

THE PETROLEUM GEOLOGY OF THE EARLY EOCENE EL GARIA FORMATION, HASDRUBAL FIELD, OFFSHORE TUNISIA

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The Hasdrubal field (offshore Tunisia) comprises an Early Eocene shallow-marine nummulitic limestone reservoir (the El Garia Formation) sourced by deep-marine mudstones and limestones of the generally age-equivalent Bou Dabbous Formation. The field is located on a NNW-SSE trending horst between a series of en-échelon normal to oblique faults, and is dip-closed except to the north where a stratigraphic pinch-out into the Bou Dabbous Formation is inferred. Middle Eocene shales and dense limestones of the Cherahil Formation form the main seal.

The El Garia Formation reservoirs significant volumes of hydrocarbons in Tunisia and Libya. A detailed micropalaeontological and nannofossil study has been undertaken of the El Garia Formation and the immediately over- and underlying formations which together form the Metlaoui Group, using subsurface data from the Hasdrubal field. This has permitted a detailed chronostratigraphic and sequence stratigraphic framework to be developed, including the recognition of three flooding events, which can partly be calibrated with second-order sequences, thus permitting the correlation of discrete reservoir units across the field. A further six microfaunal events are recognized between the Chouabine Formation and the "Compact Micrite Member" within the Metlaoui Group.

Previous depositional models for the El Garia Formation are discussed and a new model is proposed. The model partly explains why a number of wells drilled along the El Garia nummulite "bank" trend have failed to encounter the nummulite reservoir facies, and why, even where this facies was encountered, the limestones were frequently tight and/or contained limited hydrocarbons. It is also suggested that proximity to source is a critical factor, with the development of dissolution porosity by acidic pore waters migrating in advance of hydrocarbons. This is critical for enhancing reservoir quality and thus promoting the capacity to reservoir hydrocarbons, as indicated by the location of existing discoveries.

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INTRODUCTION

Nummulitic limestones form important hydrocarbon reservoirs in North Africa and have exploration potential along the northern margins of the Mediterranean as well as in the Middle East and the Indian Subcontinent. The nummulitic limestones of the Early Eocene El Garia Formation contain proven economic oil and gas reserves and continue to be an important exploration target offshore Tunisia and Libya (Anz and Ellouz, 1985) (Fig. 1). Existing discoveries within this formation in Tunisia include (reserves in brackets) *Ashtart* (350-400 MM brl), *Hasdrubal*, *Salamambo* (30 MM brl), *Didon* (30 MM brl), *Zarat* (50-100 MM brl) and *Sidi el Itayem* (30-40 MM brl), while the *Bourri* field (1,000-3,000 MM brl) is of major importance off the coast of NW Libya. In this paper, we propose a revised biostratigraphy, sequence stratigraphy and depositional model for the El Garia Formation in the offshore Gulf of Gabes with particular emphasis on data from the *Hasdrubal* field (Fig. 2).

Hasdrubal is located in the Gulf of Gabes, 100km east of Sfax and lies within the Amilcar Permit for which BG currently holds 100% equity (Fig. 2). The field reservoirs gas-condensate with a thin oil rim within Early Eocene (Ypresian) nummulitic limestones of the El Garia Formation.

The Gulf of Gabes is situated on the SE edge of the Pelagian Platform and is bounded to the west by the North-South Axis and to the SW by the Gafsa Fault Zone (Fig. 1). The area is dominated by a predominantly NW-SE structural grain, which appears to exert a significant influence on depositional facies within the El Garia Formation. In general terms, the depositional setting of the El Garia Formation in the Gulf of Gabes is that of a NE-dipping shore-attached ramp, locally modified by synsedimentary tectonics (*BG proprietary studies*). The El Garia Formation trends parallel to the strike of the ramp, but its depositional geometry is frequently disrupted by structurally controlled pelagic embayments on its basinward margin.

In terms of depositional facies, the El Garia Formation appears to be similar to the equivalent Jdeir Formation offshore Libya. However, the critical difference between the Tunisian and Libyan Ypresian plays is the absence of the structures formed by synsedimentary salt-tectonics within the Gulf of Gabes. These structures exert a significant influence on reservoir development offshore Tripolitania (Anketell and Mriheel, 2000).

Twelve wells have been drilled in the Amilcar Permit to date: *Hasdrubal-1*, -2, -3 and 4 (together defining the *Hasdrubal* field), *Melqart West-1*, *Melqart-1*, *Zitouna-1*, *Jugurtha-1*, *Melqart-101*, *Hamon-1*, *Salamambo-1*, and *Salamambo-2* (Fig. 2). *Hasdrubal-1* was drilled in 1975 by Sofratep and was plugged and abandoned as a gas and condensate discovery with flow rates of 5.8MM SCF/day and 440 b/d condensate from the El Garia Formation and with a net pay of 51m.

Wells *Hasdrubal-2* and -3 were drilled by BG E&P in 1994 and 1997, and respectively encountered 52m and 39m of net pay in the El Garia Formation, with the latter well defining the approximate northern limit of the field. Following acidisation, *Hasdrubal-2* flowed 19.1 MM SCF/day and 1,419 b/d condensate, and *Hasdrubal-3* flowed 21 MM SCF/day and 1,980 b/d oil.

Hasdrubal-4 was drilled by BG E&P in 1998 to define the southern limit of the field and encountered a net El Garia pay of 20m, with flows of 4.6 MM SCF/day and 1,800 b/d oil.

Most previous studies (Moody, 1987; Moody and Grant, 1989; Bailey *et al.*, 1989) have favoured a shallow shelf/platform setting for the deposition of the El Garia Formation, although Compte and Lehman (1974) and Loucks *et al.* (1998) put forward a ramp model which is favoured in this paper. From an exploration point of view, a ramp interpretation for the Metlaoui Group is important in that it predicts that facies will shift laterally as a result of only a modest rise in sea level, and will generally interfinger with each other.

This contrasts with a shelf/platform model, which predicts that a modest sea-level rise would cause the various facies to aggrade with less interfingering.

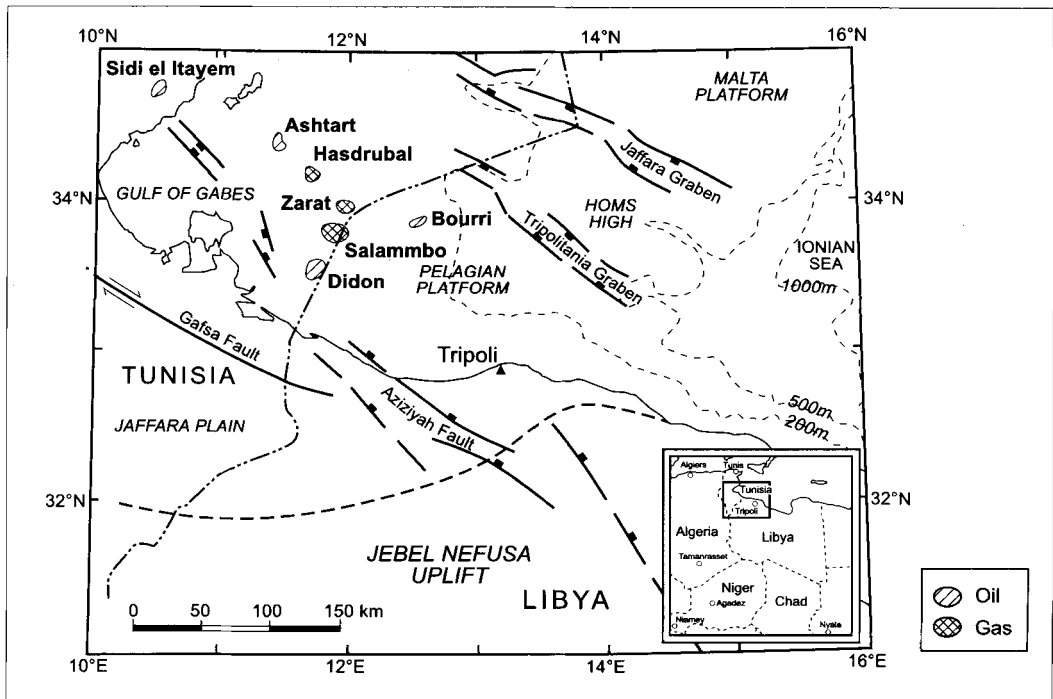


Fig. 1. Map of eastern Tunisia/ western Libya, showing major structural elements and fields producing from the Eocene El Garia Formation.

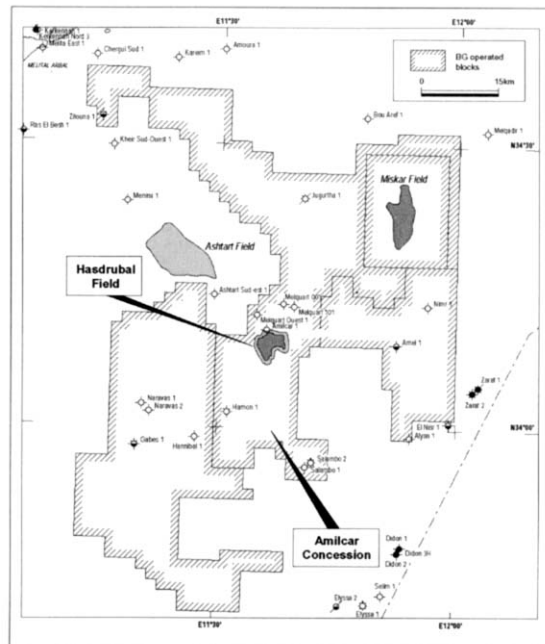


Fig. 2. Map showing the location of wells in the Amilcar Permit and the Hasdrubal field.

