An investigation of the thermal history of the Ahnet and Reggane Basins, Central Algeria, and the consequences for hydrocarbon generation and accumulation

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Abstract: In an attempt to better understand the thermal history of the Ahnet and Reggane Basins, the techniques of apatite fission track analysis and zircon fission track analysis were employed on samples from a number of exploration wells previously drilled in the study area. The results indicated clear evidence for a major heating event at *c.* 200 Ma, overprinted on the effects of heating caused by simple burial before the Hercynian uplift. It is proposed that at least two major phases of hydrocarbon generation took place within the study area; an early, pre-Hercynian phase, in which chiefly liquid hydrocarbons were expelled and a later phase, associated with a 'heat spike' at *c.* 200 Ma, in which significant quantities of dry gas were generated and expelled.

This paper arises from an investigation carried out by BHP and Sonatrach into the hydrocarbon potential of the Ahnet, Timimoun and Reggane Basins of central Algeria. The study encompassed the area shown in Fig. 1. Geographically, the area is located in the Sahara Desert of central Algeria, immediately to the north of the Hoggar and Eglab Massifs. Numerous gas discoveries have been made in the Ahnet and Timimoun Basins of District 3, whereas the Reggane Basin of District 7 has been explored to a lesser degree and to date, only a few wells on the northern fringe of the basin have encountered gas with minor oil shows. Adjacent to the northern part of District 3, on the western side, is the area known as the Cuvette de Sbaa, which contains several proven oilfields, none of which are yet in production.

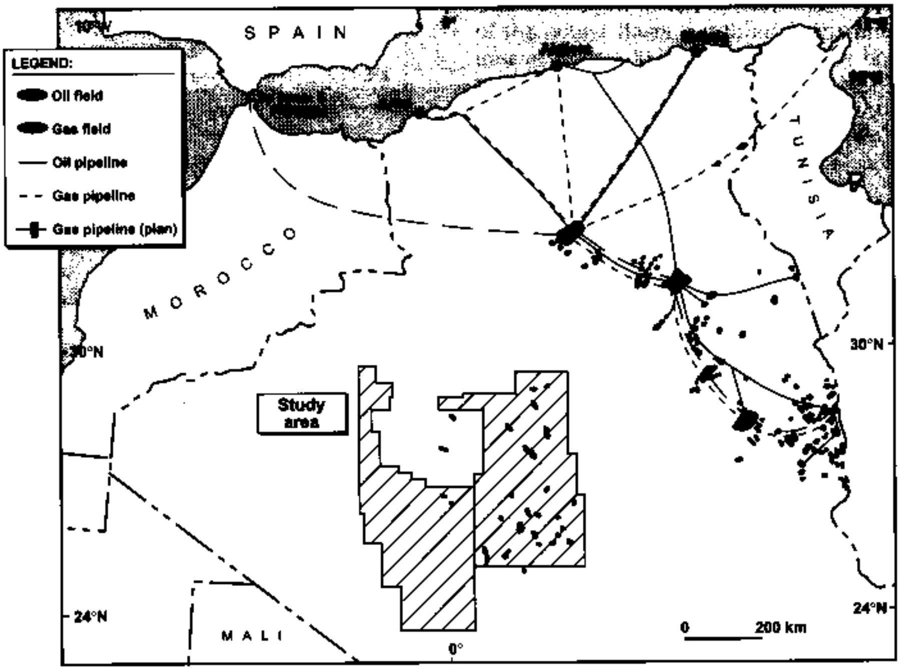

Fig. 1. Location map.

LOGAN, P. & DUDDY, I. 1998. An investigation of the thermal history of the Ahnet and Reggane Basins, Central Algeria, and the consequences for hydrocarbon generation and accumulation. *In*: MACGREGOR, D. S., MOODY, R. T. J. & CLARK-LOWES, D. D. (eds) 1998. *Petroleum Geology of North Africa*. Geological Society, London, Special Publication No. 132, 131–155.

A key aim of the study was to investigate the thermal histories of these basins and to determine the consequences of those histories for the generation, migration and accumulation of significant volumes of hydrocarbons in the study area. BHP and Sonatrach were also keen to investigate the relationship (if any) between the study area and the small oilfields encountered in Palaeozoic reservoirs in the Cuvette de Sbaa. To this end it was decided to employ the techniques of apatite fission track analysis (AFTA) and zircon fission track analysis (ZFTA) in an attempt to shed light on the thermal history of these basins.

Regional geology

The main structural elements and major basin lineaments relevant to the study area are shown in Fig. 2. The Ahnet Basin is one of a series of north–south trending basins and basement highs that exist in central and southern Algeria. The basin is northerly dipping with Cretaceous and Tertiary-Quaternary cover to the north and the Precambrian Hoggar Mountains to the south. It contains thick Palaeozoic sequences of Cambrian to Carboniferous age which include potential hydrocarbon reservoirs, source rocks and seals, together providing an excellent setting for a hydrocarbon-bearing basin.

The structural trend in the basin is dominantly north–south controlled by major sub-vertical basement lineaments. To the north of the outcrop area, the basin exhibits a more significant northwesterly trend. The structures take the form of large, elongate anticlines and domes formed compressionally, probably as a result of the Austrian tectonic event or possibly Variscan compression.

The generalized stratigraphy of the Ahnet and Reggane Basins is shown in Fig. 3. In both basins, the thickness of the preserved sedimentary sequence has been considerably modified by erosion associated with Hercynian, Austrian and Tertiary (Atlassic) earth movements.

In the Ahnet and southern Timimoun Basins, the pre-Hercynian sequence comprises Cambrian to Visean and possibly Early Namurian rocks. The thickest sequence is preserved in the north of the Ahnet Basin, with over 3000 m of Palaeozoic sediments overlying Precambrian basement at a depth of some 4000 m. The Hercynian unconformity cuts down the sequence from north to south, with only some 2000 m of Palaeozoic section having been preserved in the south of the basin (Fig. 4).

In the Reggane Basin, the pre-Hercynian sequence also comprises Cambrian to Early Namurian rocks. The basin is an asymmetric syncline (Fig. 5), with a heavily faulted northern margin, and is bounded to the north by a reverse fault complex marking the edge of the uplifted

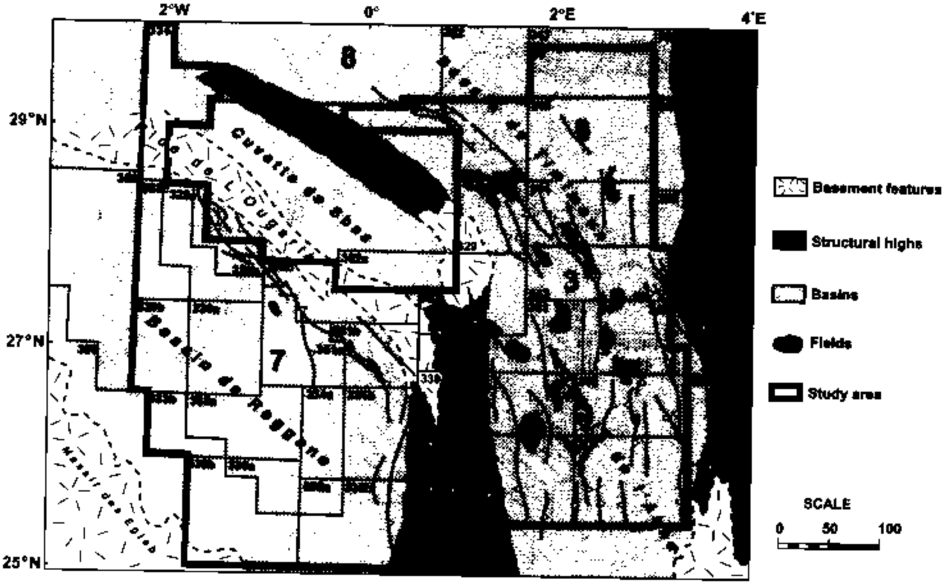

Fig. 2. The main tectonic elements of the Reggane and Ahnet Basins.

