Modeling of Hydrocarbon generation and expulsion from Tannezuft and Aouinet Ouinine Formations in southern Tunisia – North Africa

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ABSTRACT

The Ghadames Basin is part of the Saharan platform. It extended over more than 200 000 km² from eastern Algeria to western Libya and includes the southernmost of Tunisia. The Ghadames Basin is limited to the north by the west east trending Telemzane Arch and to the east by the Jeffara Basin. To the southwest and southeast, it is separated from the Illizi and Murzouk Basins by long lived structural highs(Fig.1).

The Gadhames Basin is an established oil province as evidenced by the numerous producing fields. The reserves are spread over a large range of siliciclastic reservoirs with the prospective section extending from Cambrian to Middle Triassic. Oil has been also discovered in the Early Devonian and recently in Upper Silurian sandstones.

Geochemical fingerprinting indicates that oil and gas discovered in the Ghadames Basin originated from two major source rocks: the Middle-Upper Devonian and basal Silurian hot shales. They have been deposited during transgressive events associated with sea level rises. Their lateral distribution is narrowly controlled by the Hercynian uplift and associated erosion. Both have excellent petroleum generation potential with TOC content ranging from 2 to 15% and Hydrogen indices between 350 to 700mg HC/g TOC. A regional 1D basin modeling of more than 65 wells and pseudo wells indicate different burial histories. The aerial limits of the generative portions of the Basin move through time from the deepest part of the Basin in the south to the North. Generation and associated expulsion of hydrocarbon from the Silurian source rock began during the Carboniferous with significant episodes in Jurassic and Cretaceous, while the Devonian source rock remained marginally mature over large areas to generate significant hydrocarbons for expulsion. However in the southernmost of the studied area, Devonian entered the oil Window in Late Jurassic and peaked oil in Late Cretaceous.

Generated hydrocarbons are spilled to the potential traps through the vertical faults, paleozoic carrier beds of regional extent and especially the basal Triassic sands above the Hercynian unconformity thus providing an effective path for long distance lateral migration. The Assessment of hydrocarbon generation and timing of migration have crucial implications in terms of development of Paleozoic and Triassic play concept.

INTRODUCTION

Explored since the early fifties, the Ghadames Basin in southern Tunisia is one of the more mature Tunisian basins with regard to hydrocarbon exploration.
In the early sixties, the discovery of the giant El Borma field with recoverable reserves over than 1billion barrels of oil in the Middle Triassic TAGI sandstones stimulated the exploration in the area.
The El Borma field currently remains the largest productive field in Tunisia. Continued exploration in the seventies and early eighties resulted in few additional discoveries of small to medium size in the Triassic and the Upper Devonian sandstones. On the other hand, lower flow rates were tested from the Ordovician Bir Ben Tartar fractured quartzitic sandstones in Oued Zar field. The Ordovician El Hamra and El Atchane fractured quartzite equivalent are the reservoir of producing Sabria and El Franig fields north of the Telemzane Arch.
Recently, the re-entry of old wells tested oil and gas from bypassed low resistivity Upper Silurian Acacus sandstones. New drilling confirmed the potential of these reservoirs and upgrade the Silurian play.
Exploration activity significantly slowed in the Late eighties. Increased recent success in the Algerian side renewed interest in the Tunisian part of Ghadames Basin. This success has been attributed to progress in two areas of analysis:
- improvements in seismic acquisition and imaging related to new acquisition parameters and new static correction methods.
- significant advances in basin modeling.

This paper presents a summary of the main results of a regional basin modeling survey undertaken by ETAP in an effort to reassess the hydrocarbon potential of the southern part of Tunisia including the Jeffara and Chotts Basins . Only the Ghadames Basin has been addressed in this paper.