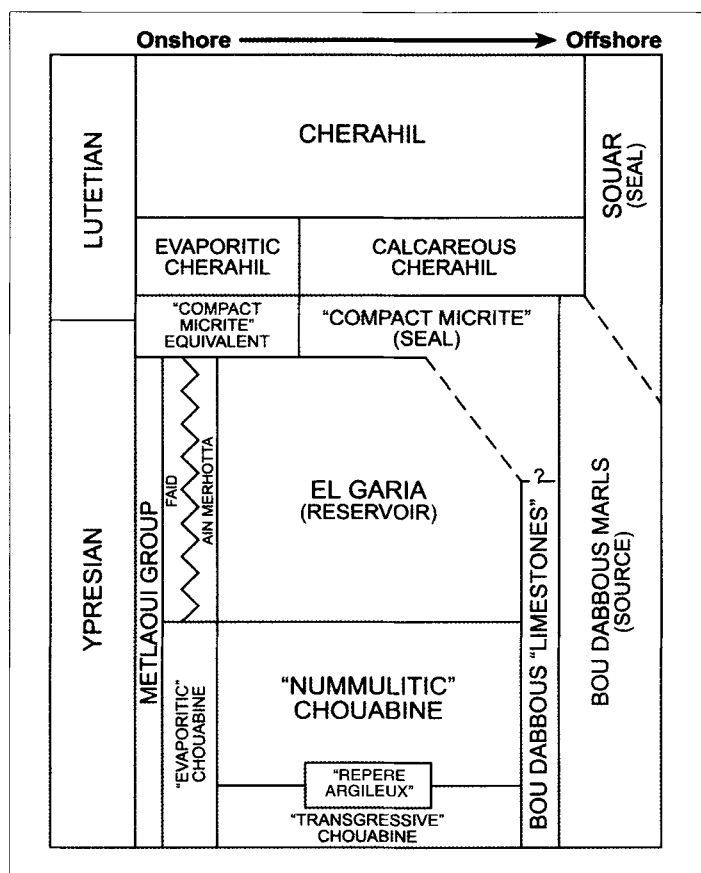


Fig. 3. Early to Middle Eocene lithostratigraphy onshore and offshore Tunisia (modified after Bailey *et al.*, 1989). The “Repère Argileux” and “Compact Micrite” are prominent markers on petrophysical logs.

LITHOSTRATIGRAPHY OF THE METLAOUI GROUP

The Early Eocene (Ypresian) Metlaoui Group was defined by Fournié (1975, 1978) and later refined by Bishop (1985, 1988), Bailey *et al.* (1989), Moody and Grant (1989) and Dridi and Sejl (1991). The group comprises the Faïd, Ain Merhotta, El Garia and Bou Dabbous Formations which are considered to form a prograding sequence, and are underlain by the transgressive Chouabine Formation (Fig.3).

Limestones of the El Garia Formation form one of three lateral subdivisions of the Metlaoui Group which can be identified in the Gulf of Gabes. These subdivisions comprise the shoreward Ain Merhotta Formation (dolomitic wackestones and evaporites); the shoal or middle ramp El Garia Formation (nummulitic and gastropod grainstones to wackestones); and the outer ramp Bou Dabbous Formation (organic-rich lime mudstones). Onshore, an additional continental facies with evaporites is known to occur and is referred to as the Faïd Formation. A transitional facies comprising nummulitic debris, referred to as the Ousselat Member, has been recognised onshore and occurs between the El Garia and Bou Dabbous Formations, but cannot be clearly identified offshore although it is considered to be the lateral equivalent of the Bou Dabbous

“limestones” recorded by Bailey *et al.* (1989). The El Garia Formation is capped by an argillaceous carbonate unit referred to as the Compact Micrite Member of the Cherahil Formation (or “Compact Micrite”), and is underlain by the Chouabine Formation. Subunits of “Member” status were recognized within these formations by Bailey *et al.* (1989) following detailed regional mapping. In more distal settings, the Cherahil Formation is replaced by the Souar Formation. The Souar Formation is informally subdivided into a lower member (“Souar A”) and an upper “Souar B”, separated by the Reineche Member. The Souar Formation generally consists of deep-water limestones, and the Reineche Member represents a distinctive shallowing event in the middle of the formation.

PETROLEUM GEOLOGY OF THE HASDRUBAL FIELD

Reservoir: the El Garia Formation

The main reservoir at *Hasdrubal* comprises variably bioturbated, dolomitised and fractured nummulitic limestones (Plates 1 and 2). Bioturbation takes the form of 3-4 cm diameter burrows due to the activity of an unidentified organism. The limestones show marked variations in clast size and degree of dolomitisation, features which have been used to create a layered reservoir model. The reservoir comprises a series of stacked, thin, laterally extensive but discontinuous sheets of nummulitic debris separated by bioturbated mudstone-wackestones. Occasional thicker nummulitic grainstone-packstone sheets occur, and are interpreted as storm or turbidite deposits. Stylolites (often hydrocarbon stained) are common at bed boundaries. Closed-system dolomitisation is prevalent in the wackestone to packstone units and commonly leads to an improvement of the poroperm properties (Macauley *et al.*, 2001). No meteoric cements have been recorded in *Hasdrubal* samples, suggesting that the El Garia Formation has not been subaerially exposed at this location. Fracturing is evident around faults, and this results in an enhancement of both horizontal and vertical permeability. The enhancement is apparent when test results are compared for the three *Hasdrubal* wells drilled by BG, however, the enhancement of vertical permeability is an order of magnitude greater than that recorded for the horizontal permeability. Total porosity values within the El Garia Formation vary regionally from 10-26% and comprise dissolution, dolomitisation, intraskeletal and fracture pore types in varying amounts with matrix permeabilities of 40-100md.

Source: the Bou Dabbous Formation

Wet gas and minor oil within the El Garia Formation are sourced by organic-rich pelagic and hemipelagic biomicrites assigned to the Bou Dabbous Formation, which is the deeper-water lateral equivalent of the El Garia Formation. The Bou Dabbous Formation comprises mudstones and limestones containing common amorphous marine (Type II) kerogen with TOC values of 0.5-2.5%. Bailey *et al.* (1989) noted that *Hasdrubal-1* condensate can be proved on biomarker and kerogen typing evidence to be derived from organic matter in the Bou Dabbous Formation, as can oil in *Ashtart-4* and oil shows in *Melqart-1*.

Seal

Regionally, the dense limestones and shales of the Middle Eocene Souar Formation and its shallow- water equivalent, the Cherahil Formation, form the main seals for the El Garia reservoir. The “Compact Micrite” and Cherahil Formations which directly overlie the El Garia Formation at *Hasdrubal* provide the seal at this field. However, given the degree of fracturing associated with faults in the area and the presence of gas shows in the Cherahil Formation, it is clear that

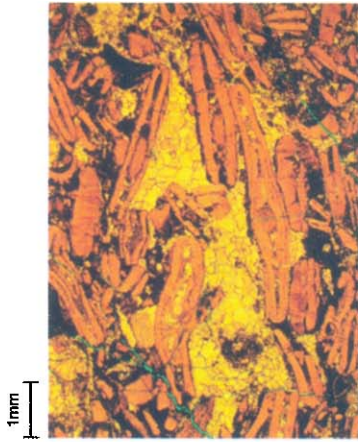


Core Slab from offshore Tunisie Hasdrubal Field, showing oil-stained stylolite. B-Form Nummulite rich El Garia Formation

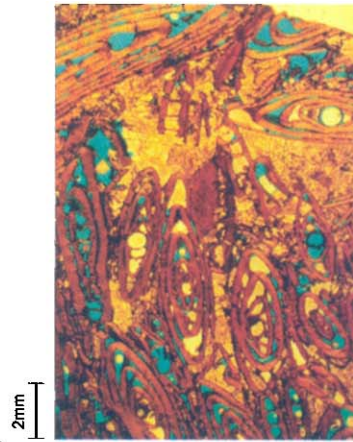
Equatorial view of A-(Megaspheric) and B-(Microspheric) Form Nummulites from the El Garia Formation, Offshore Hasdrubal Field. Note excellent intraparticle porosity in chambers of nummulites.

Hasdrubal Field Photomicrographs

Plate 1. Core photos of the El Garia nummulitic limestones from well *Hasdrubal-3*.
Left: upper surface of broken piece of core with A- and B-form nummulites.
Right: section through a core, showing crude "stacking" (partly bioturbation influenced?) of mainly B-form nummulites and oil-stained stylolite.



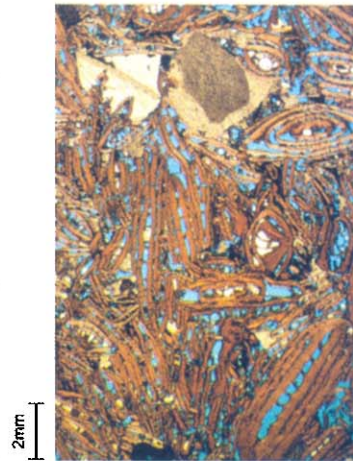
Hasdrubal-2. Nummulitic limestone with most porosity occluded by micritic groundmass and late carbonate cements.



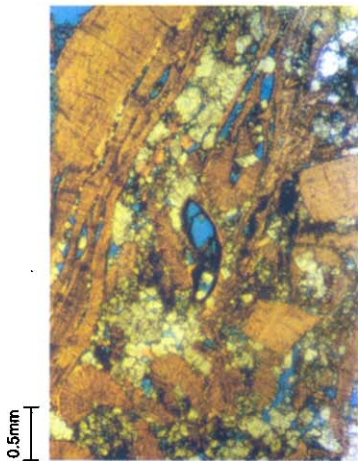
Hasdrubal-2. Nummulitic limestone (mainly A-forms) with good inter- and intraparticle porosity patchily occluded by late calcite and dolomite cement.



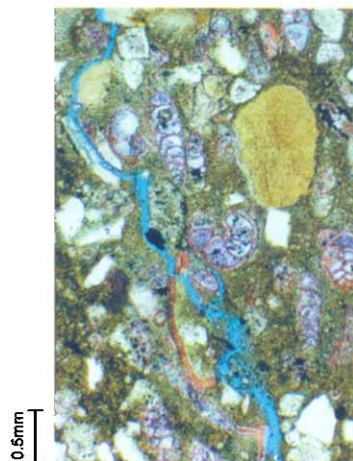
Hasdrubal-3. Nummulitic limestone with large *Discoeyclina* (bottom) and A-form nummulite (top right). Porosity is occluded by late calcite cement whilst compaction related fractures and associated pressure solution at grain boundaries is clearly visible.



Hasdrubal-2. Nummulitic limestone with excellent inter- and intraparticle porosity. Note minor late calcite cement and calcite overgrowths on echinoderm fragments on right of picture.



Hasdrubal-3. Partly dolomitised nummulitic-nummuloclastic limestone with moderate inter- and intra-particle porosity. Note planktonic foraminifer at centre.



Hasdrubal-2. Transgressive Compact Micrite capping El Garia reservoir. Note common deep water planktonic and smaller benthic foraminifera plus quartz and nummulite debris.

Photomicrographs of Hasdrubal Field Thin Sections

Plate 2. Representative photomicrographs from core samples from the El Garia Formation and Compact Micrite Member.