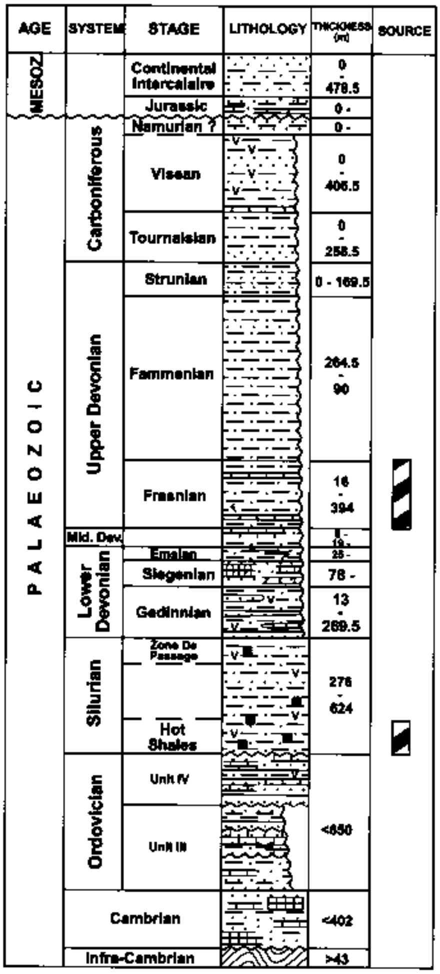

Fig. 3. Stratigraphic column

Ougarta Ridge. The thickest sequence occurs in the north of the Reggane Basin, where over 5000 m of Palaeozoic sediments are known to be present and where the Precambrian is estimated to be at a depth in excess of 6000 m.

In both basins, basement of Precambrian–Early Cambrian age is overlain by a Cambro-Ordovician sequence of both marine and continental sediments for which well control is sparse. This is overlain by thick, Silurian marine shales which in the Reggane Basin, may exceed 800 m in thickness, although no well has yet reached the base of the sequence in the basin depocentre. In the Ahnet Basin, a maximum thickness of 1000 m of Silurian sediments have been penetrated.

During the Silurian, restricted anoxic conditions led to the deposition of highly radioactive 'hot shales' which reach a maximum thickness of 70–80 m in the Ahnet Basin and may exceed 100 metres in the north of the Reggane Basin (Fig. 6). These 'hot shales' are known to have formed a significant hydrocarbon source rock for the Reggane and Ahnet Basins, as will be discussed below.

Towards the end of Silurian times, the Caledonian orogeny resulted in local uplift and the formation of significant local topography with a general tilt to the north. The sea retreated to the north and northwest, and the resulting shallow marine–continental conditions persisted throughout Lower and Middle Devonian times.

The Late Devonian succession was deposited in fully marine conditions which spread across the entire area, resulting in the deposition of a thick sequence of claystones. During the Late Devonian, the Reggane and Ahnet Basins were the principal depocentres in southern and central Algeria. During Frasnian times, continued uplift of the basin margins resulted in the development of restricted anoxic conditions leading to the deposition of a series of radioactive 'hot shales'. The Frasnian sequence reaches a maximum thickness of almost 700 m in the west of the Ahnet Basin and a little over 400 m in the Reggane Basin. The 'hot shales' occur in the lower part of the Frasnian sequence and are generally at least 50–100 m in thickness. They are best developed in the eastern and central parts of the Ahnet Basin, reaching a maximum thickness of some 300 m (Fig. 7), and are believed to be important hydrocarbon source rocks. In the Reggane Basin, the Frasnian 'hot shales' appear to be less well developed, with a maximum thickness of 231 m encountered in the sparsely drilled centre of the basin.

Mud-dominated marine deposition continued throughout the remainder of the Upper Devonian in both the Ahnet and Reggane Basins. During Strunian times, a major period of regression associated with the Bretonian phase of the Hercynian orogeny resulted in a return to shallow marine conditions. Uplift occurred on basin margins and at this time, the Ougarta region became a significant high.

Shallow marine conditions persisted throughout the Tournaisian and Visean, whereas in the Reggane Basin, the Visean sequence is also considerably affected by the presence of igneous sills, particularly in the Djebel Heirane area.

The end of the Visean seems to have been marked by a pronounced lowering of sea level and a consequent regressive phase in the Namurian. Rapid deposition continued in the Reggane Basin where up to 1000 metres of Namurian sedi-

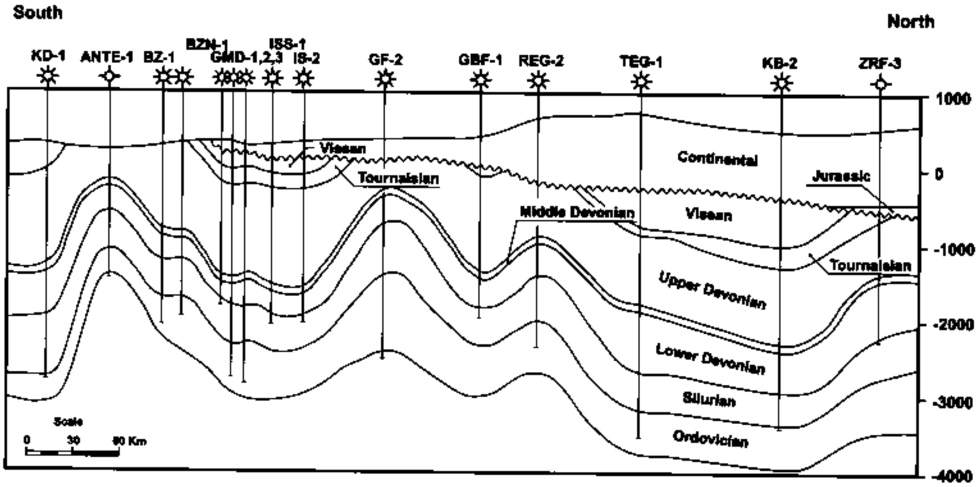

Fig. 4. Schematic cross-section of the Ahnet Basin.

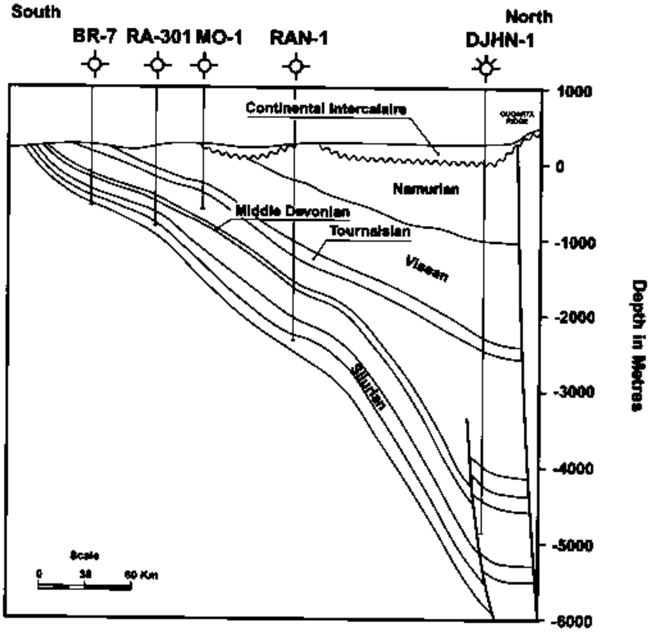

Fig. 5. Schematic cross-section of the Reggane Basin.

ments are preserved. In the Ahnet Basin, the Namurian section appears to be restricted to a northwest–southeast trending trough in the north of the basin. Drilling has shown that over 400 m is preserved in some areas.

At the end of Carboniferous times, the Hercynian orogeny resulted in some uplift, folding and faulting. The uplift caused considerable erosion of the existing stratigraphy. As will be discussed below, the magnitude of this unconformity was significantly increased by later periods of uplift and deformation. As shown in Fig. 4, the enhanced Hercynian Unconformity cuts down the sequence from north to south and with the exception of the extreme northeast of the Ahnet Basin, is overlain by the Cretaceous Continental Intercalaire or younger Tertiary rocks. Many areas, including the Ougarta Ridge, which continued to rise, remained areas of non-deposition until the present day.

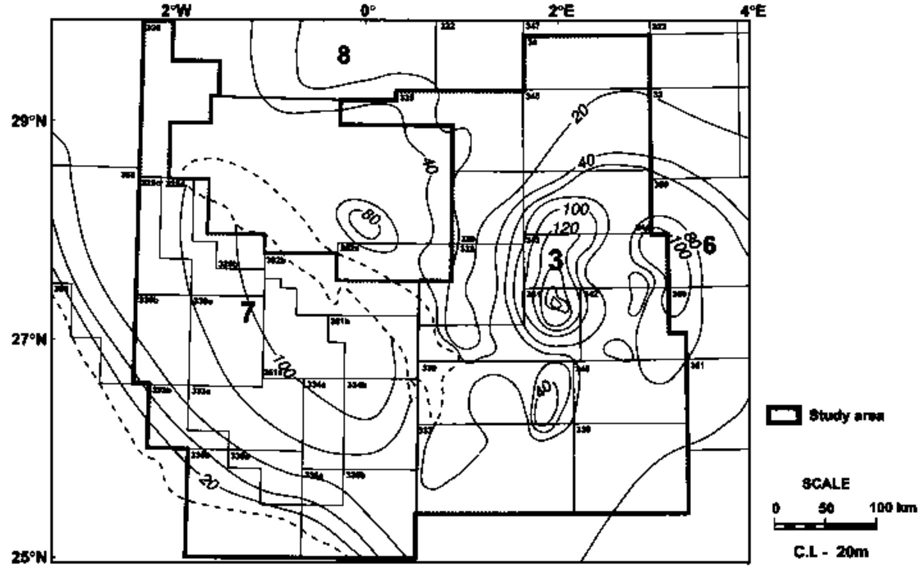

Fig. 6. Silurian hot shale isopach map.

