a western limit to the sandwave sequence and it does appear that onlap is taking place (Beicip / Franlab, 2000).

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1.1 *Late Ordovician Glacial Sequences*

A brief description of the Late Ordovician glacial sequence is required to set some regional stratigraphic context for the overlying sandwave sequence. In the Tassili N'Ager ?Late Cambrian – Middle Ordovician, sand – dominated, paralic sequences are overlain with significant unconformity by a Late Ordovician (Ashgill) glacial sequence. The basal glacial erosion surface is associated with a suite of broadly NNW – SSE trending glacial palaeo – valleys (Beuf etal., 1971 & Eschard etal., 2005), 4 – 15km across and up to 300m deep. Regional ice flow vectors are from south to north. More recent work (Dixon etal 2007) has raised the possibility that the glacial palaeo – valley's occur in discrete 'clusters' defining much larger glacial 'mega – valleys' (150 – 200km wide) that may be the signature of Late Ordovician ice streams (similar to those described by Moreau etal. 2005). In the Tassili N'Ager multiple cycles (at least 3) of glacier advance / retreat have been suggested (Beuf etal., 1971). A similar interpretation of multiple glacial / inter – glacial cycles has been made in the Late Ordovician outcrops of the Gargaf area in Libya (LeHeron etal., 2004). In very general terms the glacial sequences are dominated by sub – glacial facies associations, characterized by 'Tunnel – Valley' geometries, associated tills / glaciotectonites and coarse grained, cross – bedded, glacio – fluvial facies. The inter – glacial sequences are dominated by pro – glacial facies associations characterized by sheet – like / channelised turbidites, and debrites interbedded with graptolitic shales. Evidence of multiple glacial cycles is provided by mappable erosional surfaces that separate cycles of sub – glacial / pro – glacial facies and are characterized by mega – scale, glacial lineations (the glacial 'flutings' of Beuf etal., 1971). In the In Amenas Development some 250km to the north of the outcrop belt, however, the succession in most wells indicate that only one cycle of glacial advance / retreat is present (Prof. Doug Benn, pers. comm.. 2007), though it is worth noting that once again we are probably limited by the resolution of our 3D seismic data in this area. Notwithstanding these subsurface difficulties it is clear in the Tassili that the sandwave sequence rests unconformably on pro – glacial sediments. The upper part of.the proglacial deposits exibit indications of shallowing water with a hardground present in some wells. This hardground may be the product of isostatic rebound as the glaciers retreated. It is also clear that the pro – glacial channel sequences trend NNW – SSE with sediment transport toward the north (Beuf etal. 1971). The dominant transport direction in the overlying sandwave sequence is normal to this ie. From west to east , suggesting a major change in regional sediment distribution patterns at the close of the Late Ordovician glacial episode. It is possible that this change in sedimentation vector might be a further reflection of a short – lived phase of isostatic rebound that modified the glacial topography and locally caused the amplification of tidal currents in the area of the Eastern Tassili.

1.2 *Late Ordovician Sandwave Sequence*

The sandwave sequence is only present in the eastern Tassili N'Ager where it covers an area of several hundred square kilometers. Where present it has a sharp base typically resting directly upon channelised, pro – glacial facies. Pro – glacial sedimentary facies include classical, low – density turbidites and associated high – density turbidites as well as sustained hyperpycnal flow deposits (Hirst etal., 2002). It is difficult to estimate the depositional palaeo - water depth of these pro – glacial facies. Interbedded shales contain graptolites confirming a marine setting (Hirst etal., 2002), but provide little information concerning palaeo – bathymetry which could conceivably have been hundreds of metres. In this context it seems most likely that the locally developed hardground (In Amenas) and the subsequent high energy sandwave sequence reflects a considerable shallowing of the depositional environment ie from 100's of metres to 10's of metres. The sandwaves are developed in medium to coarse grained sand with occasional quartzose granules and are characterised by large scale, cross sets up to 4m in height with dips of 10 – 15 degrees (Beuf etal., 1971). Simple, small, vertical burrows are occasionally present. In the outcrops visited cross sets are unidirectional with palaeo flow toward the east. In the Gara Nessaret area the sandwaves outcrop on a gently dipping bedding plane with an areal extent of some 300 square kilometres, minor normal faults break this surface and outliers of the Silurian shales locally obscure the Ordovician sediments but otherwise the sandwaves are superbly exposed

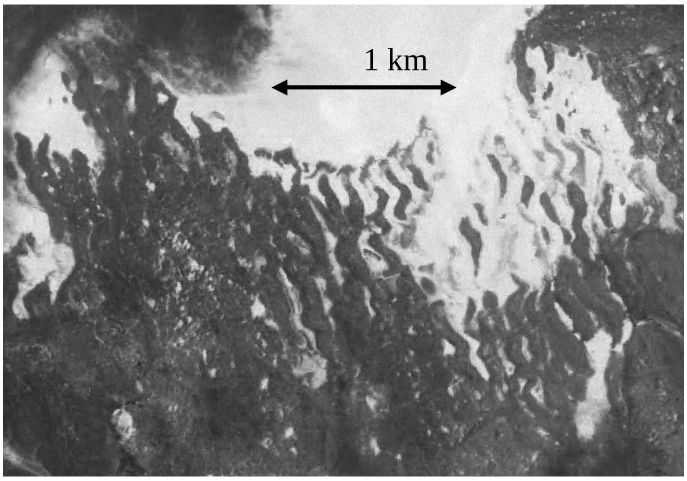

Figure 3. Ikohahoene sandwave field, Tassili N'Ager. Sandwaves are the slightly sinuous, darker features trending north west – south. east The troughs between the sandwaves are topographically low and partly filled by modern windblown sand and thus appear lighter in colour. Note more sinuous form of the sandwaves. Scale bar is 1km long.