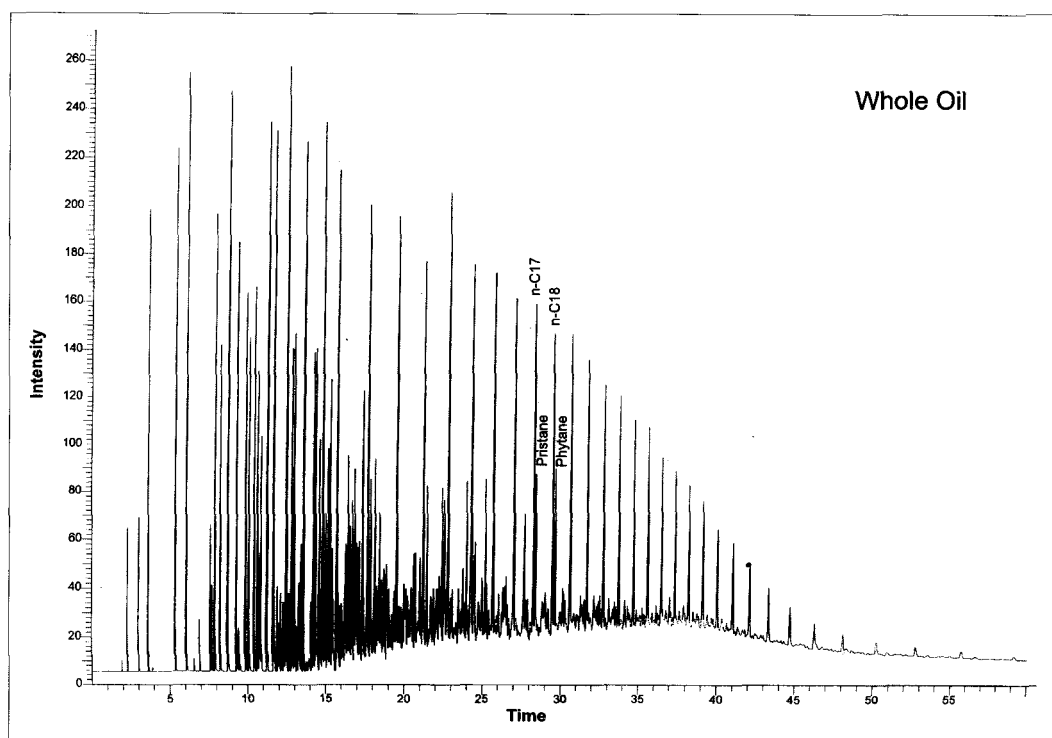


Fig. 4. Whole oil GC trace for oil from well *Hasdrubal-4*.

the seal is not perfect. The Oligocene-Early Miocene Salammbo Formation appears to act as a top seal for the *Hasdrubal* accumulation. At *Ashtart*, the “Compact Micrite” appears to have filled depositional topography on the surface of the El Garia which comprises a nummulite bank, providing both lateral and top seal.

Trap

The *Hasdrubal* field is located on a NNW-SSE trending horst block bounded by *en-échélon* normal to oblique faults. The accumulation is dip-closed except to the north where a stratigraphic pinch-out is inferred. The faults bounding and within the structure were probably initiated during the Cretaceous with subsequent reactivation and modification during the Palaeocene and late Eocene-Oligocene as evidenced from seismic interpretation of both 3D and regional 2D data, with the *Hasdrubal* structure achieving its final configuration in early Oligocene times (Philps, 2001). These structural effects are local whereas the coastal onlap curve discussed below is relevant to a more general regional model.

Petroleum Geochemistry

Oils

The oil produced from the El Garia in *Hasdrubal-4* exhibits characteristics which are consistent with generation from the Bou Dabbous Formation. Whole oil GC analysis shows it to be an unbiodegraded crude with a full range of components from C_3 to C_{39+} (Fig. 4).

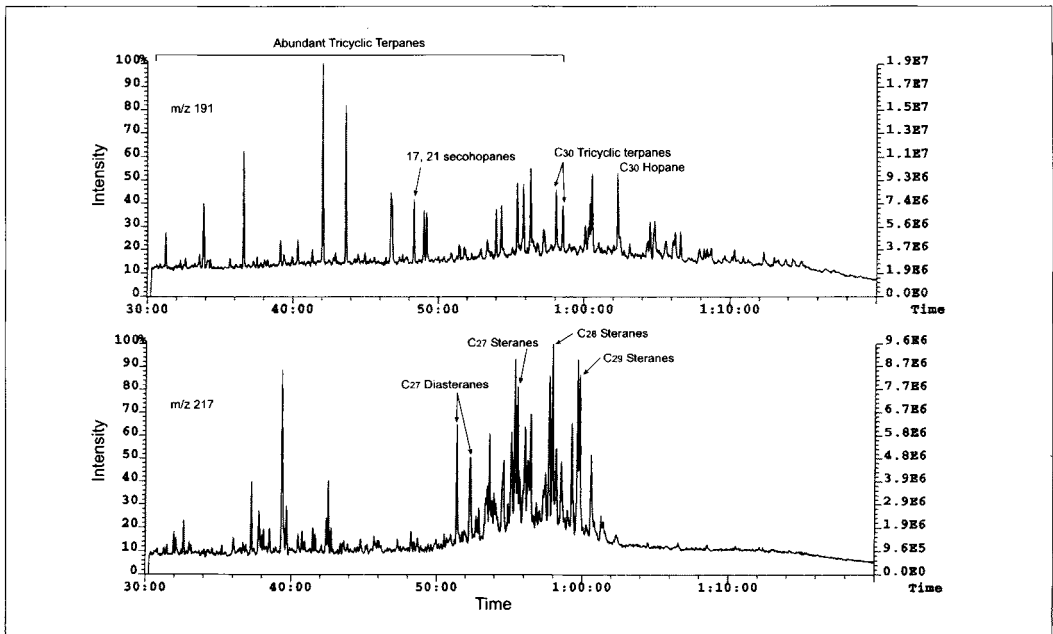


Fig. 5. GC-MS hopane (m/z 191) and sterane (m/z 217) traces for oil from *Hasdrubal-4*.

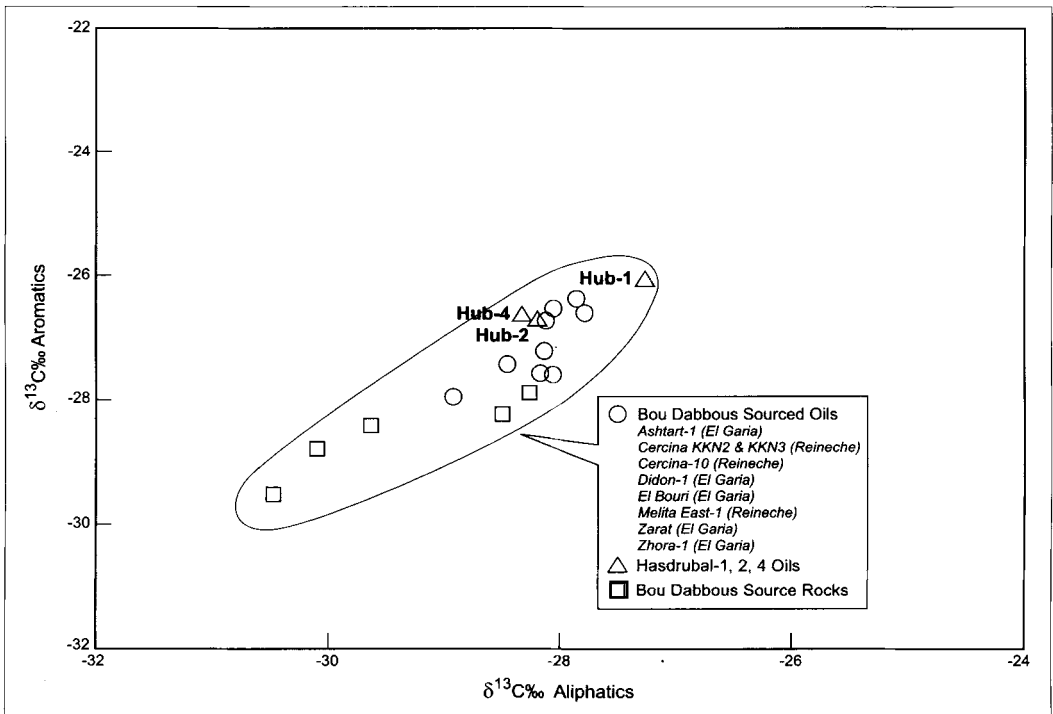


Fig. 6. $\delta^{13}\text{C}$ isotope cross-plot for oils sourced from the Bou Dabbous Formation and for Bou Dabbous source rocks.

