The importance of constraining regional exhumation in basin modelling: a hydrocarbon maturation history of the Ghadames Basin, North Africa

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ABSTRACT: Estimation of eroded overburden at unconformities is essential to accurately constrain burial histories and predict the timing of hydrocarbon maturation. In the Ghadames Basin, three independent techniques, palaeo-isopach construction, sonic velocity and vitrinite reflectance analysis, were employed. The resultant basin model suggests that only the two most significant unconformities, the Hercynian (Late Carboniferous) and Alpine (early Eocene), have a major control on timing of hydrocarbon charge.

Modelling indicates only one period of generation from the Lower Silurian shales on the western margin of the basin, with 95% hydrocarbon generation prior to Hercynian exhumation. The central basin and southern margin experienced maximum burial during Eocene time. The Middle–Upper Devonian mudstones are the main source rocks and they did not generate significant volumes of hydrocarbons over the basin centre until Cretaceous time; they are currently within the peak oil generation zone.

In Libya, on the eastern/northeastern flank of the basin, results indicate Cenozoic maximum burial, followed by up to 2000 m of Alpine exhumation. The magnitude of this exhumation has not been recognized previously, although it is a critical component of the basin model as it has a major impact on potential hydrocarbon charge in this area. Maturation models predict that the Lower Silurian source underwent two generative phases: (1) pre-Hercynian (Carboniferous) generation; and, significantly, (2) post-Hercynian (Late Jurassic–Cenozoic) generation. The identification of late hydrocarbon generation offers potential for oil and gas to migrate into post-Hercynian traps. Over the western, northern and eastern flanks, the Devonian source rocks remain immature/ marginally mature at present day.

KEYWORDS: *Ghadames Basin, hydrocarbon maturation, Hercynian, Alpine, burial history analysis, Tanezzuft, Frasnian, Libya, Algeria*

INTRODUCTION

The Ghadames Basin lies on the North African Platform and extends over parts of Algeria, Tunisia and Libya (Fig. 1). It is a large intracratonic sag basin that formed during Early Palaeozoic time and contains up to 6000 m of Palaeozoic and Mesozoic sediments. The regional Hercynian Unconformity (Late Carboniferous–Permian age) separates Palaeozoic deposits from overlying Mesozoic strata and marks a major shift in depocentre (Fig. 1). The area has been an important hydrocarbon province since the 1950s and recent improvements in seismic data quality and interpretation techniques have led to a renaissance in exploration, with a number of large oil and gas discoveries in the Algerian part of the basin over the last ten years. It is becoming clear that much greater volumes of petroleum have been generated than previously predicted, suggesting a complex, multistage history of hydrocarbon maturation and migration.

Estimation of eroded overburden, particularly at the Hercynian Unconformity, is a critical aspect of basin modelling

in this area and other workers have speculated on the amount of eroded section. These values range from 3000 m to 4000 m over the western and northern margins of the basin (e.g. Malla *et al.* 1998; Yahi *et al.* 2001; Makhous & Galushkin 2003), 300 m to 1300 m towards the south (Makhous & Galushkin 2003) and 400 m to 1500 m over the central basin area (e.g. Malla *et al.* 1998; Makhous 2001; Makhous & Galushkin 2003). Other studies by Dardour *et al.* (2003a, b, 2004), Boote & Dardour (2004) and Boote *et al.* (1998) highlighted the importance of periods of uplift and erosion associated with the Hercynian, Austrian and Alpine tectonic events, and emphasized their impact on maturation and expulsion history. However, although values have been suggested, the actual methods of estimation of eroded overburden have rarely been defined. Earlier workers (e.g. Boote *et al.* 1998; Hallett 2002; Dardour *et al.* 2004) identified the presence of the Late Eocene Alpine Orogeny across the basin, but the exhumation and thickness of the missing section associated with it were not quantified. Fission track data from Glover (1999) suggest up to 2000 m of exhumation related to the Alpine event over the Qarqaf and

Fig. 1. Location map and schematic cross-section of the Ghadames Basin showing its main structural elements and the location of wells used in the 1D modelling study.

Tihemboka arches to the far south of the basin, and these results are in general agreement with estimates obtained in this study.

This study involves regional-scale 1D basin modelling using well data from across the Ghadames Basin, providing an improved understanding of the effects of tectonics on sedimentation and hydrocarbon generation history. Considering the basin in its entirety, by incorporating data from Algeria, Libya and Tunisia, this paper aims to investigate and constrain the

influence of erosion along regional unconformities on the timing of hydrocarbon maturation and generation.

STRUCTURAL SETTING

The present-day architecture of the Ghadames Basin is the result of a number of periods of tectonism: the Caledonian (Early Devonian), Hercynian (Late Carboniferous–Permian), Basal Cretaceous (Neocomian), Austrian (Aptian) and Alpine