GEOLOGICAL SETTING

Within the Paleozoic succession(Fig.2), the Cambrian unconformably overlies the Basement. It consists of sandstones deposited in fluvial setting. The Ordovician series corresponds to fluvio-continental sedimentation that has been interrupted by a major marine depositional period, the Middle LLanvirnian Bir Ben Tartar shales possibly of source rock quality. At the end of the Ordovician, local uplift and erosion took place in response to Late Taconic orogeny.
The Early Silurian marked the onset of widespread transgression following the melting of glaciers which affected the entire basin. The maximum of transgression was reached during the Wenlockian with the deposition of the radioactive shales in restricted anoxic conditions favorable to the accumulation and preservation of organic matter. During the Upper Silurian, the sea level fall induced the deposition of sandstone and shale sequences of the Acacus reservoir Formation with sustained clastic input mainly from the southeast. The termination of this episode is marked by the Caledonian unconformity. The Telemzane Arch was initiated during this phase. After the Late Caledonian, the Ghadames basin evolved as a separate basin. Early Devonian time is characterized by sandstone and shale sequences deposited in continental to shallow marine environment reflecting gradual rise in sea level. These deposits comprise the regional reservoirs of Tadrart (F6) and Ouan Kasa (F4-F5).
The Middle Devonian is marked by the onset of a major transgression which flooded the Ghadames Basin and resulted on the deposition of the argillaceous Aouinet Ouenine Formation, a major source rock of the Gadames Basin.
The Late Devonian corresponds to shallow marine silisiclastic sedimentation of a corresponding to the Tahara Formation, a potential reservoir. Later during the Carboniferous, these shallow marine conditions persisted. The early manifestations of the Hercynian orogeny are recorded since Late Devonian. The main phase occurred during the Middle Carboniferous to Permian and mainly affected the Northern part of the Basin. Much of the Basin was emerged and the Paleozoic series were truncated. Early Mesozoic transgressive deposits related to the Tethyan rifting which affected large areas of North Africa, overlain various Paleozoic terms.

The Triassic Cycle may be divided into three Formations. The TAGI Formation is composed of shales and sandstones deposited in Fluvio-deltaic environments. The TAGI pinch out towards a remaining paleohigh in the Telemzane Arch. The Azizia Formation is composed of marine shales and carbonate interbeds and a wider extension covering the entire Basin and the Telemzane Arch.
The Upper Triassic to lower Liassic Adjaj evaporitic Formation, is the ultimate seal of the TAGI reservoir.
The Adjadj section is overlain by the Liassic B Horizon, a regional seismic marker overlain by another lagoonal to shallow marine facies : the Middle Jurassic Abreghs evaporates.
The Upper Jurassic to Lower Cretaceous series are dominated by shales progressively grading to sands. An unconformity separating the Lower Cretaceous clastics from the Mid Upper Albian dolomites is interpreted to reflect tectonic activity associated with the Austrian Orogeny. Localized structural inversions in the Ghadames Basin during this phase was responsible for trap development and reactivation of old faults. The Upper Cretaceous system is represented by alternating cycles of shallow marine to restricted lagoonal deposition. Late Cretaceous led to additional inversions under the effect of the Laramide Orogeny. The effects of the Cenozoic tectonic movements are limited to the reactivation of major faults. Following the deposition of Late Cretaceous, there was a period of non deposition lasting until Miocene. The Cenozoic section is locally represented by a thin Miocene-Pliocene series of sandstones.

SOURCE ROCKS CHARACTERIZATION

The Upper Devonian and Early Silurian shales are the main proved source rocks which have charged the Paleozoic and Triassic reservoirs in the Ghadames Basin.
The Early Silurian Tannezuft Formation has a wide distribution. It is present both in Ghadames basin and southern part of Jeffara area.
Maximum source rock quality exists in the hot shales (20 to 50m thick) located at the base of the Silurian section . The TOC content average 3% and the Hydrogen Indices vary from 250 to 450mgHC/g TOC. The Kerogen is predominantly Type II. The thermal maturity of the Silurian shales range from an immature to marginally mature stage in the north to the gas zone in the south.
The Middle-Upper Devonian Aouinet Ouenine Formation is composed of four Members, I, II, III and IV. The distribution of the Aouine Ouenine Formation is narrowly controlled by the Hercynian event and has a narrower extension than the Tannezuft Formation. The best source rock characteristics are developed in the units III and IV and particularly in the Frasnian radioactive shales. The organic matter of Aouinet Ouenine (units III and IV) source rock is dominated by type II kerogen with an average TOC content of 5% and Hydrogen indices up to 700mgHC/g TOC. Organic content in the units I and II is leaner, but these units still exhibit a reasonable potential.