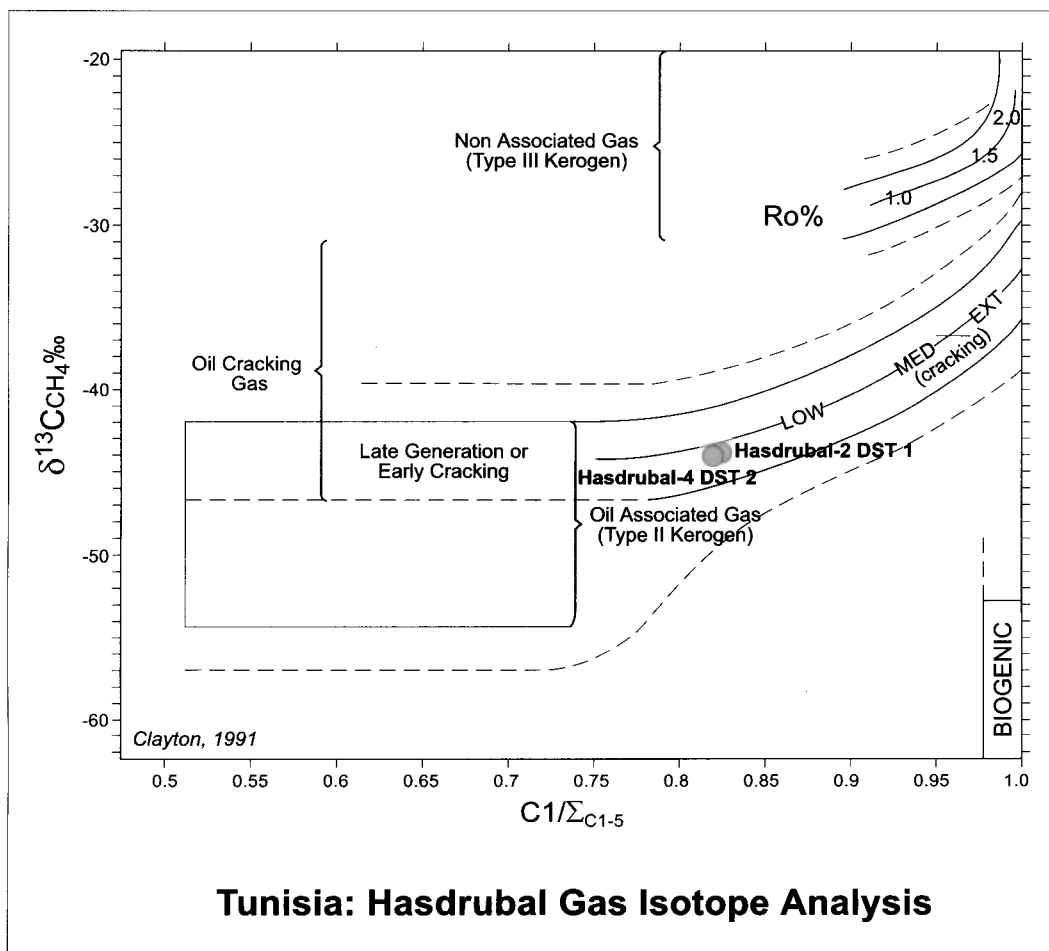


Fig. 7. Clayton Plot for gases from wells *Hasdrubal-2* and *-4*. Fraction of methane in the total gas (x-axis) is plotted against methane isotope ratio (y-axis). The level of oil cracking is shown as low, medium or extensive, while four main potential gas sources are defined: biogenic; oil-associated gas (Type II kerogen); “oil cracking” gas; and non-associated gas (Type II kerogen). The *Hasdrubal* samples plot in the oil-associated gas field.

Interpretation of the whole oil GC and the GC-MS traces of the hopane (m/z 191) and sterane (m/z 217) biomarkers (Fig. 5) indicates that *Hasdrubal-4* oil is probably sourced from a marine carbonate marly facies.

The low pristane:phytane ratio of 0.85, the ratio of methylcyclohexane relative to all C_7 non- aromatics of 25.5, and the n - C_7 : methylcyclohexane ratio of 0.53 are all consistent with a marine carbonate marly facies source rock for this oil (Barwise and Goodwin, *pers. comm*). The overall high content of tricyclic terpanes, together with the enhanced C_{28} to C_{30} tricyclic terpanes, is consistent with a marine carbonate source, as is the presence of 17,21 secohopanes which are also associated with carbonate environments. The overall moderately low diasterane content suggests a clay-poor system. In terms of maturity, the C_{32} hopane 22S/(22S+22R) and the C_{29} sterane 20S/(20S+20R) ratios (0.55 and 0.52, respectively) suggest a mature oil. The

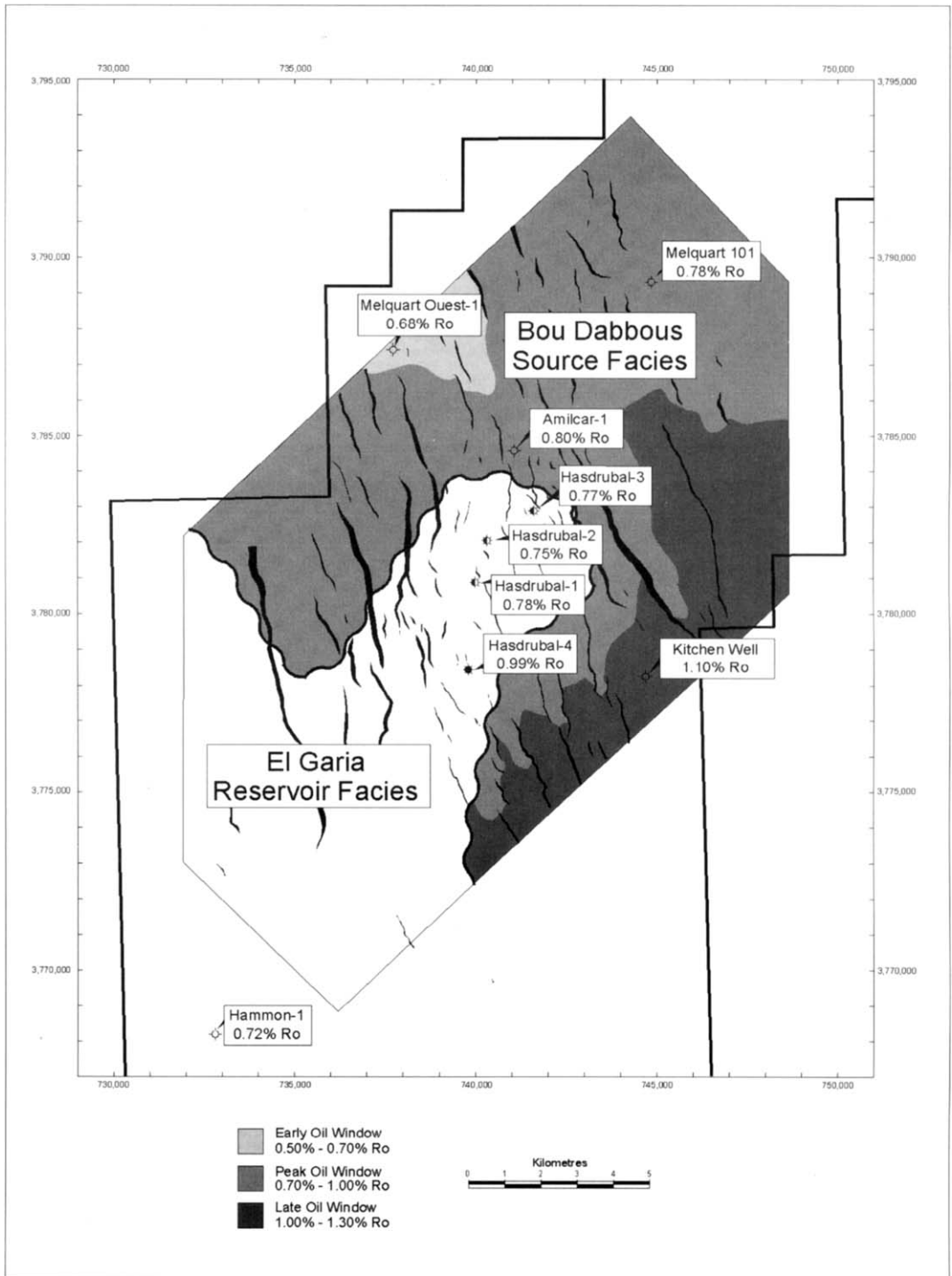


Fig. 8. Basal maturity of the El Garia and Bou Dabbous Formations. A source kitchen area is clearly present to the NE and SE of the *Hasdrubal* structure.

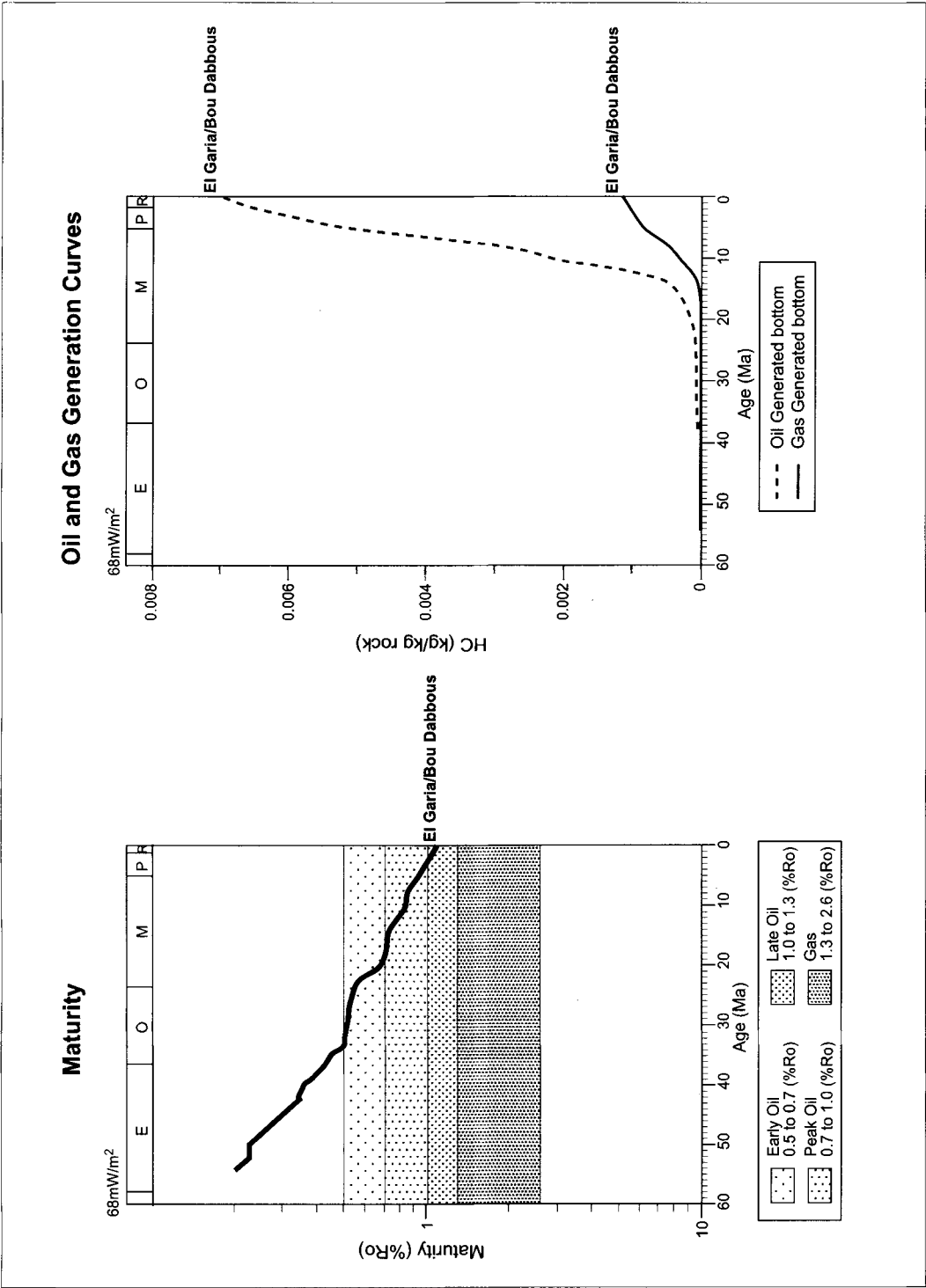


Fig. 9. 1D Modelling of the “Kitchen Well”. See text for details.