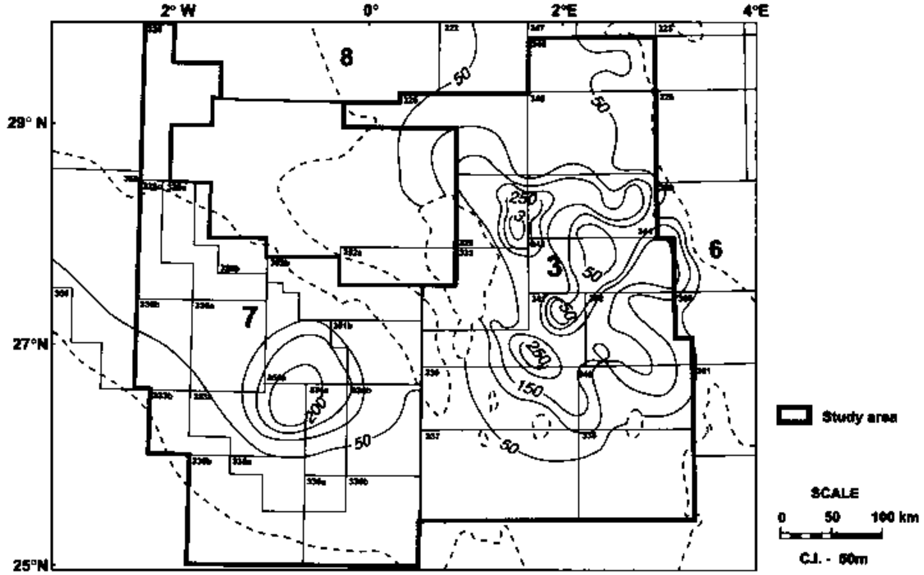

Fig. 7. Frasnian hot shale isopach map.

No sediments of Permo-Triassic age are known from the Ahnet and Reggane Basins. In the north of the Ahnet Basin, however, some 200–230 m of assumed Early–Middle Jurassic sediments were encountered, comprising claystones with some thin sands at the top of the succession. These were in turn overlain by 600–700 m of Early Cretaceous sandstones, succeeded by 260–300 m of Cenomanian–Turonian mudstones.

Discussion

In previous reviews of the burial history of the Palaeozoic section in both the Ahnet and Reggane Basins, it has been widely accepted that this history was dominated by the Hercynian orogeny, which, it was assumed, resulted in considerable uplift and erosion at the end of the Carboniferous. It was previously considered that the basins achieved maximum burial at this time and thus the source rocks reached their present state of maturity before the Hercynian and later episodes of uplift. Data resulting from the apatite and zircon fission track analyses carried out by Geotrack Inc on behalf of BHP and BP, together with associated organic reflectance measurements, have revealed the possibility of a far more complex thermal history for these basins.

Present-day heat flow is considerably greater in central Algeria and in the Ahnet Basin in particular, than in the rest of northwest Africa. It is also clear that present geothermal gradients are relatively low at 34–45°C/km in the Ahnet Basin and 26–30°C/km in the Reggane Basin when compared with palaeogeothermal gradients, which in some cases, reached 60–70°C/km. These very high heat flows undoubtedly contributed to the advanced state of maturation which is seen in the Lower Palaeozoic section.

As the timing of maximum palaeotemperatures within sequences containing prospective hydrocarbon source rocks generally coincides with maximum hydrocarbon generation, good control on the timing is a critical factor in assessing regional hydrocarbon prospectivity. Areas where the main phase of hydrocarbon generation occurred after structures were formed will clearly be more prospective than areas where structures post-date hydrocarbon generation.

To investigate the evidence of past thermal events in the rock record, it was decided to employ the techniques of AFTA and ZFTA, together with a study of whatever organic maturity data could be obtained from wells previously drilled in the study area.

Methods

AFTA and ZFTA rely on analysis of radiation damage features ('fission tracks') in detrital apatite and zircon grains, respectively, within sedimentary rocks. Fission tracks are produced continuously through geological time, as a result of the spontaneous fission of U impurity atoms. Once formed, tracks are shortened (annealed) at a rate which depends on temperature, and the final length of each individual track is determined by the maximum temperature which that track has experienced. Therefore as the temperature to which an apatite or zircon grain is subjected increases, all existing tracks shorten to a length determined by the prevailing temperature, regardless of when they are formed. After the temperature has subsequently decreased, all tracks formed before the thermal maximum are 'frozen' at the degree of length reduction they attained at that time.

For apatite, rocks which have been heated to a maximum palaeotemperature less than ≈110°C (the precise value depends on the chlorine content of the apatite grain) at some time in the past and subsequently cooled will contain two populations of tracks: a shorter component formed before the thermal maximum and a longer component representing tracks formed after cooling. The length of the shorter component indicates the maximum palaeotemperature, and the proportion of short to long tracks indicates the timing of cooling in relation to the total duration over which tracks have been retained. More complex thermal histories result in more complex distributions of track length. If the maximum palaeotemperatures exceeds ≈110°C, all tracks are totally annealed, and tracks are only retained once the sample cools below this temperature once more.

In zircon, fission tracks are more stable, and maximum paleotemperature must exceed ≈300°C (corresponding to vitrinite reflectance values of at least 5% R_0(max) before all tracks are totally annealed, with the time of cooling below ≈300°C indicated by the number of tracks accumulated since cooling began.

The annealing kinetics of fission tracks in apatite during geological thermal histories is well understood, onon the basis of study of the response of fission tracks to elevated temperatures both in the laboratory (Kaslett *et al.*, 1982, 1987; 1989*b*; Green *et al.* 1986; Duddy *et al.* 1988; Green, 1988) and in geological situations (Gleadow & Duddy 1981; Gleadow *et al.* 1986; Green *et al.* 1989*a*). Natural apatites essentially have the composition $Ca_5(PO4)_3(F,OH,Cl)$. The amount of chlorine in the apatite lattice exerts a subtle compositional control on the degree of annealing, with apatites richer in fluorine being more easily annealed than those richer in chlorine. The result of this effect is that in a single sample, individual apatite grains may show a spread in the degree of annealing, and the data are interpreted using proprietary multi-compositional kinetic equations based both on laboratory annealing studies on a range of apatites with different Cl contents, and on observations of geological annealing in apatites from a series of samples from exploration wells in which thermal histories are simple and well understood.

In studies such as that described in this paper, AFTA and ZFTA thermal history evaluation provides direct determination of the timing (as well as the magnitude) of maximum palaeotemperatures. When combined with conventional maturity indicators, particularly vitrinite reflectance (VR), AFTA and ZFTA allow identification and characterization of the major episodes of heating and cooling that have affected a sedimentary sequence. Specifically, the technique of thermal history reconstruction provides the following information: magnitude of maximum palaeotemperatures in individual samples; timing of cooling from maximum palaeotemperatures; the style of cooling from maximum palaeotemperatures (fast or slow); characterization of mechanisms of heating and cooling; palaeogeothermal gradients; section removed by uplift and erosion (where appropriate); reconstructed thermal and burial/uplift histories based on these factors. Using this information the thermal history of likely hydrocarbon source rocks can be reconstructed with confidence, on the basis of measured variables, rather than relying on modelled results which often have little rigorous basis. The resulting improvement in assessment of hydrocarbon prospectivity is clearly beneficial in reducing exploration risk.

A key element in the thermal history reconstruction is the interpretation of the palaeotemperature profile (i.e. the palaeogeothermal gradient), which allows the mechanisms of heating (e.g. deeper burial, elevated heat floor or fluid movements) and cooling (uplift and erosion, decrease in heat flow, or cessation of fluid flow) to be deduced (Duddy et al. 1991, 1994; Bray *et al.* 1992; Green *et al.* 1995).