Table 1. Stratigraphic framework for the Ghadames Basin used in the study

Era	Period	Layer name	Main erosion	Stage	Age (Ma)
Cenozoic	Tertiary/Quaternary	Late Tertiary/Quaternary	Alpine	Quaternary–Oligocene	0–22
		Alpine Unconformity		Oligocene/Eocene	22–25
Mesozoic	Cretaceous	Early Tertiary		Eocene/Paleocene	25–72
		Sequence 7d	Austrian	Senonian	72–88
		Sequence 7c		Turonian/Cenomanian	88–94
		Sequence 7b		Cenomanian/Albian	94–109
		Sequence 7a		Albian/Aptian	109–120
		Austrian Unconformity		Aptian	120–124
		Sequence 6Bb		Barremian	124–130
		Sequence 6Ba		Barremian/Neocomian	130–140
		Basal Cretaceous Unconformity	Basal Cretaceous	Neocomian	140–146
	Jurassic	Sequence 6Ag		Malm	146–155
		Sequence 6Af		Malm/Dogger	155–166
		Middle Jurassic Hiatus		Dogger/Lias	166–187
		Sequence 6Ae	Hercynian	Lias	187–208
	Triassic	Sequence 6Ad		Rhaetian/Norian	208–223
		Sequence 6Ac		Carnian	223–235
		Sequence 6Ab		Ladinian	235–239
		Sequence 6Aa		Anisian	239–245
Palaeozoic	Permian	Hercynian Unconformity			245–290
	Carboniferous	Sequence 4e	Hercynian	Westphalian/Stephanian	290–311
		Sequence 4d		Namurian	311–325
		Sequence 4c		Namurian/Visean	325–335
		Sequence 4b		Visean	335–340
		Sequence 4a		Visean/Tournaisian	340–363
	Devonian	Sequence 3c	Caledonian	Famennian/Frasnian	363–372
		Devonian Hot Shale		Frasnian	372–377
		Sequence 3b		Givetian/Eifelian/Emsian	377–389
		Sequence 3a		Emsian/Pragian/Lochkovian	389–401
	Silurian	Caledonian Unconformity		Lochkovian/Pridoli	401–409
		Sequence 2d		Pridoli/Upper Ludlow	409–411
		Sequence 2c		Upper Ludlow	411–418
		Sequence 2b		Lower Ludlow	418–424
	Ordovician	HST 2a		Wenlock	424–430
		TST2a		Llandovery	430–438
		Silurian Hot Shale		Llandovery	438–440
		LST 2a		Ashgill	440–443
	Cambrian	Upper Ordovician		Caradoc	443–464
		Lower Ordovician		Llandeilo–Tremadoc	464–510
		Cambrian		Cambrian	510–570

(Eocene–Oligocene). These tectonic episodes modified the basin architecture, altering the depocentre location, and generating fault-bounded structural highs that surround the present-day central depression (Fig. 1). The basin is bounded to the north by the Dahar–Nafusah Uplift, to the west by the Amguid–El Biod Arch, and to the south by the Qarqaf and Tihemboka arches and the Hoggar Shield. The western flank of the younger Sirte Basin defines its eastern limit.

Prior to the Hercynian Orogeny, the North African Platform displayed little regional differentiation and formed one large subsiding depositional sag basin (Van de Weerd & Ware 1994). During Late Carboniferous–Permian time the Hercynian

Orogeny caused exhumation of large parts of the Palaeozoic section, significantly modifying the basin shape and subsequent depositional axis. The intensity of Hercynian compression decreases towards the SE, which accounts for the dominant structural relief towards the north and west and the preservation of thick Carboniferous deposits towards the SE.

Renewed subsidence was initiated by extension during Triassic–Liassic time, related to rifting along the Tethys Fracture Zone and the opening of the central Atlantic (Boudjema 1987; Guirard *et al.* 1987; Yahi *et al.* 2001). This resulted in the deposition of a thick sequence of continental clastic rocks. Subsequent thermal subsidence was characterized by NW tilting and the superimposition of a broad Mesozoic extensional sag basin over the eroded remnants of the earlier Palaeozoic basin (Van de Weerd & Ware 1994; Echikh 1998), (Fig. 1).

The Alpine orogenic event, the most recent period of tectonism to have affected the basin, was caused by collision of the Africa–Arabia plate with Europe during latest Cretaceous–Eocene time (Boote *et al.* 1998; Guirard 1998). Exhumation related to this tectonic event increases in intensity eastwards across the Ghadames Basin, being greatest over the uplifted basin margins to the south (Qarqaf and Tihemboka arches) and east (Nafusah Uplift) (Underdown 2006).

Table 2. Source-rock TOC values used in 1D modelling

Name	Estimated average initial TOC (%)
S1 (Silurian hot shale)	12
S2 (Silurian hot shale)	6
S3 (Silurian hot shale)	3
S4 (Silurian minor source shale)	2
D1 (Devonian hot shale)	10
D2 (Devonian hot shale)	6
D3 (Devonian hot shale)	3
D4 (Devonian minor source shale)	2

Fig. 2. (a) Hercynian Unconformity erosion map produced from comparison of isopach and palaeo-isopach maps (contour values in metres; dots show location of input data wells). (b) Hercynian sub-crop map based on available well data (for stratigraphy, see Table 1).

STRATIGRAPHIC MODEL

A sequence stratigraphic framework has been developed for the basin, based on wireline log data from over fifty wells (Underdown 2006). The Palaeozoic of North Africa has been divided previously into five second-order sequences (Carr 2002): NA1 (Early Cambrian–Late Ordovician); NA2 (Late

Ordovician–Late Silurian); NA3 (Devonian); NA4 (Carboniferous); and NA5 (Permian). Within the Ghadames Basin three of these sequences can be identified: NA2, NA3 and NA4. Sequence NA1 cannot be recognized due to lack of data, while NA5 is absent over the study area due to erosion that occurred during Hercynian time. The Mesozoic succession can also be divided into three second-order sequences: NA6A

(Triassic–Jurassic); NA6B (Lower Cretaceous); and NA7 (Upper Cretaceous). These second-order sequences can be further subdivided into higher-order sequences (Table 1) that form the basis of the stratigraphic model used in the 1D well models.

METHODOLOGY

One-dimensional models for 34 wells distributed across the Ghadames Basin (Fig. 1) were constructed and simulated using the Genex software of Beicip-Franlab.