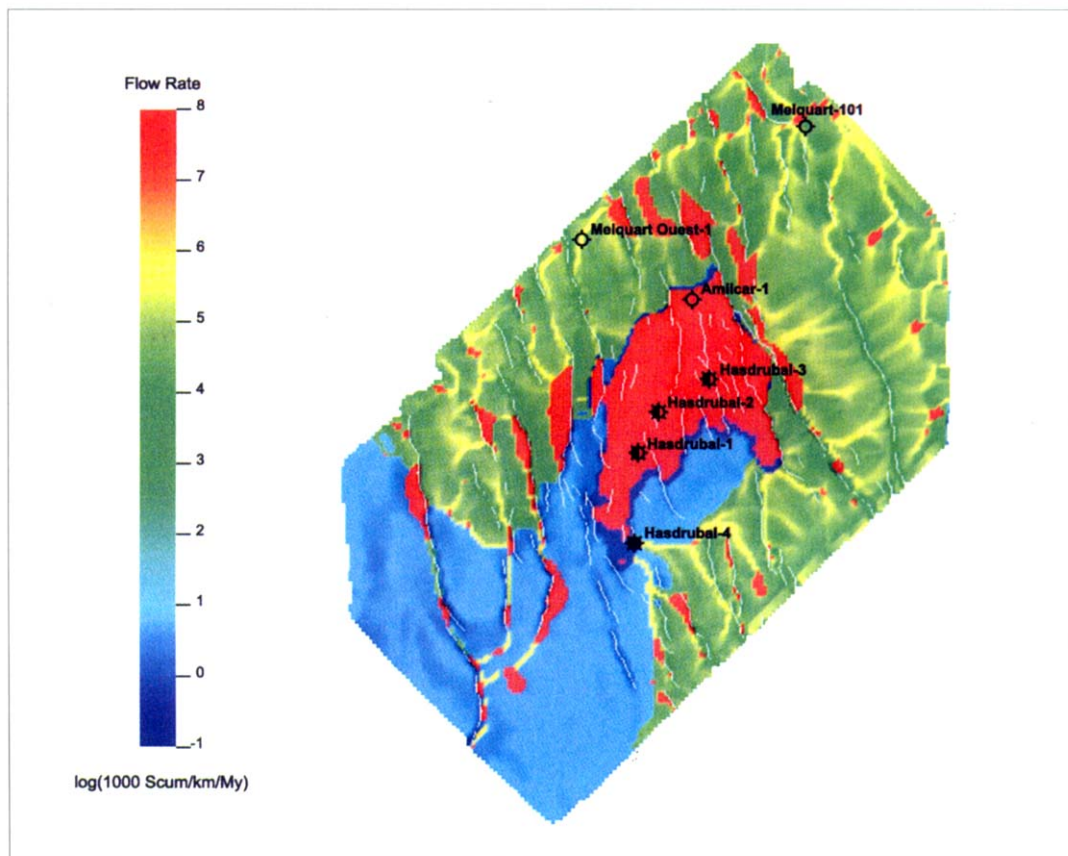


Fig. 10. SEMI (migration) modeling: oil and gas flow lines 10 to 0 Ma. The *Hasdrubal* structure filled from two main points from the kitchen to the SE. The model also shows that the fault to the east of the field is sealing.

$\delta^{13}\text{C}$ isotopic signatures of the aliphatic and aromatic fractions of *Hasdrubal-4* oil are very similar to these of other oils known to be sourced from the Bou Dabbous Formation (Fig. 6).

The concentrations of carbazoles (22.67 mg) and benzocarbazoles (13.87 mg) in *Hasdrubal-4* oil are high, and suggest close proximity to the source kitchen (Larter *et al.*, 1996). In addition, the high benzocarbazole ratio (a)/(c) of 2.11 indicates an oil migration distance of about 5km.

Gases

The gases produced from the El Garia Formation in wells *Hasdrubal-2* and *Hasdrubal-4* are consistent with a Bou Dabbous Formation source, having $\delta^{13}\text{C}$ CH_4 values of -43.80‰ and -44.05‰ respectively. These values together with their “wetness” indicate that the gases are oil-associated, have undergone slight cracking and were generated in the peak to late oil window from a Type II kerogen (Clayton, 1991) (Fig. 7).

Maturity and Migration Modelling

1D modelling of wells within the Amilcar Permit was undertaken and contoured using *Basinmod* software to construct a present-day maturity map at the base of the El Garia and

Bou Dabbous Formations (Fig. 8). This map was produced by using a top-Metlaoui depth map together with the modelled depths to the various maturity windows at the well locations. Vitrinite reflectance values for the Bou Dabbous and basal El Garia Formations in the *Hasdrubal* area vary from approximately 0.80% in *Amilcar-1*, *Melqart-101* and *Hasdrubal-1*, -2 and -3, to 1.00% in *Hasdrubal-4*. On the Hasdrubal structure and in the areas to the immediate north and west, the El Garia and Bou Dabbous Formations are within the peak oil window (Fig. 8). A “kitchen area” is clearly visible immediately to the NE and SE of the Hasdrubal structure, in which the Bou Dabbous Formation source rocks are in the late oil window. 1D modelling on a synthetic “kitchen well” (Fig. 9) indicates that oil and wet gas generation began at about 20 Ma (Early Miocene), with the main phase of generation occurring towards the end of the Miocene at about 10 Ma (Fig. 9). Although oil and wet gas are co-sourced and generated together, differential migration probably accounts for wet gas reaching the *Hasdrubal* structure prior to the oil.

3D ray-trace (migration) modelling using the *SINTEF SEMI* software on the top-Metlaoui depth grid shows that the *Hasdrubal* structure is filled at two main points from the SE kitchen; one is immediately south of *Hasdrubal-4*, while the other is to the SE of *Hasdrubal-3* (Fig. 10). Migration from the late-mature area to the NE of the structure is prevented due to the throw on a major NW-SE trending fault.

THE EL GARIA FORMATION: REGIONAL DEPOSITIONAL PATTERNS

In the major *Ashtart* and *Bourri* discoveries, nummulite banks were deposited on palaeotopographic/structural highs which protruded into the basin, such that they were surrounded by deeper-water (Bou Dabbous Formation) source facies. In these cases, the reservoir is close to the source and can be sourced from more than one direction. Similarly in *Hasdrubal*, there is strong geochemical evidence (from carbazole and benzocarbazole concentrations and ratios) and palaeoenvironmental evidence (e.g. the presence of deeper-water planktic foraminifera in the El Garia Formation) for the proximity of a deep-water source-prone embayment. Fig. 11 schematically illustrates our depositional model for the El Garia Formation in the *Hasdrubal* area. Regionally, a series of structurally-controlled embayments are envisaged cutting back into at least the outer part of the nummulite bank trend (as originally suggested by Bailey *et al.*, 1989 and supported by the structural study of Philips, 2001). Evidence for significant palaeotopographic relief on the shelf during El Garia Formation deposition is demonstrated by the fact that the El Garia can overlie the earliest Ypresian Chouabine Formation, the Palaeocene El Haria Formation and various Cretaceous units.

Most hydrocarbon production to date from the Metlaoui “play” in North Africa is from the seaward side of the nummulite bank trend (e.g. the *Bourri*, *Ashtart*, *Sidi El Itayem* and *Zarat* fields). The giant *Ashtart* and *Bourri* fields appear to be located on structural highs which protruded into the basin. This outer bank trend is favourable not only because of its proximity to the source rock, but also because it would be affected significantly by acidic waters moving in advance of the migrating hydrocarbon front. These acidic porewaters crucially enhanced the porosity of the nummulitic facies through dissolution. As the fluids moved shorewards (towards the inner bank), the acids would become progressively spent until they had little or no effect on reservoir quality. Prospects located back from the bank margin are therefore expected to have poorer reservoir potential.

BIOSTRATIGRAPHY AND SEQUENCE STRATIGRAPHY OF THE EL GARIA FORMATION

Previously, it has been assumed that the El Garia Formation is Ypresian (Early Eocene) in age, while the age of the overlying “Compact Micrite” has been shown to range from the Early

to the Middle Eocene (Loucks *et al.*, 1998). During the course of this study, some 601 thin sections were analyzed from the cored intervals within the *Hasdrubal* field, representing an average spacing (except for *Hasdrubal-1*) of about one foot (see Appendix, p.53, for a summary of the database used).

The planktic foraminiferid zonal scheme utilized in this study (Fig. 12) follows that of Toumarkine and Luterbacher (1985). Nannoplankton zones quoted are those defined by Okada and Bukry (1980). Additional samples were analyzed for nannofossils from wells *Malkadir-1* (37 samples), *Hammon-1* (six samples) and *Hannibal-1* (ten samples), and selected nannoplankton analyses were performed on 58 samples from the four *Hasdrubal* wells, in an attempt to constrain further the chronostratigraphic framework. The interval analyzed comprised the “Nummulitic Chouabine”, El Garia, the “Compact Micrite” and the basal part of the overlying Cherahil Formation. The “offshore equivalents” of these formations were also analyzed in the *Malkadir-1* well to the north of the *Hasdrubal* field.

Chouabine Formation: Planktic foraminifera recovered from the lower part of this formation suggest an Early Eocene, Zone P6 age.

El Garia Formation: Rare planktic foraminifera from near the base of the El Garia Formation indicate a mid- to late Early Eocene age (Zone P7, i.e. late Ypresian), based on the co-occurrence of *Pseudohastigerina micra*, *P. wilcoxensis*, *Planorotalites pseudoscitula*, *Morozovella subbotina/wilcoxensis*, *M. formosa gracilis* and *M. ?aequa*. This dominantly shallow-water unit is therefore considered to fall within the range of planktic foraminiferal Zones P7-P9 on the basis of deeper-water flooding episodes inferred from the presence of these planktic foraminiferids.

Bou Dabbous Formation: The Bou Dabbous Formation is well represented in well *Malkadir-1*. The formation is dated as Early Eocene (Ypresian) and is assigned to planktic foraminiferal zones uppermost P6 to lower P9 based on the occurrence of *Acarinina soldadensis*, *A. soldadensis angulosa*, *A. primitiva*, *Morozovella formosa*, *M. formosa gracilis*, *M. subbotinae*, *M. lensiformis* and *M. caucasica*. The presence of the nannofossils *Toweius oculatus*, *Cruciplacolithus mutatus*, *Zygodiscus herlynii*, *Ellipsolithus macellus*, *Helicosphaera seminulum* and *Zygrahblithus bijugatus ?nolfii* indicate a CP12a to CP8 age (Ypresian).

