AAPG Search and Discovery Article #90016©2003 AAPG Hedberg Conference, February 18-20, 2003, Algiers, Algeria.

AAPG HEDBERG CONFERENCE
"Paleozoic and Triassic Petroleum Systems in North Africa"
February 18-20, 2003, Algiers, Algeria

Late Ordovician Glaciation in Northern Gondwana, Reappraisal and Petroleum Implications

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The latest Ordovician glaciation, Late Ashigillian in age, (Hirnantian) is typically a short lived geological event which a profound influence on the Northern Gondwana particularly in Saharian regions. In term of petroleum exploration and production, this glacial event has multiple influences on reservoir, source rock and trap morphology. In this paper we will focus on stratigraphical and sedimentological aspects as well as large scale architecture which have a strong impact on reservoir prediction and also influence trap morphology.

This reappraisal is based on new works carried out:

- on outcrops in Libya and Mauritania,
- on cores, and logs in Algeria, Tunisia and Lybia,
- and on both 2D and 3D seismic in Lybia and Algeria.

A major advance derives from the establishment of a powerful stratigraphic scheme for Lower Palaeozoic series, Galeazzi et al. (2000), Galeazzi et Point (2002) which recognised large scale second order stratigraphic cycles and allows, in absence of datation, to correlate the series in spite of the use of a confusing lithostratigraphic nomenclature. This is particularly useful to define the amount of erosion at the base of glacial deposits.

Maximum advance of the ice cap and glacial fairways

Since the recognition of the ice related deposits, this was a matter of debate. Most of the time, areas mainly dominated by glaciomarine shales are considered to be in front of the ice. Our study and the reappraisal of data, clearly establish that this criteria can not be applied because these facies are present everywhere from north to south and in all glacial cycles. The key point is in fact the stratigraphic gap at the base of the late Ashgillian series which is related to the erosion of grounded shelf ice. Base on this, we can assume that the ice cap reachs at least an east-west line joining the Morocco Anti atlas to Djerba in Tunisia. This bondary is approximatively 300km north of the previous one. It could go further to the North, but this depends of the palimpspatic restoration of the Atlas Ranges which is controversial. For example in south Tunisia and Algeria the "argiles microconglomértiques" commonly rest over tremadocian El Gassi Shales which imply that middle to upper Ordovician deposits have been removed. The same observation can be made in Libya where the Hirnatian Melaz Shuqran rests over an eroded Hawaz not younger than Llanvirnian or older. This erosion is too widespread to be interpreted as an ice rafting feature. In addition this basal surface is commonly much more regular than the yougest glacial erosions surfaces suggesting a cold ice cap deeply rooted in the continent. By place, maximum thickness of glacial series fit very well with the deepest erosion of pre-glacial deposits. This indicates the occurence of wide glacial fairway or glacial streams. The best documented example defines a north south trend from the Tiehemboka to Tunisia, an other one is inferred in the Ougarta area, and a third one is developed in Libya forming a North south trend in the Murzuk basin across the western Al Qarqaf.

Glacial cycles

As all glacial episodes, the latest Ordovician records multiple cycles of advance an retreat of the ice cap. To date four to five cycles have been recorded. All the cycles are not necessarily recorded everywhere, because glacial incisions are not always superimposed but can be juxtaposed. In Libya and Mauritania where we have a good outcrop control, the detailed geometry and the lateral shift can be analysed between the cycles whilst in Algeria and Tunisia where we work on subsurface data, the shifts are inferred, however a careful analysis of Beuf et al. (1972) figures, show that numerous cycles occurs within the Tamadjert Fm. All these phases define an overall retreating of the ice cap, however each phase records an advance of the ice followed by a flooding and progradation of depositional systems coeval to the ice retreat. A type cycle starts with a glacial erosion commonly outline by a glacial pavement developped at the base of the valley. Then a rapid flooding occurs leading to the deposition of a condensed section or immediately followed by glacio-marine silty shales. Depending of regional location, sandy prograding units achieve to infill the valleys. Some other valleys are totally filled with fluvial sandstones, finally mixed infill also occurs with fluvial at the base and then deltaic systems.