BASIN MODELING

THERMAL HISTORY AND SIMULATION ASSUMPTIONS

To estimate the main periods of generation and expulsion and delineate the kitchens, a one-dimensional kinetic simulations using the GENEX software has been conducted on 65 wells spread within the southern Tunisia.
The thermal history reconstruction was based on fixed heat flow to match the calculated maturity values with the observed present day maturity indicators. The best calibration was performed using a constant heat flow varying between 1.0 and 1.93 HFU. Both source rocks are modeled as Type II with specific kinetic parameters measured on selected source rock samples. The saturation method is selected for expulsion. In this model hydrocarbon volumes that exceed 10% of the pore volume of the source rock will be expelled. This expulsion threshold has been calibrated on pyrolysis analytical data.

BURIAL HISTORY

It should be noted that the Hercynian phase have played a key role in the burial and the maturity of both source rocks. The emergence and associated erosion increase in intensity from the southern part to the northern part. Thus the source rock experienced different burial histories. In the central part there was a continuous subsidence, to the north the amount of removed section increases as illustrated by the burial diagrams(Fig.3 & 4). This uplift have ceased or slowed the thermal evolution of the source rocks and the generation of hydrocarbons. The Silurian source rock is buried to depth ranging from 2800m in the north to 5100m (seismically estimated) in the south. Whereas the Devonian source rock is buried to depths ranging from 2500m in Chouech area to 3200m in southernmost Tunisia (seismically estimated). Locally, minor erosion are associated with the Caledonian orogeny.
Since the Middle Triassic to Senonian, the subsidence rate was high to moderate, it was interrupted by a small erosion event associated with Austrian Orogeny. During the Cenezoic, there was no deposition in this area.

MATURITY

Maturity maps generated at present day show that the maturity decreases from the southern part of the basin to the northern part according to a NW/SE trend.
Present day maturity for the Silurian shales may be divided in four areas(Fig.5):

- A southern area which is in the gas phase ($1.3< Ro<2$),
- An intermediate area lying north west south sast which is in the peak oil generation ($1<Ro<1.3$),
- A third area lying in the oil zone ($0.7<Ro<1$),
- A northern area adjacent to the Telemzane Arch which is immature ($Ro< 0.7$).

The Devonian source rock has reached lower stage of maturity, two areas could be recognized(Fig.6):

- A first area corresponding to the southern part of the Basin which is mid mature ($0.7<Ro<1$),
- A second area including the Northern part which is immature.

GENERATION AND EXPULSION

In the southernmost of the studied area, the Tannezuft Formation started to generate oil at Early Carboniferous and reached peak oil generation at the Late Carboniferous. Further north in the intermediate area, it entered the oil window at the same time but was prevented from continued generation by the Hercynian uplift, it reached peak oil generation at Albian. In the northern part, it is still in the oil stage. Generated quantities of hydrocarbon range from 4tHC/m^2 in the south to 01t HC/m^2 to the north as a result of lower maturity.
Expulsion from the Silurian shales occurred since the Early Carboniferous in the southern part and since Late Jurassic until present to the north.
The Aouinet Ouenine source rock entered the oil window in the southern most of Tunisia at the late Cretaceous and still in immature stage to the north. Generated hydrocarbons range from 3 to 4t/m^2. Expulsion from Devonian source is restricted to this area and may have occurred in Late Cretaceous through Tertiary.
Elsewhere, the generation is not sufficient for expulsion.

MIGRATION PATHWAYS

Migration could occur vertically upward faults to potential traps or to the Hercynian unconformity. The contribution of the Devonian through this path is limited to the southernmost Tunisia. Oil could be also expelled to the Paleozoic sandy carrier beds: Tadrart, Ouan Kasa and Acacus which are in close stratigraphic positions to the Devonian and the Silurian source rocks respectively. Then, they migrate up dip in the carriers along northern or western directions until they were trapped in Paleozoic reservoirs or reach the hercynian unconformity. Then, the oil moved in the basal part of the Triassic section in a long distance lateral migration. The recognition of the Hercynian path widen the options of the charge of Triassic reservoirs and may result in accumulations of mixed oils.