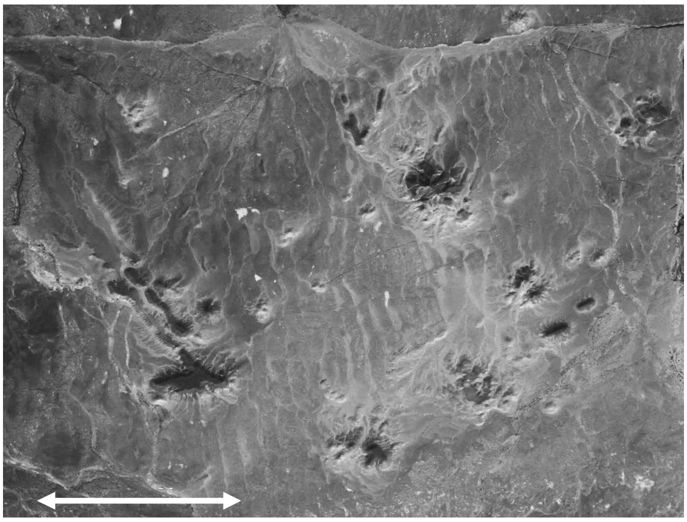

Figure 2. Gara Nessaret sandwave field, Tassili N'Ager. Sandwaves are the slightly sinuous, darker features trending north – south. The troughs between the sandwaves are topographically low and partly filled by modern windblown sand and thus appear lighter in colour. Scale bar is 2km long.

Figure 4. Gara Nessaret sandwave field, Tassili N'Ager. Detail of sandwaves showing large troughs (arrowed). Scale bar is 100m long

The sandwaves form an array of long (at least 4km) slightly sinuous (Figure 2) to locally highly sinuous (Figure 3), locally bifurcating forms the width of which varies along their length (from 90m to 160m).

A typical crest to crest distance would be 150m and a typical trough width would be 60m. Aerial photographs and Quickbird images of exceptional outcrops reveal that the internal structure of the sandwaves is dominated by large scale troughs (up to 130m wide) as shown in Figure 4 .

1.3 Post - Sandwave (Silurian) Sequence

At outcrop the sandwave sequence is overlain by a thin (1m), coarse grained, bioturbated sandstone unit that fines upward into very fine grained sandstones and siltstones that contain graptolites (Beicip / Franlab, 2000). This unit is overlain by a thick (up to 50m) sequence of organic - rich , graptolitic shales deposited in an anoxic shelfal setting. On our 3D and 2D seismic data we observe clear onlap of Silurian reflectors onto the 'Top Ordovician' seismic event and it seems likely that there was significant sea – floor relief during the deposition of the early Silurian shales. This relief has not been mapped regionally, but probably accounts for the local development of anoxic bottom conditions in the area. The Late Silurian is characterized by a significant regression and the progradation from south to north of a major deltaic system. Clinoform geometries observed on regional 2D seismic profiles (Dardour etal. 2004) suggest that the delta was prograding into relatively deep water (100's of metres). The delta system is capped by thick, shoreface and fluvial distributary channel sandbodies.. The shoreface sediments are typified by hummocky – cross stratification suggesting that the coastline was dominated by waves and storms.

CONCLUSIONS

It is our contention that the Late Ordovician sandwave field of the Tassili N'Ager formed in a relatively shallow seaway (10's of metres) that developed in response to a short - lived phase of uplift as the Late Ordovician ice – cap retreated from the area before its final demise leading to global sea - level rise. This uplift punctuates an otherwise transgressive trend and is probably the result of isostatic rebound.

Uplift changed the general pattern of northward drainage allowing new east – west corridors and connections to develop along the shallow marine shelf. Within some of these connecting seaways powerful tidal currents reworked the earlier glaciogenic sediments eastwards in a series of giant sandwaves. As the isostatic pulse waned, water depth increased and the sandwaves were preserved on the sea floor to be blanketed by organic – rich, graptolitic shales that onlapped the remaining sea – floor relief. In the subsequent regression the pattern of northward regional drainage was restablished with the progradation of a major deltaic system. In the subsurface of the Ghadames / Illizi Basin some 250km north of the outcrop belt similar sandwave facies are recognized in some cores from the In Amenas Gas Development. Development well spacing in the field is 3 – 4 km . Unfortunately the 3D seismic data from the field area cannot resolve the sandwave units and the well spacing is too great to characterize the geometry of the sandwave array. Indeed the absence of sandwaves in some of the wells suggests that locally the sea floor was swept clear of the high energy sandstones. In order to optimally develop the sandwave reservoir a better understanding of the geometry and oriention of the subsurface sandwave field is required

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