Model construction

In basin modelling the conceptual model represents a condensed description of the geological evolution of the basin under consideration (Welte & Yüklér 1981; Welte & Yalçın 1987) and is thus based on the geological framework of the study area. It provides the temporal framework required to structure the input data for the computer simulation (Wygrala 1988; Poelchau *et al.* 1997). Stratigraphic analysis provides one of the most important inputs to the conceptual model. The sedimentation history of a basin is subdivided into a continuous series of events, each with a specified age and duration. Each stratigraphic event represents a time span during which deposition (sediment accumulation), non-deposition (hiatus) or uplift and erosion (unconformity) occurred. The model for the Ghadames Basin used in the current study contains a maximum of 40 events (layers) and is summarized in Table 1. Models were constructed from the Cambrian (570 Ma) to Recent. Where well penetration was not deep enough to reach the Cambro-Ordovician sediments, the thickness of the layers not penetrated by a well were interpolated from available data from surrounding wells.

Input parameters

Each layer within the model has to be designated a type ('Unconformity'; 'Formation'; 'Missing Formation'), thickness, age and duration, and lithology. This information was obtained from analysis of the wireline logs and available well reports. The thickness of eroded sediments is a critical input parameter and is discussed in detail in the following section.

Palaeobathymetry data are used to reconstruct the total subsidence that has occurred within a basin. Within the Genex software, palaeobathymetry is used only for subsidence calculations and to display burial curves with respect to sea-level. It has no influence on the temperature and the geochemical calculations. The estimated values of palaeobathymetry throughout the history of the Ghadames Basin used in the models were obtained from a combination of published values (e.g. Yahia 1999; Makhous & Galushkin 2003).

Palaeo-surface temperature defines the surface temperature evolution through time. Genex uses information on palaeo-latitude, palaeobathymetry and palaeo-environment to predict this.

In order to reconstruct the thermal history of a sedimentary basin the palaeoheat flow must be calculated in addition to the heat flow at present day (Yalçın *et al.* 1997). Although basal heat flow is an important input parameter in basin modelling, it is often difficult to define, as is its evolution through time. Heat flows used in the reconstruction of the thermal history of a basin therefore need to be calibrated against available maturity profiles, such as vitrinite reflectance. The Genex modelling software requires the input of heat flows through time at the bottom of the basement. This means that the basement is included in the calculations and, therefore, crustal radiogenic heat flow is considered.

Parameters specified for each source-rock interval include the specific kerogen type, the kerogen kinetics, the total organic carbon (TOC) content, the source-rock thickness, the saturation threshold for expulsion and the pressure regime. The TOC value entered is the estimated average initial content of organic carbon over the effective source-rock thickness. This may be significantly higher than the present measured organic carbon content in mature source rocks, due to expulsion of hydrocarbons.

The two main source-rock intervals within the Ghadames Basin are the Lower Silurian (Tanezzuft) and Middle–Upper Devonian (Frasnian) shales and 'hot' shales. Table 2 presents the source-rock classification used in the 1D modelling. This classification of varying source-rock quality is based on the present-day distribution of average TOC content across the basin, but takes into account that initial values are likely to have been significantly higher in areas of the basin where the source rocks presently record high levels of maturity.

Estimation of timing and magnitude of exhumation

Where large-scale erosion has occurred, the estimation of the thickness of eroded sediments and the original lithology of the missing section is a crucial input parameter in basin modelling. This impacts on the timing of hydrocarbon maturation of the source-rock intervals.

The stratigraphic sequence of the Ghadames Basin contains several unconformities that eroded section during its evolution (Table 1). The main erosional events are: the Caledonian (Early Devonian); the Hercynian (Late Carboniferous–Permian); the Basal Cretaceous (Neocomian); the Austrian (Aptian); and the Alpine (Eocene–Oligocene). Of these, sensitivity analysis indicates that only the Hercynian and Alpine tectonic events have a significant effect on the timing and level of hydrocarbon maturation within the basin (Underdown 2006).

A variety of techniques can be employed to attempt to quantify the timing and magnitude of exhumation (Corcoran & Doré 2005). Within this study, initial estimates of erosion at the main unconformities have been calculated by comparing present-day isopach and palaeo-isopach maps. The latter were constructed for each sequence by extrapolating contours beyond present-day sub-crop boundaries (honouring the regional trends) to provide an interpretation of the original depositional thickness. Integration of these maps allows the production of erosion maps along the major unconformities and gives an insight into the structural evolution of the basin, highlighting the importance of erosion on present-day preserved thickness. Erosion beneath the Hercynian Unconformity is calculated to increase from a few hundred metres in the SE in Libya, to more than a thousand metres to the north and west in Algeria (Fig. 2). These results agree with estimates obtained independently from vitrinite reflectance gradients analysed for a number of wells within the basin (Underdown 2006). The amount of Hercynian erosion is observed to increase towards the Amguid–El Biod Arch in the far west of the basin in Algeria, where an estimated 2500 m of sediment has been removed (Fig. 2). Hercynian erosion removes Late Carboniferous (Namurian–Westphalian) aged strata in the central and southern parts of the basin, while further north and east it cuts down to Upper Devonian and Late Carboniferous aged sediments. In the extreme north and west of the basin Hercynian erosion has cut down to Ordovician/Silurian deposits.

Nearly all Cenozoic deposits have been removed and Upper Cretaceous sediments outcrop at the surface over large areas of the basin. To ascertain an accurate thickness for eroded

Fig. 3. Heat flow history model for the Ghadames Basin used in present study. Modelled heat flows are similar during the Palaeozoic; higher Cenozoic heat flow values required over southern and western margins to calibrate the BHT data accurately.

sediment along the Alpine Unconformity, examination of regional correlations and isopach/ palaeo-isopach maps has been integrated with available sonic velocity, thermal maturity data (vitrinite reflectance or equivalent) and apatite fission track data, to provide information on both the timing and amount of exhumation associated with the Alpine Orogeny.