This interpretation clearly establish that most of the so-called glacial succession is in fact commonly deposited in a marine environment. This confirms the pioneering works of Legrand which was claiming that transgression occurs before the Silurian.

Glacial depositional systems

Basically very few convincing continental tills have been recognised. The most typical glacially related facies correponds to the glacio-marine shales either deposited in a shelf setting with iceberg discharge or possibly in a lacustrine environment when no marine fauna is present. Others glacially related features such as slumped or liquified shelf sandy series occur. They could be related to permafrost features affecting preexisting deposits or subglacial systems associated to kettle melting. They are usually preserved just above or immediately below the erosional surfaces. The most common depositional systems correponds to deltaic systems either fluvial dominated or wave and storm influenced, they are not diagnostic of glacial succession. Gilbert types deltas are common, and gravity driven deposits related to density flows in a prodeltaic setting can be observed.

Three main types of fluvial depositional systems occur:

- Typical braided deposits are common; they correspond to glacial outwash and often infill the basal part of the valley. A very well developped channel system is present usually very close to the top of the series, near the Silurian shales, forming for example part of the M' Kratta Fm. Or the Upper Mamuniyat in Libya. In absence of convincing glacial evidence, the incision could be link to the isostatic rebound which enhanced proglacial incision

- Surprinsigly meander belt complexes also occur, they are not common in pro-glacial setting where the slope of the graded profile is very steep. Their occurence in northern Gondwana, suggest mature fluvial system not far away from the bayline.

- Flood dominated systems form one of the most peculiar facies association in this environment; it consists of superimposed climbing dunes successions forming sheet like bodies. Others flood dominated systems occur with typical well bedded sheet floods. In some valleys in Libya, the complete valley fill is fluvial and starts with meander systems, then grade in flood dominated succession suggesting an increase of the fluvial profile possibly recording a progradation.

Large scale architecture

Since their recognition by beuf et al. (1972) in the Tassili, numerous glacial valleys have been identified, in outcrops, in Mauritania and Libya. With the development of 3D survey, the shape of the valleys are now very well documented mainly in Libya but also in Algeria. These valleys define a network and are either juxtaposed or superimposed within the fairways. Each valley is filled by a single stratigraphic cycles however they can be reincised with numerous glacial pavements. The width range from 1 to 10 km. There location could be driven by the structural grain, or this grain could be reactivated by the ice loading in normal fault. Very often gravity instabilities of pre-glacial deposits can be observed along the valley flancks. Their incisions seems to be related to the ice rather then fluvial processes. In this respects very few convincing examples of tunnel valley have been observed except in Mauritania. The valley fill can dramatically change, some valleys being fill until the interfluve, some other are underfilled, leading to the preservation of pre-glacial buried hills below the Silurain shales. The final geometry of the late ashgillian succession have many similarities with the Quaternary succession in North Sea or in Celtic Sea where a grounded ice shelf had occur. This complex architecture and the resulting lateral and vertical facies changes explain why is so difficult to come with a good reservoir prediction in such a type of environment. This is valid from the regional exploration scale to the local scale i.e. prospect evaluation and field appraisal. Similarly to the deep offshore only 3 D seismic can allow to come with a good prediction of both geometry and sand content within the valleys.

The occurrence of the underfilled valley provides a new plays type correponding to buried hills with pre-glacial sandstones encased in Silurian source rock and acting as seal.

Silurian trangression

Silurain transgression is usually interpreted as the post glacial trangression, we have already seen that the first transgression occurs during latest Ordovician. It means that the glacial retreat is punctuated. In this respect, the Silurian transgression probably records the final melting. The transgression is diachroneous depending of the preexisting topography. Source rock seems to occur predominantly in regional lows, either resulting from glacial erosion or fluvial incision possibly related to the isostatic rebound. These lows in combination with late deformation will control the migration pathways. The sandy glacial deposits or the lowermost silurian transgressive sandstones deposited immediately below the source rock is the first reservoir to be filled or at least used for the migration has indicated by the abundance of shows. When the Late ashgillian succession is more shally or silty, it could form a waste zone or at least strongly reduce the potentail column.