CONCLUSION

Thermal modeling at basin scale indicates that maturity and associated generation and expulsion vary in time and space. The maturation of the Silurian and the Devonian shales are primarily affected by the Hercynian orogeny, the intensity of which increased northwards.

The maturity of the Silurian and the Devonian shales decrease from the south to the north. The maturity of the Silurian shales range from an immature stage to the north to a dry gas zone to the south. The Devonian source rock exhibits lower stage of maturity ranging from a mid mature to an immature stage.

Concerning the generation, it should be noted that the generative portion of the basin moves through time from the southern part of the basin to the northern part. The generation and associated expulsion from the Silurian source occurred from Carboniferous with significant episodes during the Late Jurassic and Late Cretaceous.

The generation from the Devonian source started since the Late Jurassic in the southern part but was significant for expulsion only in restricted areas.

These results have crucial implications for the exploration in the Ghadames Basin, and particularly for the Triassic targets in terms of timing of trap development. Most of the structures are Hercynian to Mid-Upper Triassic in age and prior to the main phase of generation and expulsion.

Reservoirs are provided by the numerous Paleozoic siliciclastic intervals and especially by the Middle-Upper Triassic TAGI sandstones.

The main migration routes are the vertical faults, the widespread Paleozoic carrier beds and especially the Hercynian unconformity. The latter provides favorable pathways (to charge potential Triassic traps) for a long distance lateral migration of hydrocarbon from the generative areas through a roughly East-West and NE-SW directions. This model suggests a possible Devonian contribution from more mature areas in the Algerian side of the Ghadames Basin.