Sonic velocity analyses of Lower Silurian and Middle–Upper Devonian mudstone intervals indicates a regional increase in apparent exhumation eastwards across the Ghadames Basin (Underdown 2006). The present-day basinal depocentre to the west displays the thickest Mesozoic succession, and apparent exhumation is at a minimum (100–200 m). This increases significantly towards the south and east up to 2000 m in the vicinity of the Qarqaf, Tihemboka and Nafusah arches. This southwards and eastwards increase in apparent exhumation contrasts with the observed pattern of Hercynian erosion, which increases towards the north and west (Fig. 2), implying that exhumation recorded along the Qarqaf, Tihemboka and Nafusah arches must relate to a period of younger Alpine exhumation. Hercynian erosion had a minimal effect to the far south of the basin, where an almost complete Palaeozoic section is preserved.

Calibration parameters

Corrected bottom-hole temperature (BHT), drill stem test temperature (DST) and thermal maturity data (R_o equivalent) were used to calibrate the temperature history of the basin.

The thermal history of the basin has been calibrated against maturity profiles using vitrinite reflectance, graptolite and chinitoza data obtained from proprietary well reports. The observed equivalent vitrinite reflectance values were compared to the calculated values obtained following the Easy% R_o

algorithm of Sweeney & Burnham (1990). This is the most widely used model for vitrinite reflectance calculation and is based on a chemical kinetic model that uses Arrhenius rate constants to calculate vitrinite elemental composition as a function of temperature and time.

There is a lack of published information on kerogen kinetics for the source rocks in the Ghadames Basin, and limited access to proprietary analytical material meant that it was not possible to specify variations in kerogen kinetics across the basin or stratigraphically. An average standard activation energy value for Type II kerogens of 52 Kcal mole⁻¹ was used throughout the model.

1D MODELLING SIMULATION RESULTS

Heat flow history

The heat flow model (Fig. 3), which was developed based on knowledge of the tectonic history of the basin and calibration to available maturity data, suggests: a gradual decrease in bottom basement heat flow throughout the Palaeozoic, following cessation of the Pan-African Orogeny; a heat flow maximum occurring as a result of Triassic–Liassic rifting, due to extension and thinning of the lithosphere; subsequent cooling during the Jurassic–Cretaceous thermal sag phase; and a renewed thermal peak during Upper Cretaceous–Cenozoic time, which was greatest over the southern margin of the basin and decreased in magnitude northeastwards. This increase in geothermal gradient towards the south, in the vicinity of the Qarqaf Arch, is interpreted to be related to Cenozoic hotspot activity (e.g. Lesquer *et al.* 1990), and linked to the significant volcanic rocks deposited in the area at this time. Further east in Libya the wells cannot be calibrated with the lower present-day

Fig. 4. (a) Vitritine reflectance profile from a well on the western margin of the basin showing two maturity gradients (a shallow gradient during the Palaeozoic, and a steep gradient during the Mesozoic), implying that pre-Hercynian maximum burial occurred in this area; (b) a typical vitritine reflectance profile over the central basin area, which fits to a regression suggesting the Palaeozoic maturity profile has been annealed by subsequent Mesozoic-Cenozoic reburial to a greater depth, and there is no vitritine discontinuity across the unconformity.

BHTs using such high Cenozoic heat flow values as those required to the south and west.

Accurate calibration of observed and modelled thermal data (vitritine reflectance and BHTs) can be achieved using elevated Palaeozoic heat flow values in the Libyan part of the basin. However, considering the pre-Hercynian tectonic setting of a broad intracratonic sag basin, the mechanism for such a change in heat flow across the basin, from Algeria to Libya, is unclear and unlikely. An alternate and more probable method to calibrate the vitritine reflectance data may be achieved through varying erosion values along the major unconformities in the basin.

Impact of unconformities on model calibration

Having defined the other input parameters (e.g. lithology, age, palaeobathymetry, heat flow history, etc.), these were maintained constant, and 1D models developed using a range of erosion values for the main unconformities within the basin: Hercynian, Basal Cretaceous, Austrian and Alpine. Sensitivity analyses indicate that estimated erosion values for the Basal Cretaceous and Austrian unconformities have a negligible effect on model calibration when taken within realistic limits. Only erosion at the Alpine and Hercynian unconformities has any significant effect on calibration and observed hydrocarbon maturation.

Hercynian erosion Hercynian erosion has a varying effect on model calibration across the basin. On the western margin the vitritine reflectance data plot with two regression curves (Fig. 4): (1) high values with a shallow gradient in Palaeozoic-aged sediments; and (2) lower values with a steeper gradient in the Mesozoic. Palaeozoic values record a maximum pre-Hercynian burial depth. By contrast, in the central basin area only one regression is evident (Fig. 4), indicating that maximum

burial occurred during Cretaceous–Cenozoic time. In the latter case, the vitritine profiles produced by burial prior to Hercynian uplift have been annealed by subsequent Mesozoic reburial. Only vitritine profiles display the characteristic double regression when depth of burial prior to Hercynian exhumation is greater than present-day burial depth. In the central Algerian part of the basin, sensitivity analysis suggests that varying Hercynian erosion between 0 m and 3000 m has no effect on model calibration (Fig. 5), due to significant Mesozoic/Cenozoic reburial.