Two typical end-member cases are illustrated in Fig. 8. A measured palaeogeothermal gradient the same as the present-day geothermal gradient but displaced to higher temperatures is indicative of heating caused by deeper burial followed by uplift and erosion (see Fig. 8a). A measure, palaeogeothermal gradient higher than the present-day geothermal gradient that intersects the present-day ground surface at a palaeotemperature similar to the present-day surface temperature is indicative of heating caused predominantly by higher heat flow with cooling caused by decline in heat flow (see Fig. 8b). In detail, the timing of cooling determined using AFTA or ZFTA is critical in allowing the absolute magnitude of uplift and erosion to be attributed to a particular unconformity and quantified.

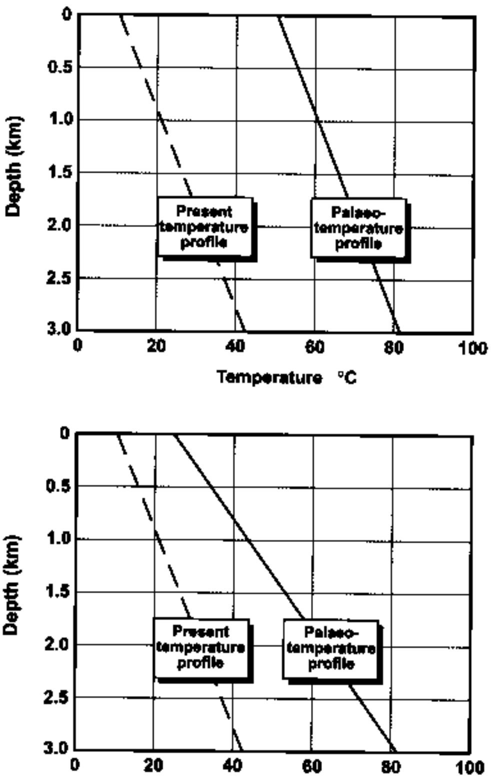

Fig. 8. Thermal history reconstruction.

Although this technique allows the main elements of a basin's thermal history to be reconstructed, thermal history techniques in general (i.e. fission track analysis, VR, biomarkers, hydrocarbon generation, etc.) cannot currently give quantitative information on either the duration of heating or the thermal history before time of maximum palaeotemperatures, as illustrated in Fig. 9.

Results

The results of the AFTA and ZFTA studies have identified a major period of heating at about 200 Ma (Late Triassic–Early Jurassic) which affected the Palaeozoic section. This heating event involved very high geothermal gradients over a large part of the study area, which implies a phase of regional heating.

In summary, the principal events in the burial and thermal histories of the Reggane and Ahnet Basins are thought to be as follows:

(1) Modest geothermal gradients during Devonian–Carboniferous times. Increased burial led to the onset of thermal maturation in the Lower Palaeozoic sequence with early oil generation and possibly gas generation from Ordovician, Silurian and Devonian source rocks in deeper parts of the Ahnet and Reggane Basins and in the Sbaa Basin.

(2) Hercynian uplift was probably relatively minor over much of the area, significant effects being largely confined to the Sbaa Basin and the northern Ahnet Basin (Table 1). A modest increase in heat flow, accompanied by deposition and increased depth of burial before the uplift, was followed by a cooling phase and a suspension of hydrocarbon generation.

(3) During the Permo-Triassic, little or no deposition occurred and no further generation of hydrocarbons took place during this period.

(4) In Late Triassic times, a major thermal event took place. Igneous rocks were extensively intruded in the Reggane Basin, as discussed above, and in the north of the Ahnet Basin, increased heat flow resulted in very high geothermal gradients in excess of 100°C/km! The causes, magnitude and duration of this heat pulse are unknown, but it was probably related to continental 'under-plating' or introduction of hot material into the crust beneath central Algeria. Although this event was probably of relatively short duration, the thermal effects were considerable. Source rocks were rapidly heated beyond the threshold for hydrocarbon generation, and existing liquid hydrocarbons were cracked to

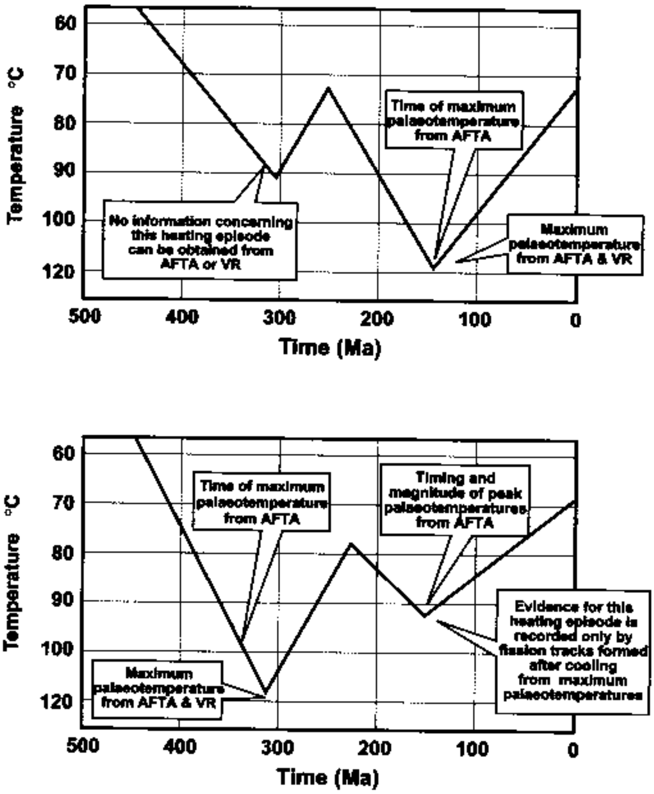

Fig. 9. Cooling history plots.

gas. It seems likely that the Sbaa Basin remained structurally high after the Hercynian event and was therefore not affected by this Late Triassic event. It is probable that no further maturation took place in the Sbaa Basin.

(5) The thermal event was followed by a Late Triassic–Early Jurassic phase of deformation which folded the recently intruded sills and increased the amount of uplift and erosion at the existing Hercynian unconformity.

(6) Further deposition in the Jurassic and Early Cretaceous may have been confined to the northwest of the Ahnet Basin, but was, in any case, modified by a further phase of uplift in mid-Cretaceous times, which resulted in the removal of yet more section at the Hercynian unconformity.

(7) post mid-Cretaceous deposition resulted in modest burial and heating of the section, insufficient to increase maturity.

(8) Finally, Tertiary inversion led to uplift and erosion of Cretaceous sediments.

The location of the geochemical study wells is shown in Fig. 10, and the paleotemperature profiles obtained for some of the study wells are given in Figs 11–14.

These profiles, which show present geothermal gradient, together with the estimates of palaeotemperature derived from AFTA, ZFTA and vitrinite reflectance measurements, give clear evidence in each case of the sampled section having cooled from elevated palaeotemperatures after deposition. In the case of reflectance measurements, it should be noted that, as land plants appeared in the Late Devonian–Carboniferous, true vitrinite cannot be identified in sections older than this. Measurements in the older Palaeozoic section, therefore, rely on other organic matter. In this study, reflectance measurements were made on graptolites, which appear to overestimate palaeotemperature, and on chitinous material, which appears to underestimate palaeotemperature.

The highest estimates of palaeotemperature occur in wells ECF-1 and ZRFW-1 (Figs 11 and 12) where palaeotemperatures in excess of 300°C are recorded. It is equally clear that in the west of the Ahnet Basin, for example at

Table 1. *Estimates of removed sections for major events in the thermal history of central Algeria*

	Removed section estimates		
Well	Hercynian (m)	Early Jurassic (m)	Tertiary (m)
Area A: Timimoun–N Ahnet Basin			
AFF-1	No evidence	1243 (648–2792)	600
KB-2	No evidence	849 (418–1555)	1400
MJB-1	No evidence	1181 (533–2566)	600
TEG-1	No evidence	906 (679–1261)	480 (193–1079)
ZRFW-1	No evidence	690 (590–799)	800
ECF-1	> 2500	874 (369–1294)	> 895
Area B: Eastern Ahnet Basin			
IS-2	No evidence	1059 (802–1387)	600
Area C: Southern Ahnet Basin			
ANT-1	No evidence	740 (637–911)	1000
BH-3	No evidence	1812 (1066–3438)	1350
Area D: Western Ahnet Basin			
MSR-1	No evidence	No quantitative analysis possible	740 (395–1426)
OTLH-1	No evidence	896 (686–1254)	84 (< 441)
Sbaa Basin			
OTRA-1	840 (545–2003)	925 (> 112)	321 (107–1119)
Reggane Basin			
RG-1	No evidence (4527–1890)	702	> 446

OTLH-1, much lower palaeotemperatures were experienced, leading to a somewhat less mature section, as will be discussed below.

In the Reggane Basin, paleotemperature profiles, as in the case of RG-3, have been locally severely modified by the effect of Late Triassic intrusions, which are common in the central and northern parts of that basin (Fig. 13).