Fig.1 : Location map

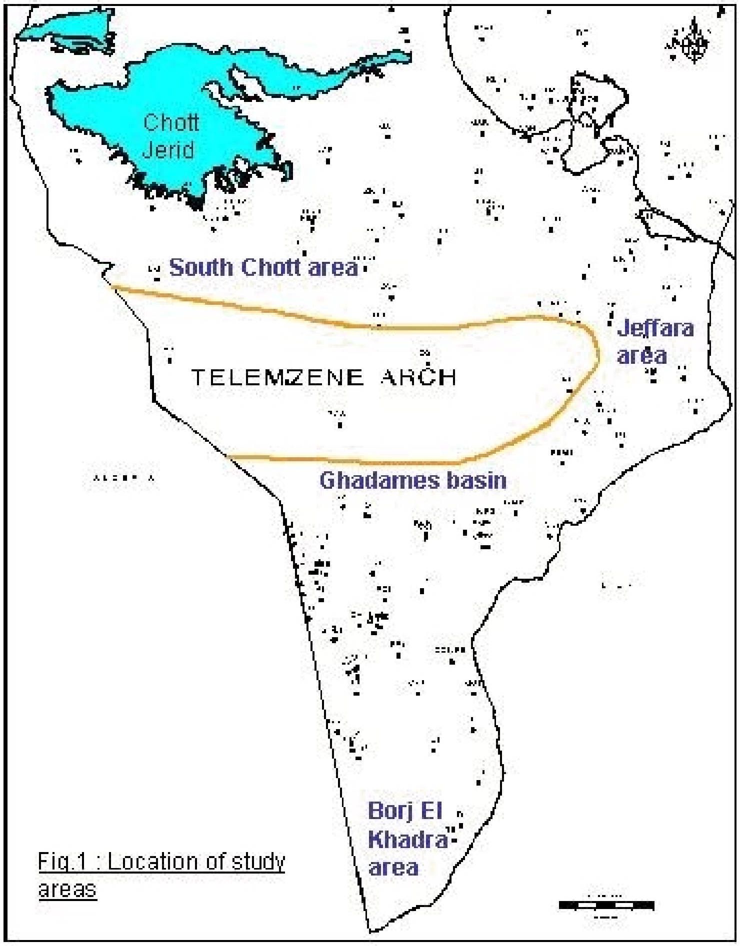

Fig.1 : Location of study areas