Observed vitritine profiles show an increase in maturity at equivalent depths moving eastwards across the basin (Fig. 6). Calibration of wells on the eastern flank requires an increase in calculated maturity profile, while not affecting the established temperature profile. This can be achieved in several different ways: (1) decreasing Hercynian erosion duration, thereby leaving the sediments buried at greater depths and hence higher temperatures, for longer; (2) increasing Palaeozoic heat flow and, therefore, temperatures that the Palaeozoic sediments experienced at that time; (3) increasing Hercynian erosion and hence burial depth and temperature of the sediments prior to Hercynian exhumation; or (4) increasing Alpine erosion and hence increasing Mesozoic–Cenozoic burial depth and temperatures the sediments experienced more recently. Which one, or combination, of these scenarios is used in the modelling may have significant effects on hydrocarbon maturation history over the eastern part of the basin.

Alpine erosion The effect of Alpine erosion on model calibration varies depending on the location within the basin. In the central basin area, over eastern Algeria and western Libya, accurate model calibration is achieved using Alpine erosion values of between 0 m and 400 m (Fig. 7). In this central area, models cannot be calibrated using higher erosion values, as this would result in an increase in the calculated vitritine profile due to the

Fig. 5. Hercynian erosion sensitivity plots showing the effect on vitrinite reflectance and temperature calibration for a well in the Ghadames central depression. Varying the amount of Hercynian erosion has a negligible effect on present-day temperature calibration and effects the vitrinite reflectance calibration only when Hercynian erosion is great enough to make the pre-Hercynian depth the maximum depth of burial (4000 m erosion scenario).

greater burial depths reached, while at the same time causing a decrease in the calculated temperature profile. However, observed present-day temperature profiles on the eastern flank of the basin are lower than those further to the west (Fig. 3), thus allowing an accurate temperature calibration using increased Alpine erosion values. Therefore, over the eastern

flank of the basin, models require lower recent heat flows to calibrate with the observed downhole temperature data, and the higher vitrinite reflectance values can be calibrated by increasing the maximum burial depth through the use of elevated values of either Hercynian (Palaeozoic burial depth) or Alpine (Cenozoic burial depth) erosion.

Fig. 6. Observed vitrinite reflectance variation over the Ghadames Basin (see Fig. 1 for approximate data point locations). Vitrinite reflectance values progressively increase at equivalent depth moving eastwards across the basin. The Jurassic section in the east is at an equivalent depth to the Devonian in the west.

Burial history models and their effects on source-rock maturation history

Accurate calibration of wells can be achieved using different erosion scenarios and current data do not allow a unique model of basin development. To ascertain the impact of varying amounts of erosion on hydrocarbon maturation and generation for the two main source-rock intervals within the basin (the Lower Silurian basal Tanezzuft and the Middle–Upper Devonian Frasnian radioactive shales), sensitivity analysis was conducted using different erosion scenarios for wells across the basin.

Central basin In the central (Berkine) basin, maximum burial occurred during Late Cretaceous/Cenozoic time (Fig. 8) as a result of the deposition of a thick succession of Mesozoic sediments (Fig. 1). Accurate calibration with observed BHT and vitrinite reflectance data can be achieved using Hercynian erosion scenarios of between 0 m and 3000 m, and the different values of erosion used have a significant impact on the timing of hydrocarbon maturation of the Lower Silurian and Middle–Upper Devonian source-rock intervals (Fig. 8). Three Hercynian erosion scenarios were modelled in order to investigate their effect on maturation history: 500 m (minimum limit), 1150 m (most likely) and 2000 m (maximum limit).

In each of the modelled scenarios three clear stages in maturity evolution can be observed (Fig. 8): (1) a progressive maturity rise during the Palaeozoic; (2) a period of static maturity following Hercynian exhumation; and (3) renewed maturity rise as Mesozoic reburial exceeds the pre-Hercynian

Fig. 7. Alpine erosion sensitivity plots showing the effect on vitrinite reflectance and temperature calibration for a well in the Ghadames west/central depression. Accurate calibration is achieved using Alpine erosion scenarios of 0–400 m in this area. Increasing erosion values above this level causes an increase in the calculated vitrinite reflectance profile and a concurrent reduction in the calculated temperature profile.

Silurian source rock:

Devonian source rock:

Fig. 8. Vitrinite reflectance, transformation ratio and burial history plots for the basal Tanezzuft (Silurian) and Frasnian (Devonian) source-rock intervals for different Hercynian erosion scenarios for a well in the central basin area.

burial depth. The timing of the onset of this second period of increasing maturity is related directly to the amount of Hercynian erosion modelled (the greater the value of erosion, the later the onset of renewed maturity rise).

The Lower Silurian (Tanezzuft) source-rock interval enters the oil window during the Carboniferous Period in each of the modelled scenarios and is currently in the condensate and wet gas zone, with a calculated transformation ratio (TR) of around

95%. Two periods of generation are modelled: 75–90% of generation potential is realized prior to Hercynian exhumation, with the remaining 10–25% generated during Jurassic–Cretaceous time. Using Hercynian erosion values of less than 1500 m, the Middle–Upper Devonian (Frasnian) source rock does not begin to generate hydrocarbons until Cretaceous time. However, when the very high Hercynian erosion scenario (2000 m) is used the Frasnian source starts to generate

Silurian source rock: **Devonian source rock:**

Fig. 9. Vitrinite reflectance, transformation ratio and burial history plots for the basal Tanezzuft (Silurian) and Frasnian (Devonian) source-rock intervals for a well on the western margin of the basin.

hydrocarbons during the Carboniferous Period, prior to Hercynian exhumation. It currently has a TR of around 55%, with plenty of generation potential preserved at present day.

Hercynian erosion is a key factor controlling the TR of both the Lower Silurian and Middle–Upper Devonian source-rock intervals prior to Hercynian exhumation; greater erosion values result in higher TRs being reached prior to exhumation and, hence, reduced generation potential preserved into the Mesozoic–Cenozoic eras.