Data from OTRA-1 in the Sbaa Basin (Fig. 14) indicates that palaeotemperatures were generally much lower than in the surrounding basins, probably because of the continued relative elevation of this area since Silurian times.

Figures 15–18 show the reconstructed thermal histories of a number of wells within the study area. In each case, the AFTA–ZFTA data provide evidence for two important phases of heating, or more correctly, cooling. These correspond to the Late Triassic–Early Jurassic event at about 200 Ma and the Late Cretac-

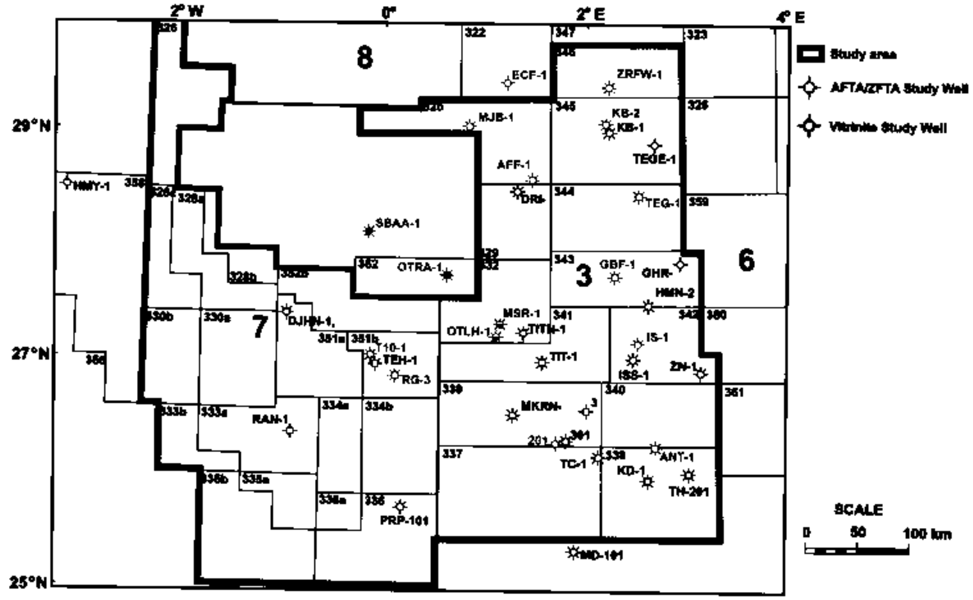

Fig. 10. Well database map.

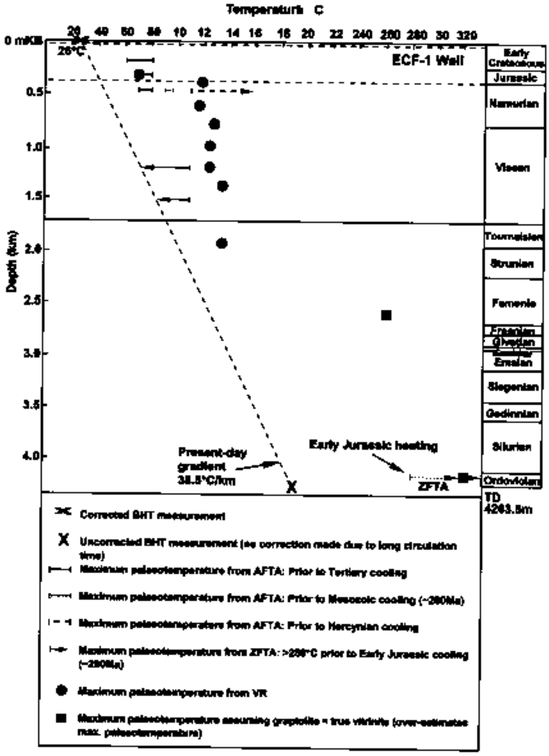

Fig. 11. Palaeotemperature profile for well ECF-1. TD, Total depth.

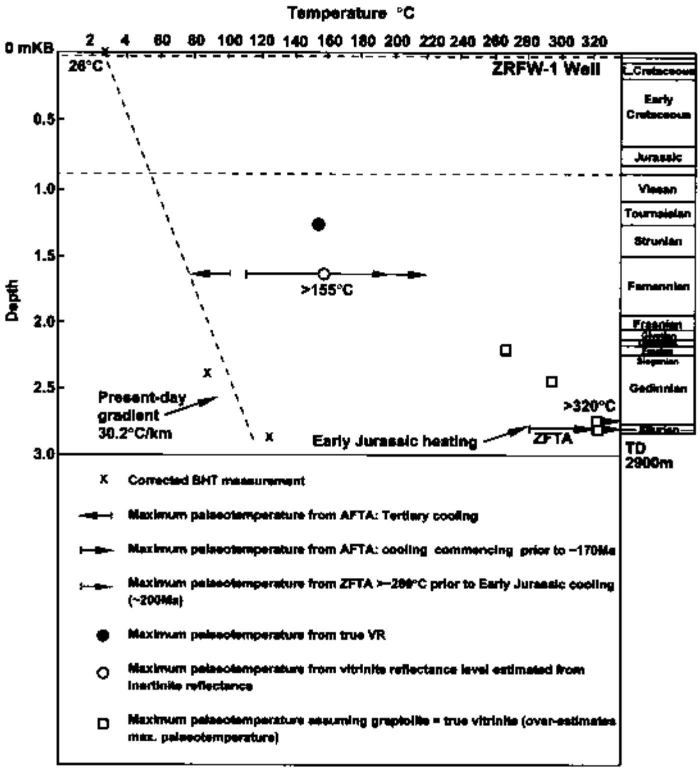

Fig. 12. Palaeotemperature profile for well ZRFW-1.

eous–Early Tertiary event, as mentioned in the summary above. In some cases, evidence exists for a possible early event, the 'Hercynian event'.

As discussed above, it had previously been assumed that the major heating event to affect the Ahnet and Reggane Basins had occurred before Hercynian uplift and erosion, implying a mid–late Carboniferous timing with the consequence of significant oil and gas generation and migration having occurred before this event.

This hypothesis was given currency by an earlier AFTA study carried out by BP. Because of the high degree of Tertiary heating observed in the wells analysed in this study, the AFTA data gave virtually no control on the timing of this early event, other than to identify it as pre-Cretaceous. It was clear, however, that a pre-Cretaceous heating event had occurred and this was assumed to be earlier than the Hercynian uplift. In particular, ZFTA results from a single sample in well MJB-1 (Fig. 16) gave an age of 310 ± 31 Ma. This was seen as compatible with the assumed timing of Hercynian tectonism and was interpreted as a complete overprinting of the zircon system, with cooling at that time.

Wells chosen for the BHP study had experienced less Cretaceous burial and heating and therefore provided better data on the timing of this early event, which complemented the BP data set. Clear evidence was obtained from wells TEG-1 and ZRFW-1 showing the youngest fission track ages to be *c*. 200 Ma, in Late Triassic times (Figs 17 and 18). Figure 19 shows that the Reggane Basin is considered to have undergone a similar thermal history to the Ahnet and Timimoun Basins. It is now considered, therefore, that although a Hercynian event occurred, it was of less significance, in terms of regional heating, than the Late Triassic event at 200 Ma, which was followed by Early Jurassic tectonism.

Evidence from well OTRA-1 (Fig. 20) in the Sbaa Basin indicates that the measured maturity levels may be attributed to heating before the known Hercynian uplift. This was due to either post-Namurian burial by up to 2000–2500 m of section which was subsequently removed with the Hercynian uplift, or a similar amount of uplift which took place between the Silurian and the Namurian to remove an older unknown section. Thus the observed maturities may have

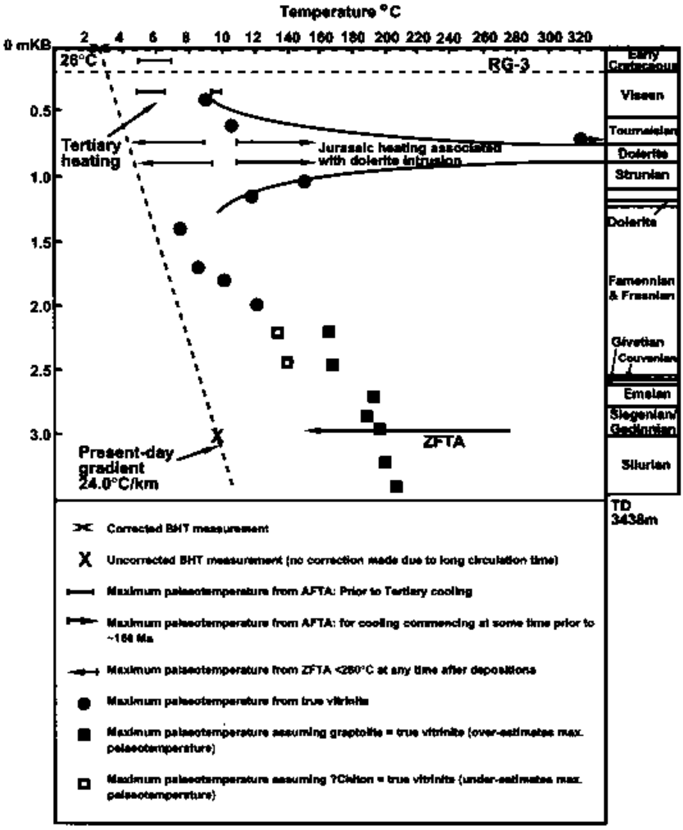

Fig. 13. Palaeotemperature profile for well RG-3.