Compact Micrite Member: The age of the “Compact Micrite” in the *Hasdrubal* wells is constrained to within the earliest Lutetian (early Middle Eocene) by the presence of the nannofossil *Cyclicargolithus floridanus*, indicating an age no older than Zone CP12, and by the presence of *Sphenolithus obtusus* at the base of the overlying Cherahil Formation indicating Zone CP13. This age is supported by the presence of planktic foraminifera indicating an age close to the Early/Middle Eocene boundary (i.e. Zones P9/P10), including *Acarinina* spp. and also by the presence of the typically Ypresian-Lutetian foraminiferid *Baggina bismuthi*.

Cherahil Formation: Data from *Hasdrubal-1* records the occurrences of the ostracods *Loculicytheretta semirugosa*, *L. quibqueloculita* and *L. prima* through the lower Cherahil Formation, confirming a relatively complete Lutetian interval (Bismuth *et al.*, 1978). An age no older than Lutetian is confirmed by the occurrence of the planktic foraminiferid *Morozovella lehneri* less than 14m above the top of the El Garia Formation within the lower Cherahil.

Souar Formation: The lower part of the Souar “A” Formation in the *Malkadir-1* well shows no obvious microfaunal change at its contact with the underlying “Compact Micrite”. A P10/P11 Middle Eocene (Lutetian) age is assigned based on the occurrence of the planktic foraminifera *Morozovella aragonensis*, *M. lehneri*, *Acarinina broedermanni*, *A. pentacamerata*, *Globigerina higginsii* and *Catapsydrax dissimilis*, together with the typical Middle Eocene

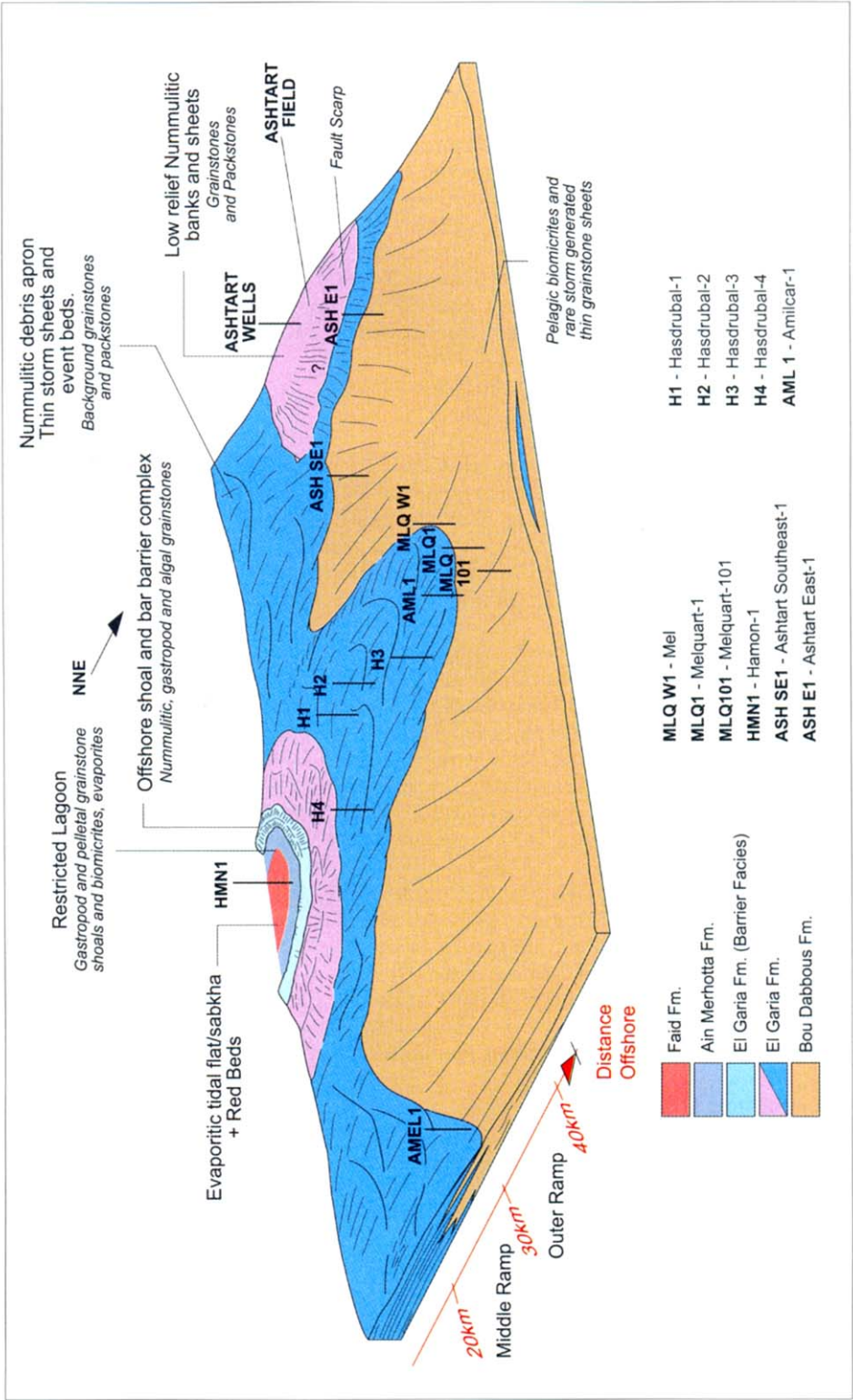


Fig. 11. Depositional model for the offshore El Garia Formation.

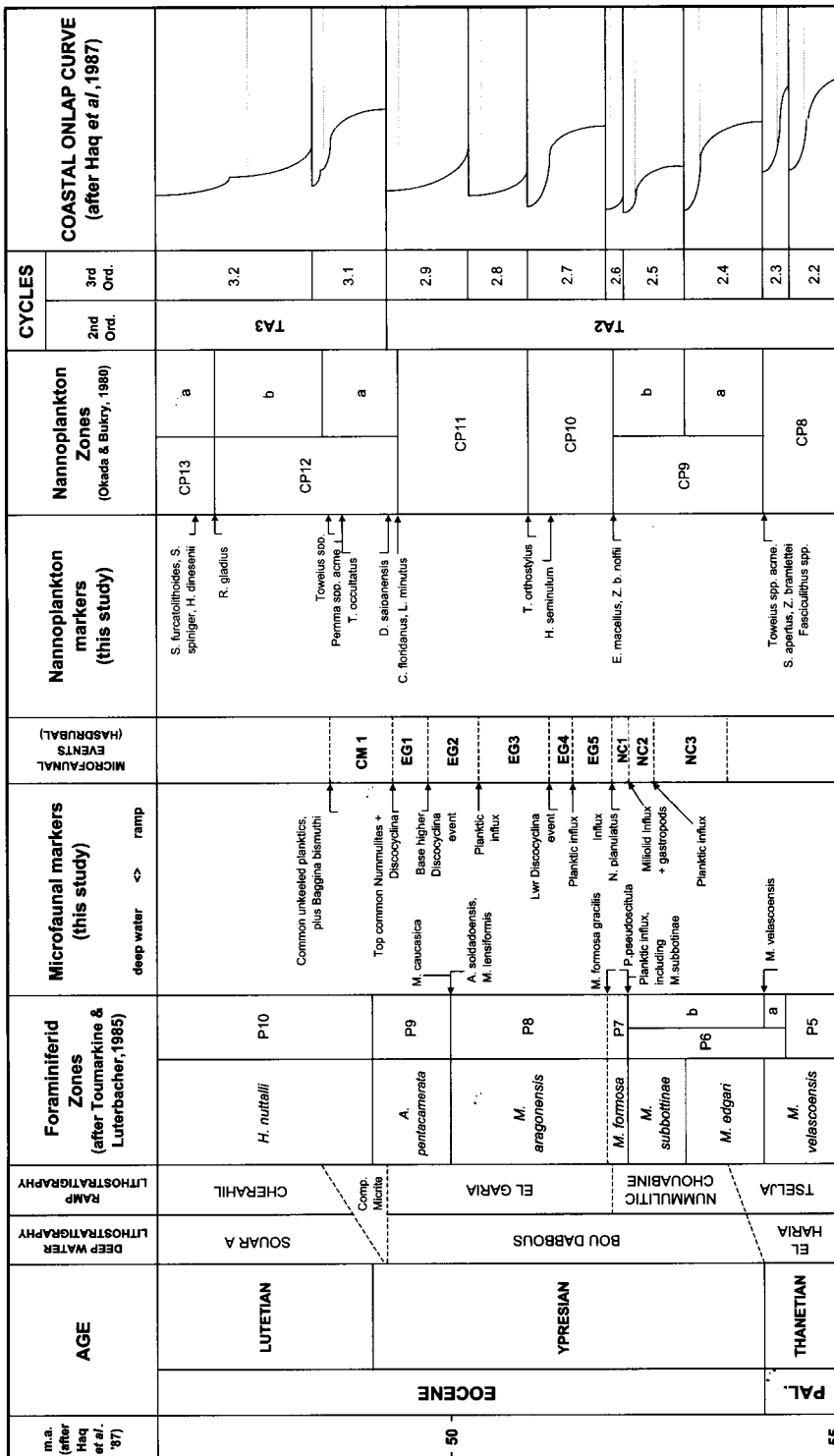


Fig. 12. Biozonation scheme and sequence stratigraphy for the Palaeogene, offshore Tunisia.

benthic foraminifera *Marginulinopsis tuberculata* and *Stainforthia* spp. Calcareous nannofossils include *Sphenolithus furcatolithoides*, *S. spiniger*, *Cruciplacolithus vanheckae* and *Reticulofenestra dictyoda* which are typical of the middle Middle Eocene (middle Lutetian), together with *Bramlettius serraculoides*, *Campylosphaera dela*, *Helicosphaera dinesenni* and *Reticulofenestra callida* which are typical of nannoplankton zones CP13/CP14 i.e. middle to late Lutetian. Cuttings from the Souar A – “Compact Micrite” interval in the *Malkadir* well yielded evidence for the penetration of older nannofossil zones including CP12b (early Lutetian) based on the occurrence of *Rhabdosphaera gladius* and upper CP12a (basal Lutetian) based on the occurrence of abundant *Reticulofenestra* spp., *Discoaster saipanensis*, *D. tanii nodifer*, *Lanternithus minutus* and *Pemma* sp.