Western margin On the far western margin of the basin, towards the Amguid–El Biod Arch, Mesozoic–Cenozoic reburial reached depths only equivalent to the pre-Hercynian burial depth during the Cenozoic Period (Fig. 9). Changing Hercynian erosion values in this area alters the maximum burial depth and hence affects the calibration with observed vitrinite reflectance values. For this reason, only one Hercynian erosion scenario can be calibrated accurately with the vitrinite reflectance data in this area (Fig. 9).

Again, three stages of maturity evolution can be identified: (1) a progressive rise in maturity throughout the Palaeozoic; (2) a long period of static maturity (≈ 260 Ma) following Hercynian exhumation; and (3) a very slight maturity rise during Late Cenozoic time, as Mesozoic–Cenozoic reburial marginally exceeds the pre-Hercynian burial depth.

In this area, around 95% of the Lower Silurian source-rock generation potential was realized during the Carboniferous Period, with little to no generation potential remaining for the Mesozoic–Cenozoic eras (Fig. 9). By contrast, the Middle–Upper Devonian source interval, although reaching the oil window during Late Carboniferous time, presently still has around 90% of generation potential preserved (Fig. 9) and has only recently reached sufficient burial depths to resume generation.

Eastern/northeastern margins In the eastern and northeastern margins of the basin the higher vitrinite reflectance values observed in wells at equivalent depth, compared to those further west in the central basin area (Fig. 6), can be calibrated in different ways. As a result, two different burial history models have been developed (Fig. 10) and their differing hydrocarbon generation histories investigated.

- **Model A (pre-Hercynian maximum burial):** Using this model, accurate calibration is achieved through the use of high Hercynian erosion values (up to 1700 m) and decreased Hercynian erosion duration. A second version of this model gives similar calibration results using elevated Palaeozoic heat flows and moderately reduced Hercynian erosion values. In these models, Alpine erosion is low (100–200 m) across the basin, which assumes a period of very slow sedimentation or hiatus throughout the period of thermal activation and exhumation during the Cenozoic Era.
- **Model B (Cenozoic maximum burial):** Applying this model, accurate calibration is achieved by using much lower Hercynian erosion values (500–800 m) that are more consistent with estimates derived from comparison of isopach and palaeo-isopach maps, and significantly increased Alpine erosion values (500–1700 m). The intensity of the Alpine orogenic event increases towards the Hamra region to the east (Boote & Dardour 2004). Relatively thick Cenozoic deposits are preserved to the north (offshore Libya; Rusk 2001; Hallett 2002) and east (Cyrenaica/ Sirte Basin; Belhaj 1996; Gumati *et al.* 1996; Rusk 2001; Hallett 2002). However, they are generally absent in the Hamra region, with Cretaceous-aged rocks cropping out over the majority of this area at present day. It is proposed that Cenozoic sediments, found elsewhere in western Libya, were originally deposited across the region and subsequently

removed during the Alpine tectonic event (Model B). However, the possibility that there was only limited Cenozoic sedimentation in this area, as appears to be the case further west in the Berkine region, is addressed in Model A.

Using Model A, assuming that the observed vitritine reflectance profile represents pre-Hercynian maximum burial, only one Hercynian erosion scenario can be considered, as changing the value of Hercynian erosion will alter the maximum burial depth and, hence, affect calibration with the observed vitritine reflectance data. Using this model, two stages in the maturity evolution of the source-rock intervals can be seen (Fig. 11). A progressive maturity rise during the Palaeozoic is followed by a period of static maturity after Hercynian exhumation that lasts until the present day. No renewed increase in maturity is witnessed, as Mesozoic–Cenozoic burial would be insufficient to reach the pre-Hercynian burial depth (Fig. 11).

Using this pre-Hercynian maximum burial model, the majority of hydrocarbon generation potential of the Lower Silurian source rock (95%) would be realized during the Carboniferous Period, prior to Hercynian exhumation (Fig. 11). By contrast, the Middle–Upper Devonian source interval would only just have entered the oil window prior to Hercynian exhumation and would currently not have generated sufficient hydrocarbons ($TR < 5\%$) for significant expulsion to have occurred (Fig. 11).

When considering the favoured Cenozoic maximum burial scenario in the eastern Libyan margin (Model B), the observed vitritine reflectance values are assumed to result from Mesozoic–Cenozoic burial, and calibration can be achieved using different values of Hercynian erosion. As in the basin centre (Fig. 8), three Hercynian erosion scenarios were modelled for a well on the eastern margin in order to investigate the effect on maturation history (Fig. 12): 500 m (minimum limit), 800 m (most likely value) and 2000 m (maximum limit).

In each of these erosion scenarios, three stages of maturity evolution are observed. The progressive maturity rise during the Palaeozoic is followed by a period of static maturity following Hercynian exhumation, and then a renewed rise in maturity as Mesozoic–Cenozoic reburial exceeds the pre-Hercynian burial depth. Again, the timing of the onset of this second period of increasing maturity is related directly to the amount of Hercynian erosion modelled (Fig. 12).

The Lower Silurian source-rock interval enters the oil window during the Carboniferous Period, except when using the minimum Hercynian erosion scenario (500 m), when it does not enter the oil window until Early Jurassic time (Fig. 12). It is currently in the late mature ($1.0\text{--}1.3\%R_o$) stage of oil generation in all the cases considered. The plot of TR against time (Fig. 12) indicates that between 50% and 95% of hydrocarbon generation potential was realized during the Carboniferous Period, prior to Hercynian exhumation, depending on the Hercynian erosion scenario used. The remaining 0% to 45% was generated during Jurassic–Cretaceous time, as the Mesozoic burial depth exceeded that reached prior to Hercynian exhumation. At

Fig. 10. (a) Vitritine reflectance calibration plot comparing burial history models A and B on the eastern margin of the Ghadames Basin; (b) burial history plot for Model A (pre-Hercynian maximum burial) for a well on the eastern margin of the basin (note reduced Hercynian erosion duration used in this model, increasing the length of time the sediments were at their maximum pre-Hercynian burial depth and temperature); (c) burial history plot for Model B (Cenozoic maximum burial) for a well on the eastern margin of the basin.