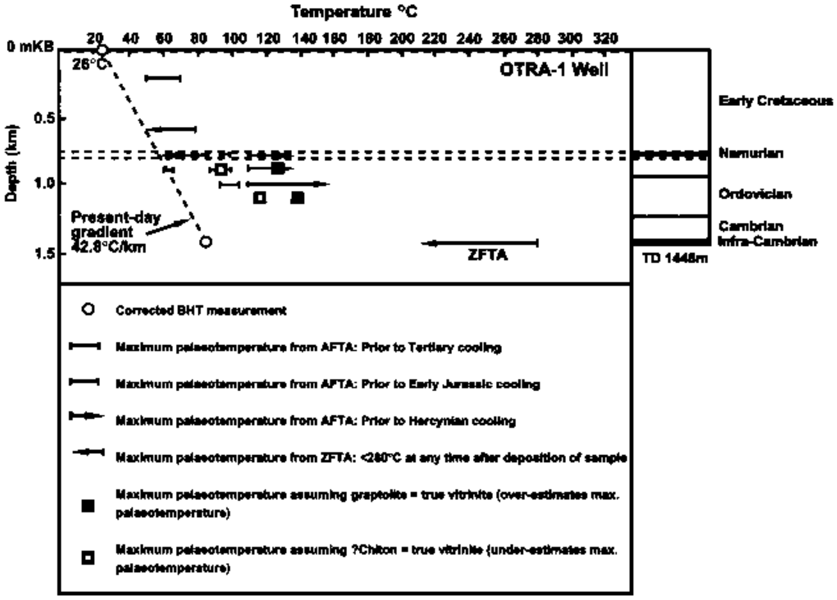

Fig. 14. Palaeotemperature profile for well OTRA-1.

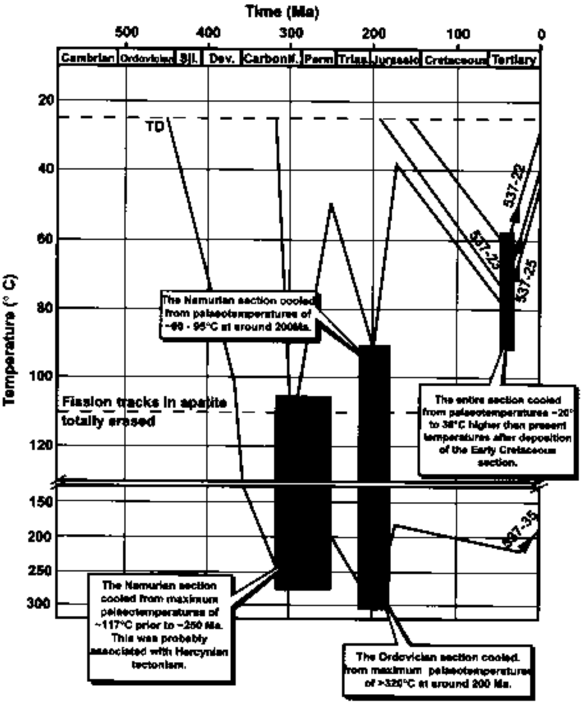

Fig. 15. Schematic illustration of the thermal history reconstruction for well ECF-1 based on AFTA, VR and ZFTA data.

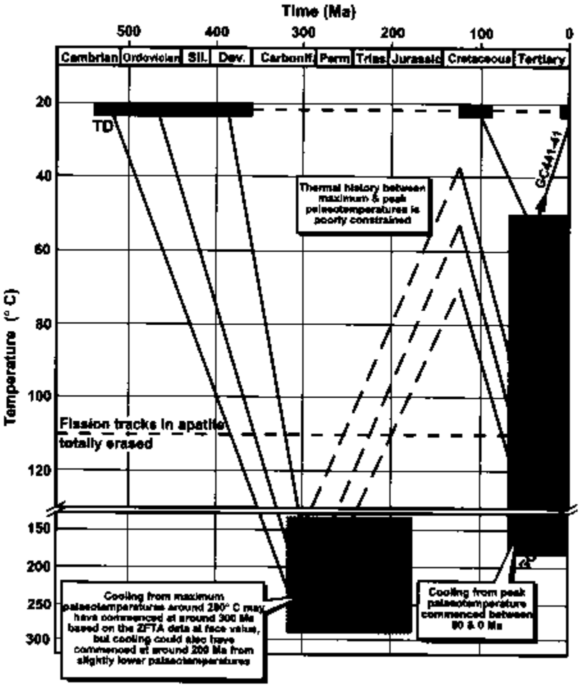

Fig. 16. Schematic illustration of the thermal history reconstruction for well MJB-1 based on AFTA, VR and ZFTA data.

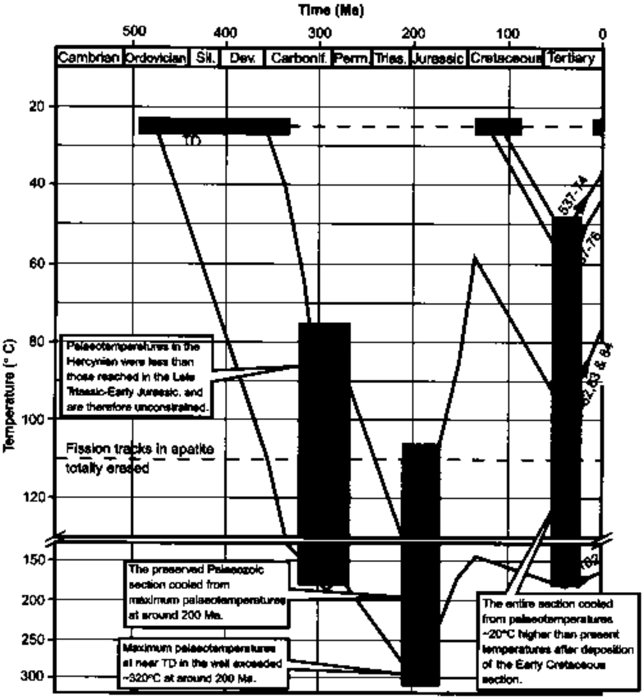

Fig. 17. Schematic illustration of the thermal history reconstruction for well TEG-1 based on AFTA, VR and ZFTA data.

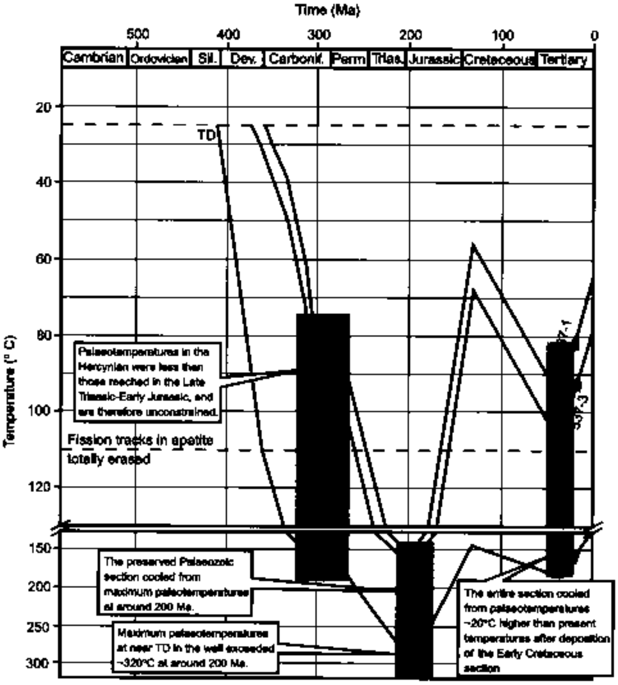

Fig. 18. Schematic illustration of the thermal history reconstruction for well ZRFW-1 based on AFTA, VR and ZFTA data.