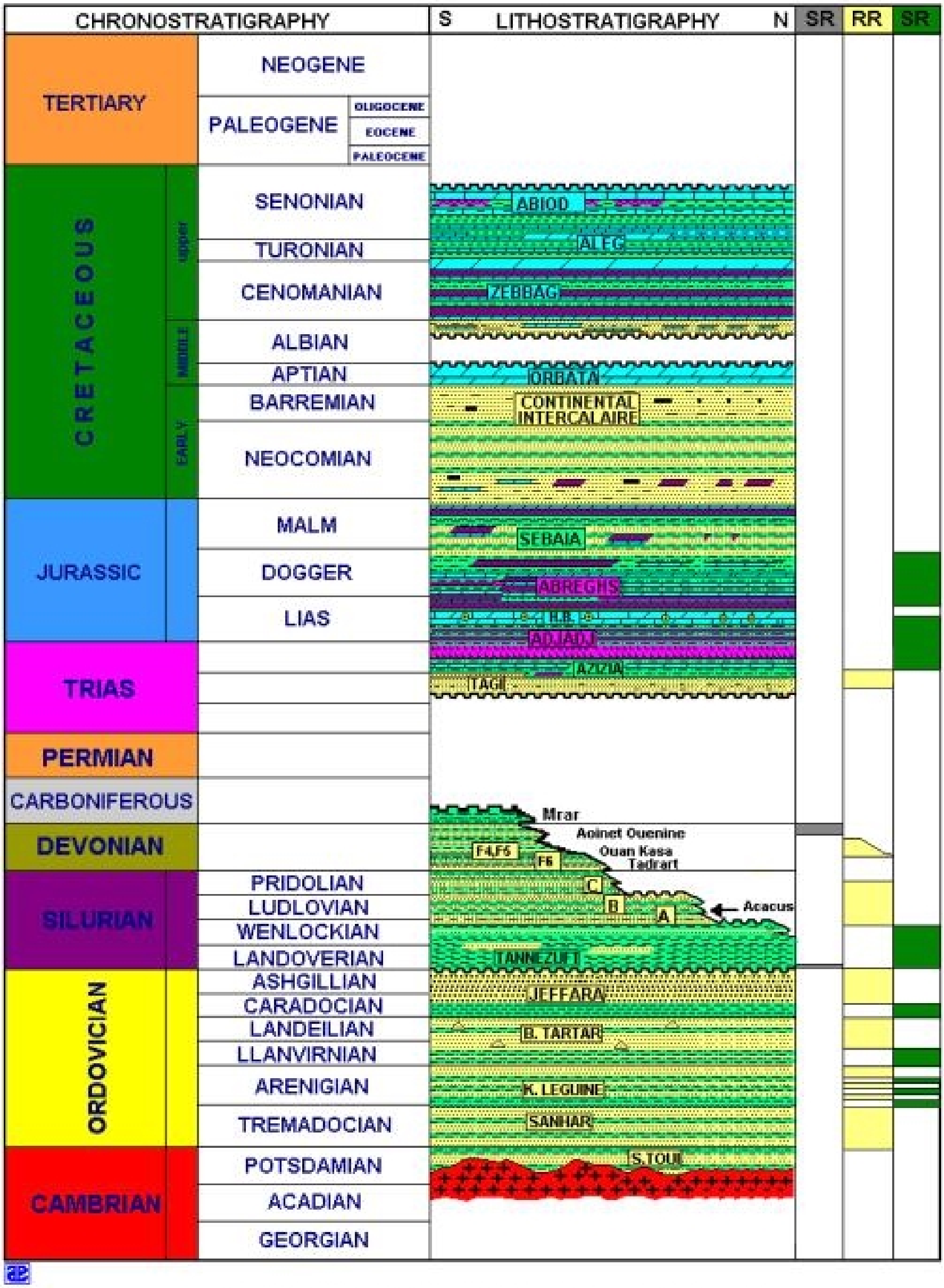

Fig.2 : Lithostratigraphic chart of Ghadames basin

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