Silurian source rock: **Devonian source rock:**

Fig. 11. Vitrinite reflectance, transformation ratio and burial history plots for the basal Tanezzuft (Silurian) and Frasnian (Devonian) source-rock intervals for a well on the eastern margin of the basin using a pre-Hercynian maximum burial model (Model A).

Silurian source rock: **Devonian source rock:**

Fig. 12. Vitrinite reflectance, transformation ratio and burial history plots for the basal Tanezzuft (Silurian) and Frasnian (Devonian) source-rock intervals for different Hercynian erosion scenarios for a well on the eastern margin of the basin using a Cenozoic maximum burial model (Model B).

present, 95% of generation potential has been reached using each of the erosion scenarios. However, the amount of

Hercynian erosion modelled has a very significant impact on the generation potential preserved into the Mesozoic Era.

When more moderate values of Hercynian erosion are used (500–800 m) 30% to 50% of hydrocarbons from the Lower Silurian source are generated during Jurassic–Cenozoic time (Fig. 12), compared to 0% when using Model A (pre-Hercynian maximum burial; Fig. 11). The Middle–Upper Devonian source rock is still immature/marginally mature at present day when using the Cenozoic maximum burial model (Model B), with a TR of around 2%.

DISCUSSION

Model calibration in the basin centre can be achieved using a wide range of erosion scenarios. Erosion at key unconformities, using reasonable estimates of lost section, has a negligible effect on model calibration due to pre-Hercynian vitrinite profiles being annealed by significant Mesozoic reburial. However, constraining the amount of Hercynian and Alpine erosion is important as it has a significant impact on maturation and generation history, particularly of the Lower Silurian source-rock interval.

Although it is not possible to define a unique burial history model, as calibration can be achieved using a variety of erosion scenarios, there is strong evidence to support Palaeozoic maximum burial in the western margin, towards the Amguid–El Biod Arch, and Mesozoic/Cenozoic maximum burial in the southern margin and basin centre. However, in the northern and eastern margins of the basin, the modelling parameters are less definitive. A key factor is whether the vitrinite profiles in wells on the northern and eastern basin flanks are representative of the Palaeozoic burial and thermal regime (Model A) or the Mesozoic–Cenozoic burial and thermal regime (Model B). The model used will have a strong impact on the timing of hydrocarbon generation of the Lower Silurian source-rock interval in these areas (Figs 11, 12).

A comparison of maturation distribution prior to the Hercynian and Alpine exhumation events for the Lower Silurian source-rock interval, using the two different burial history models in the northern and eastern basin margins, is presented in Figures 13a and 14a. These maps show a general northwestwards increase in maturation of the Lower Silurian source rock using both the pre-Hercynian (Model A) and Cenozoic (Model B) maximum burial models. However, closer examination reveals that in the eastern and northeastern margins the value of maturation prior to Hercynian exhumation is lower when using the Cenozoic maximum burial model (Fig. 14a), suggesting the possibility of more hydrocarbon generation potential from the Lower Silurian source preserved into the Mesozoic Era. The Middle–Upper Devonian source rock remains immature/marginally mature in the northern and eastern flanks of the basin using both the pre-Hercynian (Model A) and Cenozoic (Model B) maximum burial models (Figs 13b and 14b).

Burial history analysis using a variety of independent techniques (comparison of isopach and palaeo-isopach maps, sonic velocity analysis, vitrinite reflectance analysis and apatite fission track analysis) favours a Cenozoic maximum burial model (Model B) in the northern and eastern margins of the basin (Underdown 2006). All indicate substantial amounts (1500–2000 m) of late Alpine exhumation in the northern and eastern flanks of the basin in Libya.

The known hydrocarbon distribution within exploration wells and fields across the basin provides one method of model calibration, as it is essential that any maturation model can reproduce as accurately as possible the oil/gas recorded from present-day well data. Both oil and gas accumulations are known to exist in Palaeozoic reservoirs in the eastern Libyan

part of the basin. As modelling suggests, the Middle–Upper Devonian source rock is immature/early mature in this part of the basin (Figs 11–14), and analysis of source-rock quality and thickness also indicates limited generative potential; it is likely that these hydrocarbon pools have been sourced from the Lower Silurian source-rock interval. However, no published oil/source correlations are available to verify this at present. When using a pre-Hercynian maximum burial model (Model A) in this area, around 95% of Silurian hydrocarbon generation potential would have been achieved during the Carboniferous, prior to Hercynian exhumation (Fig. 11). This result is in contrast to previous studies (e.g. Dardour *et al.* 2003a) that invoke pre-Hercynian maximum burial in this area, but predict significant generation from the Lower Silurian source during the Mesozoic. In this study it has not been possible to calibrate the observed vitrinite reflectance data using a pre-Hercynian maximum burial model in the eastern basin and still preserve significant generation potential from the Lower Silurian source into the Mesozoic/Cenozoic eras. By contrast, when using a Cenozoic maximum burial model (Model B), around 30% of generation potential is preserved into the Mesozoic and subsequently liberated during Cretaceous–Cenozoic time (Fig. 12). This late-stage hydrocarbon generation would greatly favour accumulation in post-Hercynian traps, with a lower risk for the preservation of trap integrity and the increased likelihood of hydrocarbon pools being conserved. Mesozoic reservoirs must be sourced from post-Hercynian generation; either by vertical migration from the Silurian source, or by long-distance lateral migration through the Triassic sandstones from the Devonian source in the west, where it has a greater level of maturity at present day. It is possible that pre-Hercynian hydrocarbons are preserved in the basin in Palaeozoic reservoirs, but the intensity of tectonic deformation would place a high risk of breaching for any older pre-Hercynian traps. The potential for re-migration of hydrocarbons within Palaeozoic traps must also be considered.