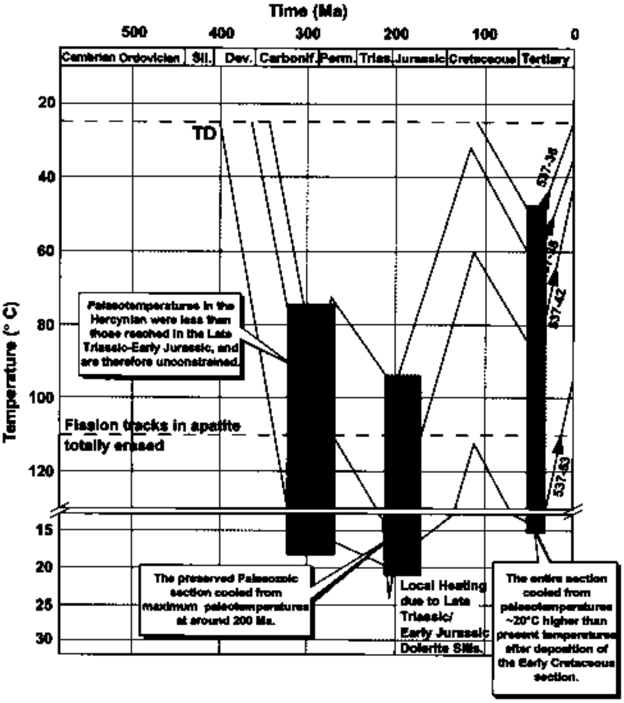

Fig. 19. Schematic illustration of the thermal history reconstruction for well RG-3 based on AFTA, VR and ZFTA data.

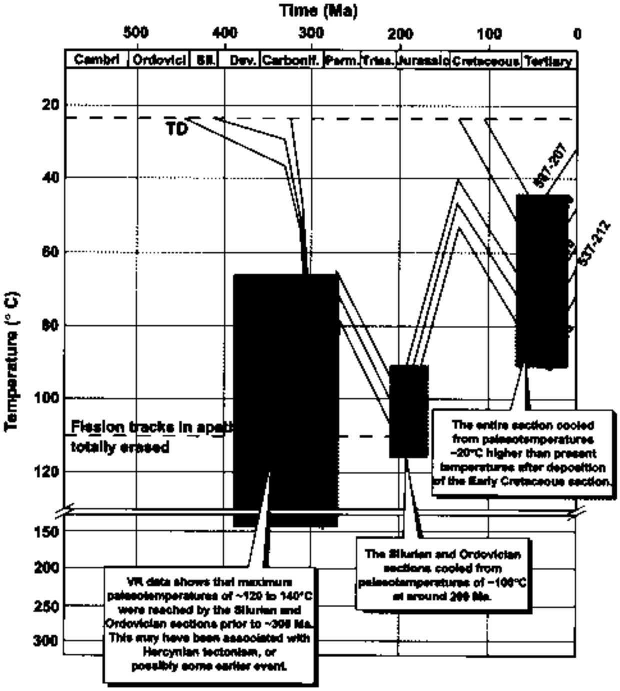

Fig. 20. Schematic illustration of the thermal history reconstruction for well OTRA-1 based on AFTA, VR and ZFTA data.

been achieved in some otherwise unknown post-Silurian, pre-Hercynian event, although this seems unlikely.

The strong evidence for the late Triassic heating event from the majority of study wells indicates that this was an important, regional event. Figure 21 shows the constraints on the palaeogeothermal gradients associated with this event. Values in the range 60–80°C/km are typical, representing a considerably greater heat flow than at present.

Determining the cause of this important event is problematic. Stratigraphic evidence suggests that it was probably not accompanied by major deposition and significant increased burial, and no Triassic rocks are known from the area, even where the Jurassic is thought to be preserved. Two possible explanations present themselves. Either the region underwent a large increase in basal heat flow or the heating was linked to the voluminous emplacement of intrusive igneous rocks in the Reggane Basin. As mentioned above, doleritic intrusions are common throughout the Reggane Basin and local heating effects are clearly visible from the geochemical data, as in the case of RG-3 (Fig. 13). No such intrusive rocks are known from the Ahnet Basin, although the high levels of thermal maturity seen in some of the northern wells, with coke textures being observed in organic material from some wells, may indicate underlying intrusions.

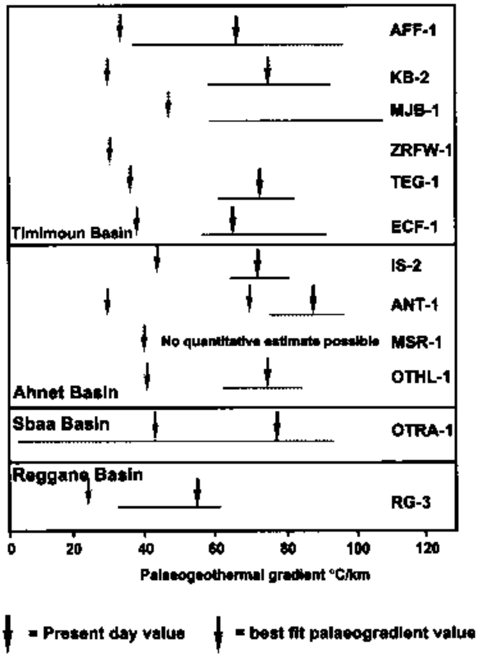

Fig. 21. Late Triassic–Early Jurassic palaeogeothermal constraints.

It should also be noted that raised geothermal gradients alone are insufficient to explain the estimated palaeotemperatures, which are often of the order of *c.* 10–120°C at the Hercynian unconformity. It is clear that considerable additional burial, followed by uplift and erosion, would be required to achieve the observed degree of maturity. The estimates of uplift and erosion are given in Table 1. The estimated amount of section removed is typically about 1 km and is likely to be related to a Late Triassic–Early Jurassic phase of uplift superimposed on an earlier Hercynian uplift. Evidence of this early Mesozoic phase of deformation is also provided by the presence of folded intrusive rocks in the southern part of the Ahnet Basin.

Good evidence for the later, Tertiary heating event is provided by a number of wells which show consistent evidence for cooling from a period of elevated palaeotemperatures at *c.* 50–30 Ma. The interpreted small degree of post-Cretaceous heating is confirmed by the limited vitrinite reflectance data from the Cretaceous section in the wells analysed. The relative similarity of Tertiary and present-day geothermal gradients suggests that post-Cretaceous heating was due to simple burial.

Figures 22–25 provide summaries of the thermal histories for the different regions of the study area. In each case, with the exception of the Sbaa Basin, the temperature histories are dominated by a heat 'spike' at 200 Ma.

Conclusions: maturity and hydrocarbon generation

At present, the organic maturities of older Palaeozoic rocks at even modest depths of burial usually exceed the level required for the generation of dry gas (2% R_0 equivalent), whereas those in the younger Palaeozoic (Carboniferous) beneath the Hercynian Unconformity typically lie within the oil window (or lower). This uniform pattern of maturities would appear to be an effect of the consistent Late Triassic heating of the basins. The current observed maturities of the two principal source rocks in the basin, the Silurian and Frasnian hot shales, are shown in map form in Fig. 26 and Fig. 27 respectively. These maps are based on measured and computed maturities, based

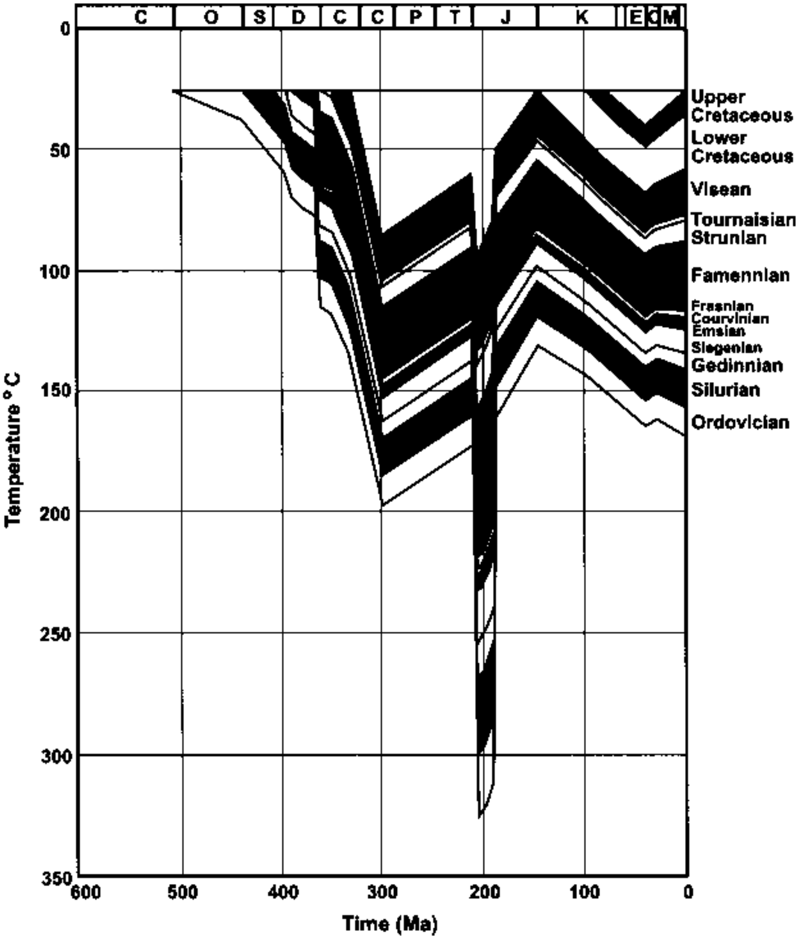

Fig. 22. Temperature–time history of the northern Ahnet–Timimoun Basin (TEG-1).