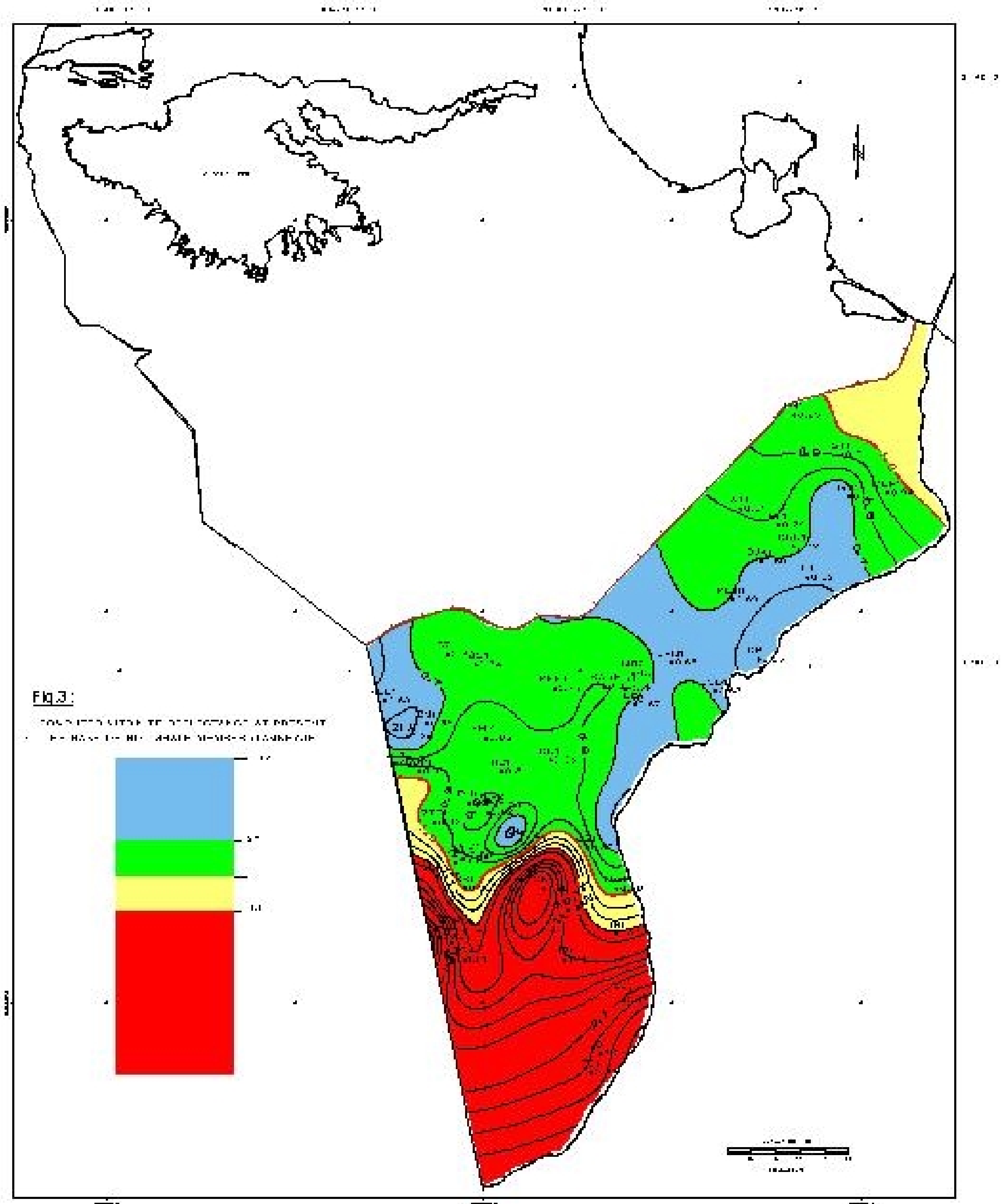
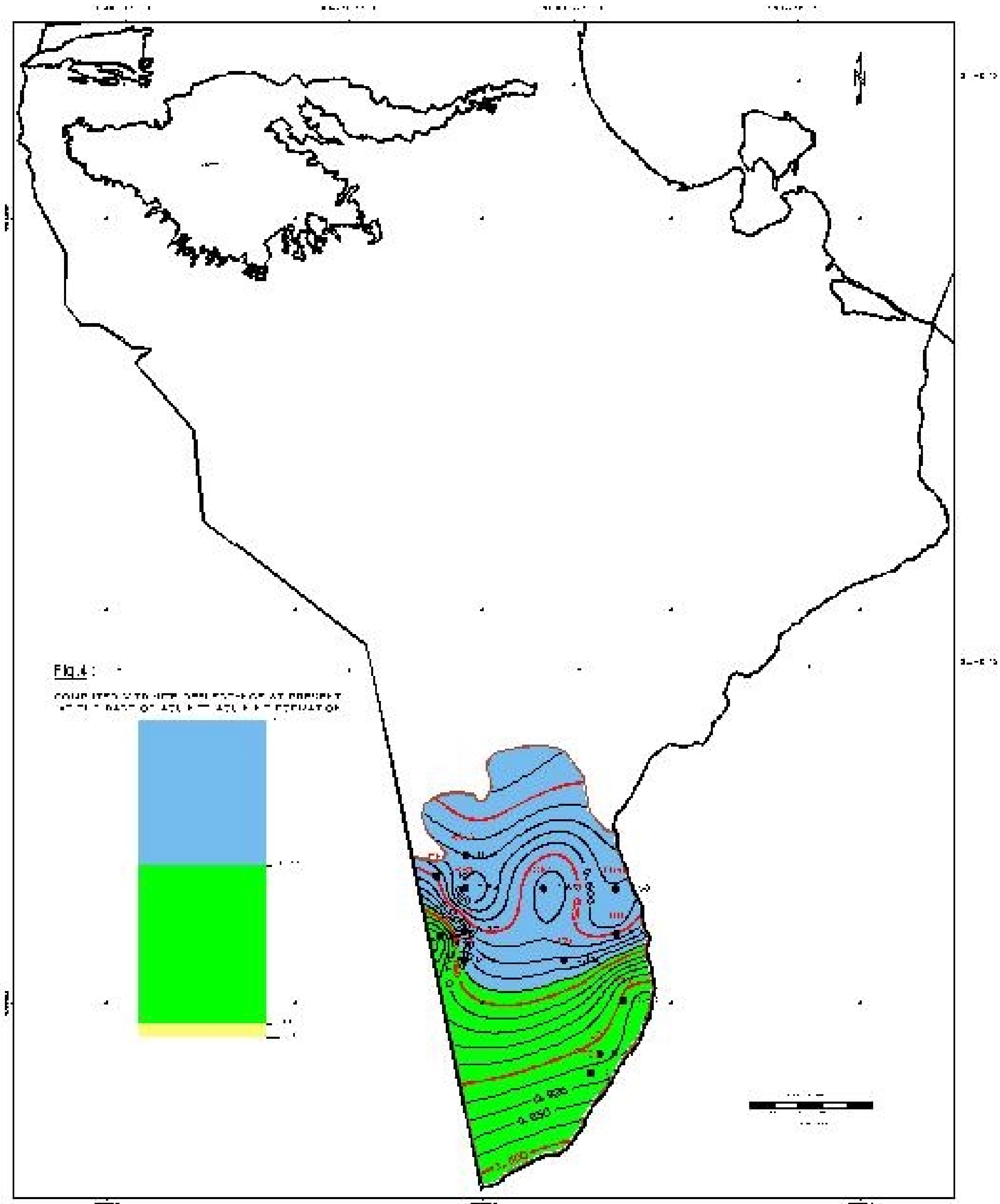