Microfossil Events

Nine consistently recognisable microfaunal events of correlative value within the “Compact Micrite” and El Garia and “Nummulitic Chouabine” Formations (i.e. over the reservoir interval) have been identified. These comprise (from latest to earliest):

Foraminiferal Events

1. “Compact Micrite” (CM1): Common planktic foraminifera including *Acarinina* spp.
2. El Garia (EG1): Top *in-situ* *Nummulites* (top El Garia).
3. El Garia (EG2): Base Upper *Discocyclina* event.
4. El Garia (EG3): Influx of rare planktic foraminifera (P8 Zone).
5. El Garia (EG4): Lower *Discocyclina* Event.
6. El Garia (EG5): Major influx of planktic foraminifera (P7 Zone) and top common ostracods.
7. Nummulitic Chouabine (NC1): Influx of *Nummulites planulatus*.
8. Nummulitic Chouabine (NC2): Influx of miliolids and gastropods.
9. Nummulitic Chouabine (NC3): Influx of rare planktic foraminifera (intra P6 Zone).

All these events are palaeoenvironmentally controlled; however, the recognition of three potentially widespread flooding surfaces allows a field-wide subdivision to be made. Within the nummulitic grainstones and packstones of the El Garia Formation, the presence of large, flat *Discocyclina* is useful as these forms tend to occur at the top of the reservoir interval in all four wells (event EG2). In *Hasdrubal* -2, -3 and -4, this interval is separated from a lower *Discocyclina* event (EG4) by a minor influx of planktic foraminifera, although this planktic event has not been recognised in *Hasdrubal-1* due to the absence of thin sections over the relevant interval.

Nannofossil Events

The consistent recovery of *Sphenolithus obtusus* at the base of the Cherahil Formation in the *Hasdrubal* field and in the basal Souar Formation at the *Malkadir-1* well confirms a consistent Early Lutetian (Zone CP12) age at this stratigraphic level from the shelf area into a more open-marine location.

Cyclacargolithus floridanus occurs in the “Compact Micrite” in the *Hasdrubal* wells, but was not recorded from flooding phases recognised within the El Garia Formation. However, it is recorded in the upper part of the Bou Dabbous Formation in well *Malkadir-1*. This suggests that the interval represented by the uppermost Bou Dabbous Formation in the offshore area is absent in the corresponding El Garia Formation, the top of which is known to be marked by a well-developed omission surface.

In addition to the above events, limited nannofossil analyses of the *Hasdrubal-3*, *Hasdrubal-4* and *Hannibal-1* wells have revealed persistent reworking, including the presence of Late Cretaceous taxa in the basal El Garia Formation and in the top of the “Nummulitic Chouabine”

Formation in wells *Hasdrubal-3* and *Hannibal-1*. Reworked Palaeocene nannofossils are recorded in *Hasdrubal-4* and in *Hannibal-1* at the top of the “Nummulitic Chouabine”. These events may yet prove to be of great correlative value. The presence of *Nephrolithus frequens* at 2,764m in *Hannibal-1* indicates reworking of Late Maastrichtian sediments. Within the Late Palaeocene El Garia Formation in well *Malkadir-1*, reworked Cretaceous nannofossils including *Prediscosphaera cretacea* and *Watznaueria barnesae* were recorded, while the reworked Cretaceous (Albian-Maastrichtian) nannofossil *Eiffellithus turrisseiffelii* was recorded from the uppermost part of the Bou Dabbous Formation.

SEQUENCE STRATIGRAPHY AND CORRELATION WITH THE GLOBAL SEA LEVEL CURVE

A tentative attempt has been made to correlate the interval between the Chouabine Formation and the “Compact Micrite” in the *Hasdrubal* field (and between the Souar and Bou Dabbous Formations in the *Malkadir* well) with the coastal onlap curve of Haq *et al.* (1987) (Fig. 12).

Souar Formation: The *Malkadir-1* well penetrated the basinal equivalent (Souar Formation) of the “Compact Micrite” and Cherahil Formation, which occur in the *Hasdrubal* field. The basal part of the Souar Formation (Souar A Member) in *Malkadir-1* yielded a rich and diverse nannofossil assemblage indicating a maximum flooding surface assignable to the third-order cycle TA 3.1 of Haq *et al.* (1987). The nannofossil and planktic foraminiferal assemblages recovered from the overlying Souar A interval (up to the base of the Reineche Member) are tentatively assigned to cycle TA3.3. There is no firm evidence for planktic zone P10, suggesting a possible hiatus between the Souar A and underlying “Compact Micrite” (c.f. Bailey *et al.*, 1989), and this may explain the absence of an obvious TA 3.2 cycle equivalent.

Compact Micrite Member: The “Compact Micrite” (CM1) in the *Hasdrubal* field represents a major flooding surface which correlates with the TA3.1 third-order cycle of Haq *et al.* (1987), the base of which represents the Early/Middle Eocene boundary and the onset of the worldwide Middle Eocene transgression. The unit’s basal boundary with the underlying El Garia Formation probably represents a depositional hiatus because the upper surface of the latter formation is frequently burrowed, and the base of the “Compact Micrite” contains abundant evidence for substrate colonization, condensation and a marked increase in water depth. Diagenetic studies in the *Hasdrubal* field indicate that the El Garia Formation was not subaerially exposed prior to the deposition of the “Compact Micrite” (Macaulay *et al.*, 2001). Nannofossil assemblages over this interval in the *Malkadir-1* well are richer and more diverse, supporting the idea that this interval represents a maximum flooding surface.

El Garia and Chouabine Formations: The EG3 planktic foraminiferid event is tentatively correlated with the TA2.7 third-order cycle of Haq *et al.* (1987). The EG5 planktic foraminiferal influx constitutes the best-developed and most obvious flooding surface in the El Garia Formation. The assemblage is relatively diverse and more importantly contains taxa, which have overlapping ranges within planktic Zone P7. This equates with the TA2.6 third-order cycle of Haq *et al.* (1987). A high diversity ostracod assemblage is associated with the lower part of this planktic-rich interval and also extends into the underlying section.

A lower nummulite-rich unit (NC1) is recognised in wells *Hasdrubal-2* and *-3* near the top of the “Nummulitic Chouabine”. It has been only tentatively defined in *Hasdrubal-1* due to the lack of thin sections and core samples over this interval. However, this event is absent in *Hasdrubal-4*, indicating a facies break or even a minor hiatus at this level. The ostracod-rich unit identified in *Hasdrubal-2*, *-3* and *-4* within the uppermost Chouabine Formation is coincident with the miliolid/gastropod event in *Hasdrubal-4*, while in wells *Hasdrubal-2* and *-3*, these two levels are separated by a discrete nummulite-rich unit. Micropalaeontological

data in *Hasdrubal-1* are insufficient to verify the presence of these two levels. The miliolid/gastropod unit close to the top of the "Nummulitic Chouabine" (NC2) may relate to a significant sea-level fall and a short-term progradation of the nummulitic facies. The minor influx of planktic foraminifera (NC3) recognized in wells *Hasdrubal-2*, -3 and -4 may be tentatively equated with the next flooding event, i.e. within the third-order cycle TA2.5.

It is interesting to note that the planktic flooding events NC3 and EG5 are both preceded by a level rich in oyster debris. A stable lowstand period marked by an abundance of oysters was therefore followed by a flooding events rich in planktic foraminifera.

Regionally, the major earliest Early Eocene (Ypresian) flooding event (cycle TA2.4) is widely recognized at the base of the "Transgressive Chouabine" (Bailey *et al.*, 1989). This event has not been reached in any of the *Hasdrubal* samples analyzed during the present study. The Chouabine Formation is characterized by abundant phosphate, possibly indicating upwelling conditions associated with the transgression. This formation shows marked regional variations in thickness, filling much of the shelf topography prior to the deposition of the El Garia Formation. The Chouabine Formation thins updip and becomes lithologically less distinctive with a decreasing phosphate content.

In the *Malkadir-1* well, where the El Garia and Chouabine Formations are replaced by the deeper-water Bou Dabbous Formation, the third-order cycles TA2.8-2.7, TA2.6, TA2.5 and possibly TA2.4 can tentatively be identified. In this well, there is no definite evidence for the existence of cycle TA2.9, and this may have been eroded from the boundary between the Bou Dabbous Formation and the overlying "Compact Micrite".

DISCUSSION: A DEPOSITIONAL MODEL FOR THE EL GARIA FORMATION

Previous Work

Moody (1987) and Moody and Grant (1989) extrapolated facies distributions observed onshore to areas offshore. They considered each formation within the Metlaoui Group to comprise a series of broadly shoreline-parallel belts of relatively uniform width. This was an extension of the model established by Bishop (1975) and later revised by the same author (Bishop 1985, 1988). With this model in mind, it was assumed that once the nummulite bank trend (El Garia Formation) had been identified, future exploration would simply involve drilling a series of wells along strike, all other factors being equal (i.e. source, seal and trap presence and effectiveness). Unfortunately, the model proved to be unsuccessful. Some subsequent wells were dry or produced insignificant volumes of hydrocarbons, encountering either a limited thickness of El Garia Formation nummulitic facies or poor-quality reservoir (Bishop, 1988). The model may be an oversimplification of the depositional system and assumed that reservoir sequences offshore would be very similar to those examined onshore. The onshore distribution of the various units which make up the Metlaoui Group is controlled by the penecontemporaneously uplifted "Kasserine Island" palaeohigh, around which a series of broadly concentric and parallel units were deposited in a shelf/platform setting.

The model of Bailey *et al.* (1989) drew attention to the complex interplay between established (Mesozoic) structural trends and patterns of sedimentation during the Early Eocene, and on subsequent reservoir diagenesis and hydrocarbon generation. The model required the presence of structurally-induced topographic highs which acted as nuclei for the development of nummulite banks or shoals. Shoals developed along the seaward-facing margins of structurally-induced basins or embayments within which dysaerobic conditions enhanced the source potential of carbonates and mudstones being deposited. This model, while recognizing the inter-relationships of structural and palaeoenvironmental controls on the deposition of both source and reservoir facies, failed to consider fully the impact of eustatic sea-level changes and thus a potential sequence stratigraphic interpretation.