CONCLUSIONS

Sensitivity analysis has highlighted that the correct estimation of the amount of eroded overburden at regional unconformities in the Ghadames Basin is essential for accurate prediction of hydrocarbon maturation histories. Hydrocarbon generation from the Lower Silurian and Middle–Upper Devonian source-rock intervals across the Ghadames Basin was controlled primarily by the Hercynian and Alpine orogenies. Other less significant unconformities have little effect on basin modelling. In some parts of the basin, with the available data, multiple models can be developed, calibrated using a variety of Hercynian and Alpine erosion scenarios and thermal regimes. Integration of all available data is required to constrain the models to produce a ‘best-fit’ solution. High values for Hercynian erosion would predict increased pre-Hercynian burial and elevated temperatures and, hence, larger volumes of hydrocarbons generated prior to Hercynian exhumation. More moderate estimates of Hercynian erosion result in greater preservation of hydrocarbon generation potential into the Mesozoic/Cenozoic eras.

Burial history modelling, calibrated with observed data (BHT and %R_o), suggests that the far western margin of the basin underwent pre-Hercynian maximum burial, while the central basin and southern margin experienced maximum burial depths only recently, during Eocene time. In Libya, on the eastern, northeastern and southern flanks of the basin the available data are open to interpretation, with a number of possible scenarios.

(a)

The best-fit model predicts Cenozoic maximum burial (Model B), with up to 2000 m of Alpine exhumation over the Dahar–Nafusah, Qarqaf and Tihemboka arches (Underdown 2006). This late-stage exhumational event is poorly documented for the area, but has a critical impact on the timing of hydrocarbon generation of the Lower Silurian source rock in the eastern (Libyan) flank of the basin.

The Middle–Upper Devonian (Frasnian) source rock did not start to generate significant volumes of hydrocarbons in the

central (Berkine) basin area and its southern flank (towards the Qarqaf Arch) until the Cretaceous Period, and is currently within the peak oil generation zone. Transformation ratios are presently around 50% to 60% in the basin centre and 90% towards the far south. In the western, northern and eastern flanks of the basin the Middle–Upper Devonian source is currently still immature/marginally mature, and has not generated sufficient volumes of hydrocarbons for significant expulsion to occur.

(b)

Fig. 13. (a) Maturity distribution of Lower Silurian source rock using a pre-Hercynian maximum burial model (Model A) over the eastern and northern margins of the basin: (A) prior to Hercynian exhumation (at 290 Ma); and (B) prior to Alpine exhumation (at 25 Ma). (b) Maturity distribution of Upper Devonian source rock using a pre-Hercynian maximum burial model (Model A) over the eastern and northern margins of the basin: (A) prior to Hercynian exhumation (at 290 Ma); and (B) prior to Alpine exhumation (at 25 Ma).

One-dimensional modelling results suggest that in the present-day central depression (eastern Algeria) the Lower Silurian source rock is currently overmature and in the dry gas generation phase. Further east, in Libya, it is modelled to be in the mid to late stage of oil generation at present day (when using the proposed Cenozoic maximum burial model

(Model B)). It underwent two distinct generative phases in the central basin and its southern margin: (1) a period of pre-Hercynian (Carboniferous) generation, with maturation levels reaching the main stages of oil generation and transformation ratios ranging from around 70% to 90%; and (2) a period of post-Hercynian (Late Jurassic–Cenozoic) generation,

(a)

as Mesozoic reburial exceeded pre-Hercynian burial depths. In the far western margin of the basin, towards the Amguid-El Biod Arch, only one main stage of hydrocarbon generation from the Lower Silurian source rock is observed: a pre-Hercynian phase where the Lower Silurian source entered the condensate/wet gas generation zone during Late Carboniferous time and around 95% of hydrocarbon generation potential was realized prior to the period of Hercynian exhumation.

The pre-Hercynian maximum burial model (Model A) for the Lower Silurian source interval in the eastern and north-eastern flanks of the basin predicts around 95% of hydrocarbon generation potential would have been realized prior to Hercynian exhumation, leaving little to no generation potential in this area during the Mesozoic/Cenozoic eras. Results from a number of independent burial history analysis techniques (Underdown 2006), supported by the distribution of discoveries already made in the basin, favour a Cenozoic maximum burial

Fig. 14. (a) Maturity distribution of Lower Silurian source rock using a Cenozoic maximum burial model (Model B) over the eastern and northern margins of the basin: (A) prior to Hercynian exhumation (at 290 Ma); and (B) prior to Alpine exhumation (at 25 Ma). (b) Maturity distribution of Upper Devonian source rock using a Cenozoic maximum burial model (Model B) over the eastern and northern margins of the basin: (A) prior to Hercynian exhumation (at 290 Ma); and (B) prior to Alpine exhumation (at 25 Ma).

model (Model B), incorporating significant late Alpine exhumation. Modelling in this study quantifies this exhumation in the range of 1000 m to 2000 m. This suggests there remains significant potential for further hydrocarbon accumulations generated from the Lower Silurian source rock within the eastern Libyan part of the Ghadames Basin.

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