Fig.3 :



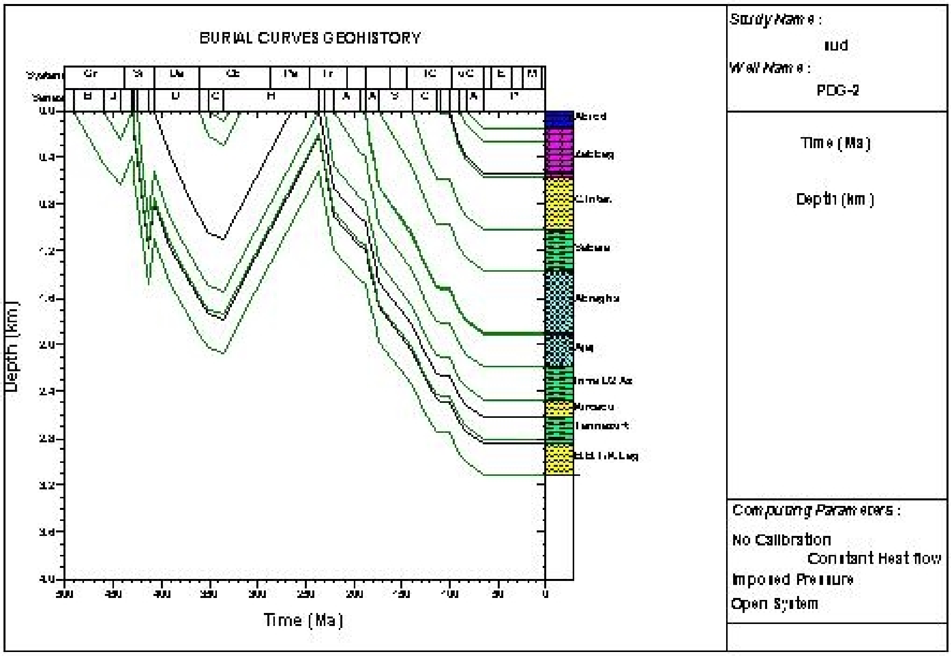


Fig. 6 : Burial history of PDG-2 well (Northern part of Ghadames basin).

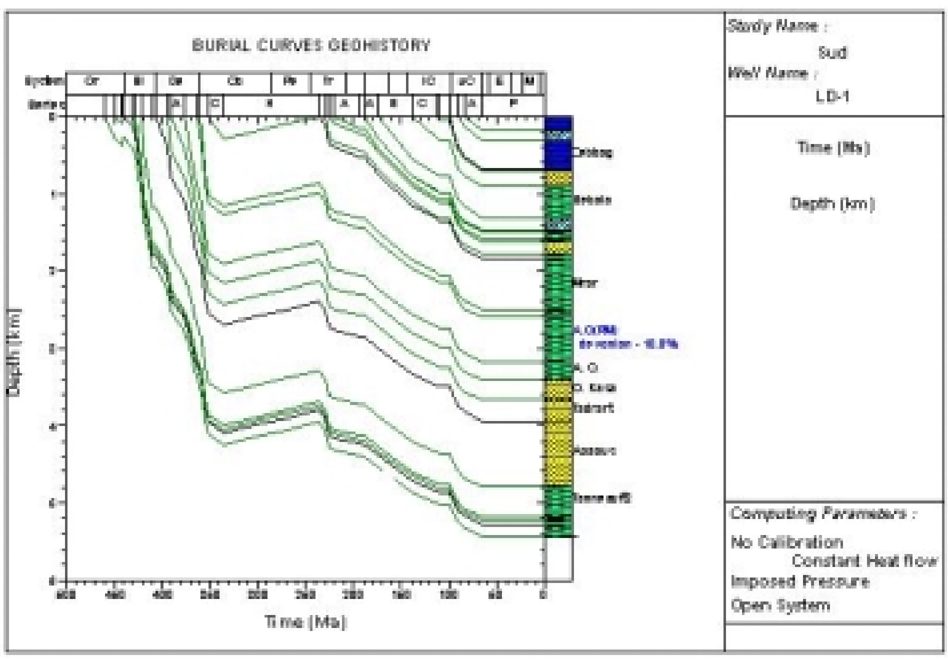


Fig 5 : Burial history of LD-1 well (Southern part of Ghadames basin).