More recently, Loucks *et al.* (1998) put forward a model based on a combination of outcrop studies and examination of the offshore *Ashtart* field. This proposed that the El Garia Formation was deposited on a ramp and noted that the formation was significantly bioturbated (consistent with our own observations). However, this model is not applicable to *Hasdrubal*. For example, a facies comprising robust, inflated tests of the foraminifera *Discocyclina* was identified by Loucks *et al.*, and was considered to have been deposited in shallower waters than the nummulite-rich facies. However, the facies has not been identified in wells along strike in the Amilcar Permit. Moreover, publications including Henson (1950) and Ghose (1977) record the genus *Discocyclina* (especially in the Eocene) as occurring in deeper waters than *Nummulites*. Robust, lenticular forms of this genus are thought to have occupied fore-reef (fore-bank) palaeoenvironments, while larger, flatter forms are thought to have occupied deeper, quieter waters.

Both Loucks *et al.* (1998) and Bailey *et al.* (1989) identified an inferred facies belt rich in sea-grasses within which they proposed that the *Nummulites* may have lived. However, although sea-grasses are very rarely preserved as fossils (den Hartog, 1970), they are virtually unknown before the Middle Eocene (most records coming from the Neogene). Studies of the extant nummulitids *Operculina* and *Heterostegina* (Reiss and Hottinger, 1984) — the former is morphologically very similar to *Nummulites* — show that they can occupy a wide range of substrates from coral rubble to carbonate mud. Moreover, they are mobile and are not associated with sea-grasses or other aquatic plants. Loucks *et al.* (1998) also identified a facies rich in calcareous red algae. However, in the several hundred thin sections we have examined covering the entire El Garia interval, we have only found red algae in two samples and in both cases they were rare and fragmented.

A new model for the *Hasdrubal* field

Our preliminary model for the *Hasdrubal* area was that the El Garia Formation represents part of a nummulitic shoal complex, which was envisaged to grade offshore (i.e. to the north) via a nummulitic debris apron (the Ousselat Member) into the basinal facies of the Bou Dabbous Formation. This model was based on the models of Moody (1987) and Moody and Grant (1989) discussed above. It predicts that relatively uniform, cross-bedded nummulitic packstones and grainstones would occur over the *Hasdrubal* area.

Following the drilling of well *Hasdrubal-3*, the model was revised to one envisaging a broad middle-ramp facies belt, comprising banks of nummulitic grainstones-packstones, generated within a background of interbedded fine bioclastic (nummulolithoclastic) packstones and wackestones. In common with the previous model, the Ousselat Member was thought to form an offshore transition from the El Garia Formation to the Bou Dabbous source facies. Further detailed petrographic, micropalaeontological and sedimentological studies of the *Hasdrubal-3* core started to reveal an absence of bank-type structures (*sensu* Racey, 1995), and the lack of a nummulolithoclastic debris apron.

On completion of the *Hasdrubal-4* well, all available data was re-assessed and a new model was developed (Fig. 11). It became clear that tectonism has had a significant control over sedimentation (Bailey *et al.*, 1989; Philips 2001) although tectonism is only superimposed locally onto more regional sea-level changes. Data from the *Hammon-1* well to the SW of *Hasdrubal* was reinterpreted, together with seismic data which demonstrated that *Hammon-1* was drilled on an exposed fault-bound high. The *Hasdrubal* accumulation was then reinterpreted integrating sedimentological and micropalaeontological data. The reservoir was suggested to be a narrow tongue of redeposited nummulitic material flanked by deep-water embayments in which mudstones had been deposited. Again, a transition zone (the Ousselat Member) between the El Garia and Bou Dabbous Formations could not be recognized, and there was apparently a direct transition between the two units.

In the *Hasdrubal* field area, the El Garia Formation consists of nummulitic wackestones to grainstones, which locally contain fairly common (2-5%) large, flat *Discocyclina* and rare

planktic foraminifera. The *Discocyclina* are often complete, but where they are broken, this is compaction-related. These *Discocyclina*-rich beds are considered to indicate deposition in fairly deep waters, near the base of the euphotic zone, in a low energy setting, as is supported by the presence of unbroken planktic and deep-water smaller benthic foraminifera. Consequently, it is inferred that the *Nummulites* were transported into this deep-water, mid-ramp setting either by turbidity currents (perhaps triggered by tectonic activity) or storm currents. Evidence is provided by the fact that the *Nummulites* are frequently broken and abraded and show some sorting by size. As discussed by Racey (1995, 2001), hydrodynamic studies have shown that nummulites had low bulk densities (0.305 g/cm^3), low pick-up velocities ($18\text{--}34 \text{ cm s}^{-1}$) and low settling velocities, close to those observed for coarse grains of sand. Consequently, they would be relatively easily transported especially following the organism's death. Bioturbation is common locally, and would be unlikely in an autochthonous nummulite bank. The nummulite tests and fragments show no evidence of boring or encrustation, suggesting they were originally deposited in a continuously agitated environment. This tends to suggest the presence of nummulitic build-ups in a more proximal up-ramp setting that were subsequently reworked. However, it is not clear whether this nummulitic material was derived from along strike and up-dip, or whether it was washed directly across the ramp perpendicular to the coastline. Predicting the likely location of *in-situ* nummulitic banks with improved reservoir quality (due to a lower mud content) is difficult. It cannot be solved using dipmeter data which, for the *Hasdrubal* wells, show an almost totally random distribution of depositional dips, partly due to bioturbation. Furthermore, chasing nummulite banks up-dip may prove to be a fruitless exercise even if palaeocurrent data were available, as it is possible that banks *per se* never really became established, with material being continually swept down ramp as storm sheets and/or fault-triggered turbidite flows.

Hasdrubal-3 is the most distal well in terms of depositional environment (Fig. 11), and cores generally contain more common, large flat *Discocyclina* and *Nummulites*, which could indicate deeper waters. *Hasdrubal-4* on the other hand is the most proximal well, in that cores from the lower part contain common oysters, with fewer large, flat *Discocyclina* and generally larger, fatter *Nummulites*. Nummulite fragments often dominate the matrix in *Hasdrubal-4*, while mud matrix is more common in *Hasdrubal-3*, again indicating a probable proximal to distal transition. *Hasdrubal-2* is similar to *Hasdrubal-3* in this respect, whilst *Hasdrubal-1* provided insufficient material to be integrated into the model with confidence.

All four wells show similar planktic foraminiferal abundances and diversities in several distinctive and correlatable events. The presence of planktic foraminifera in *Hasdrubal-2* and -3 is interpreted in terms of their relative proximity to areas of deeper-marine circulation. The presence of plankton in the more proximal *Hasdrubal-4* well suggests a deep-marine embayment near (to the ?south of) the *Hasdrubal* field, which extends at least as far "shoreward" as *Hasdrubal-4*.

The location of the El Garia nummulitic shoals "sourcing" the nummulitic reservoir in *Hasdrubal* are believed to have been structurally controlled. Philps (2001) notes that salt migration along the footwalls of listric faults during the Early Eocene caused fault-block rotation, which affected the Jurassic to Eocene succession. Nummulitic shoals accumulated along the partially emerged crests of these tilted fault blocks. Subsequent movements along these faults may have triggered down-ramp transport of these nummulite grainstones-packstones.

CONCLUSIONS

1. The main reservoir in the *Hasdrubal* field (Gulf of Gabes, offshore Tunisia) comprises redeposited Lower Eocene nummulitic limestones of the El Garia Formation which have been variably bioturbated, dolomitised and fractured. We describe a revised ramp depositional model for the El Garia Formation offshore Tunisia, which includes a series of pronounced embayments containing deeper-marine source rocks.

2. *Hasdrubal* is sourced from mudstones and limestones assigned to the Bou Dabbous Formation which were deposited in a deep-water embayment to the SE of the field. 1D modelling of the area suggests that this embayment is in the late oil window, while 3D migration modelling indicates that wet gas and oil migrated from this kitchen area into the *Hasdrubal* structure. The carbozole concentrations are high and, together with the benzocarbozole (a)/(c) ratios in the *Hasdrubal* oil, confirm the reservoir's close proximity to the source kitchen.

3. The two largest oilfields (*Ashtart* and *Bourri*) in the El Garia trend comprise nummulite accumulations situated on structural highs which protruded into the basin and were almost surrounded by Bou Dabbous source rocks; therefore, potential migration pathways are short. Such nummulite accumulations were also optimally placed for the formation of secondary dissolution porosity due to acidic pore-waters associated with a migrating hydrocarbon front. These acids became progressively spent as they advance "up-ramp", such that in more "proximal" nummulite-rich settings they had a limited effect on porosity.

4. The presence of three flooding events across the *Hasdrubal* field, which can be partially calibrated with second-order sequence cycles, assists in the correlation of discrete reservoir units across the field. The ages of the various formations and members of the Metlaoui Group have been refined allowing them to be placed in a regional sequence stratigraphic framework.

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APPENDIX

THE FOLLOWING dataset was available for biostratigraphic and palaeoenvironmental analysis, together with sedimentological core logs for the El Garia interval from all of the listed wells except *Malkadir-1*. The *Malkadir-1*; *Hannibal-1* and *Aliyan-1* wells are all located outside the Amilcar Permit.

Hasdrubal-1: Only 24 thin sections of generally poor quality were available. These were screened and 20 were selected for study. These did not cover the full sequence, being generally restricted to the uppermost and lowermost parts of the sequence. Samples studied in detail included one from the "Compact Micrite", six from the uppermost El Garia, three from the lower part of the El Garia and seven from the Chouabine. Consequently there are significant data gaps. Sixteen core samples were examined for nannofossils.

Hasdrubal-2: One hundred and sixty eight thin sections were available for study, covering the "Compact Micrite", El Garia and Chouabine. Twenty core samples were examined for nannofossils.

Hasdrubal-3: One hundred and eighty two thin sections were examined covering the "Compact Micrite", El Garia and Chouabine. Ten core samples were examined for nannofossils.

Hasdrubal-4: Two hundred and twenty seven thin sections were examined covering the Cherahil, "Compact Micrite", El Garia and Chouabine. Twelve core samples were examined for nannofossils.

Malkadir-1: A total of thirty seven nannofossil analyses have been carried out over the section 2,300m - 2,480m, comprising twenty seven in the Bou Dabbous, five in the "Compact Micrite", four in the El Haria and one in the Souar Formation. An existing microfaunal (foraminiferal) database covering the Reineche to top El Haria succession was also re-evaluated

Hammon-1: Six nannoplankton analyses were carried out over the basal Cherahil Formation section.

Hannibal-1: Ten nannoplankton analyses were carried out, primarily on the basal Cherahil and Nummulitic Chouabine units.

Aliyan-1: The published data as presented by Bailey *et al.* (1989) was also re-evaluated