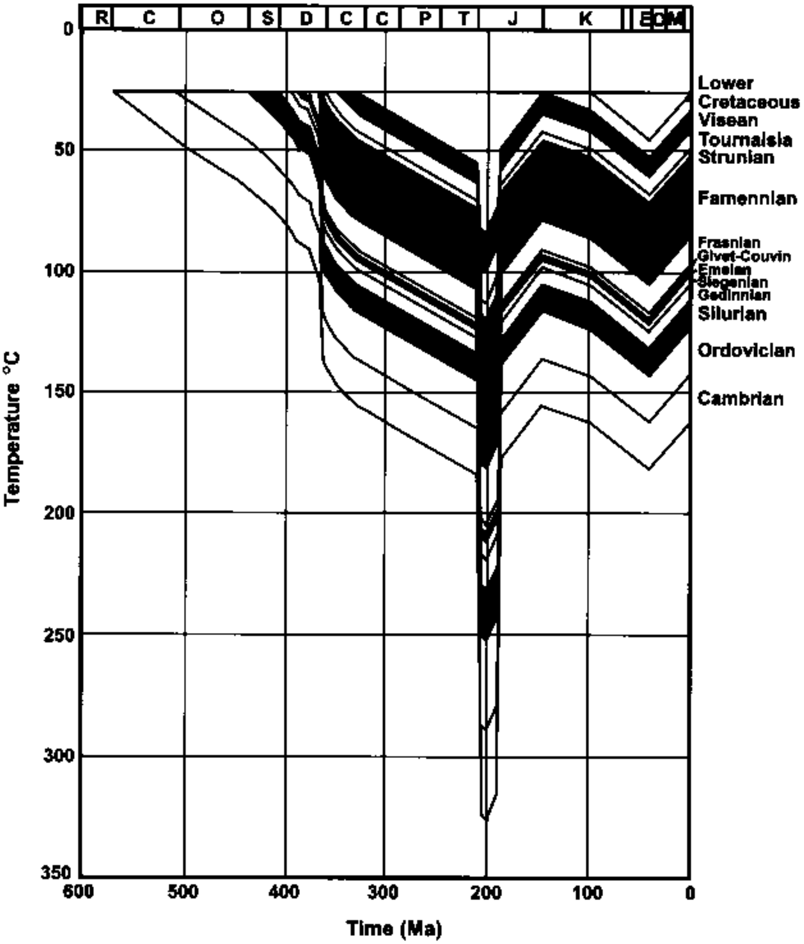

Fig. 23. Temperature–time history of the eastern Ahnet Basin.

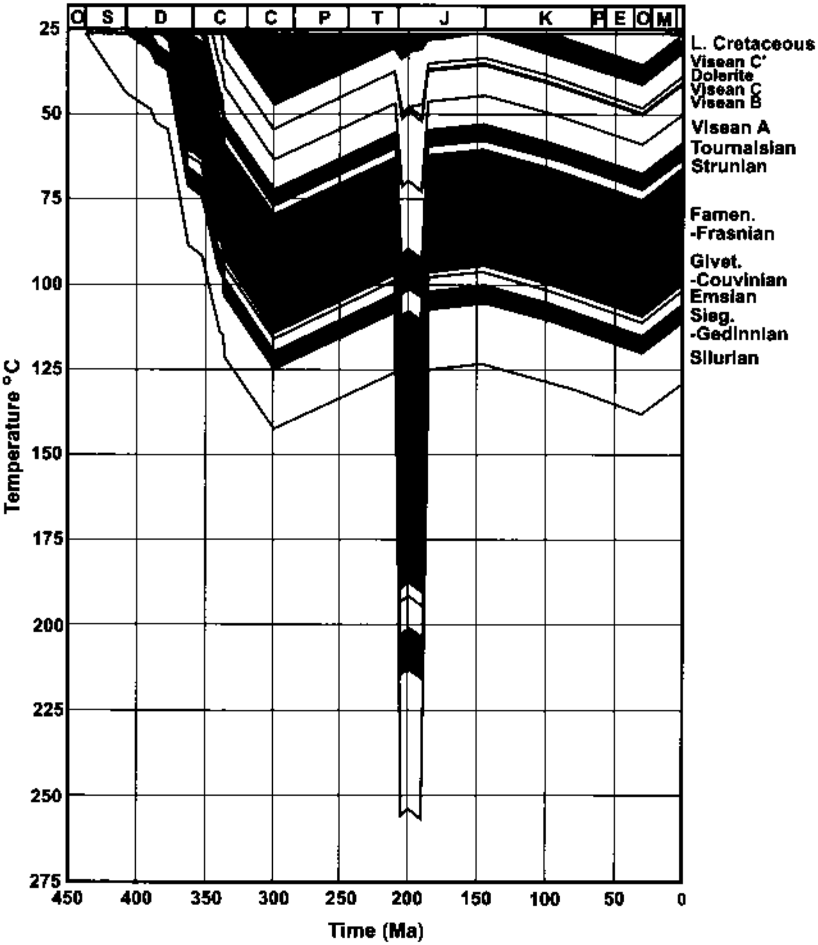

Fig. 24. Temperature–time history of the Reggane Basin (RG-3).

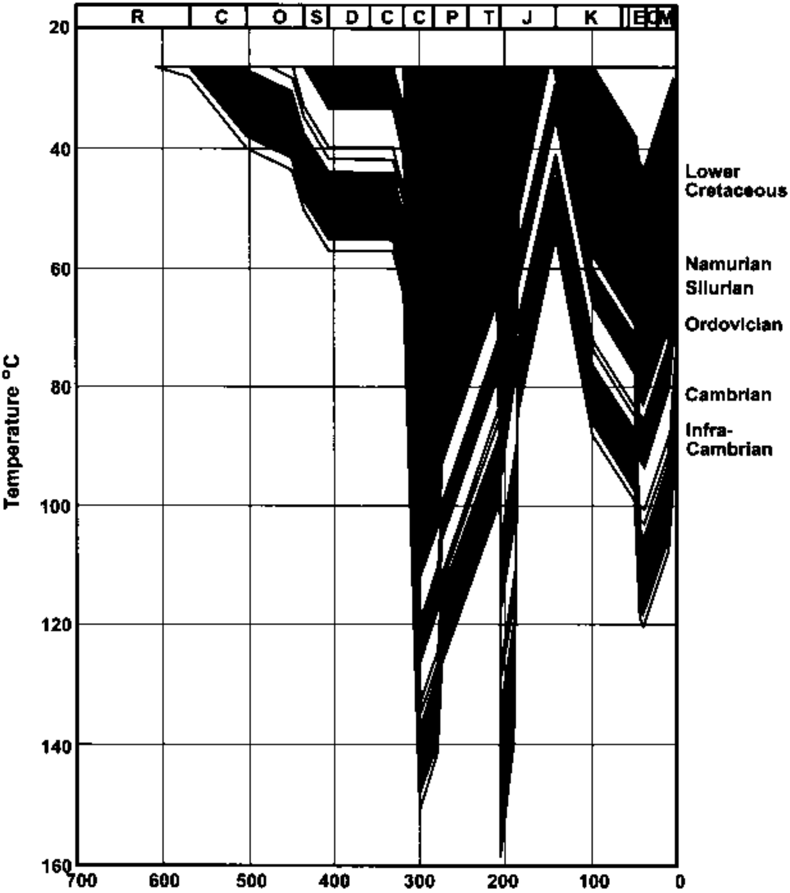

Fig. 25. Temperature–time history of the Sbaa Basin (OTRA-1)

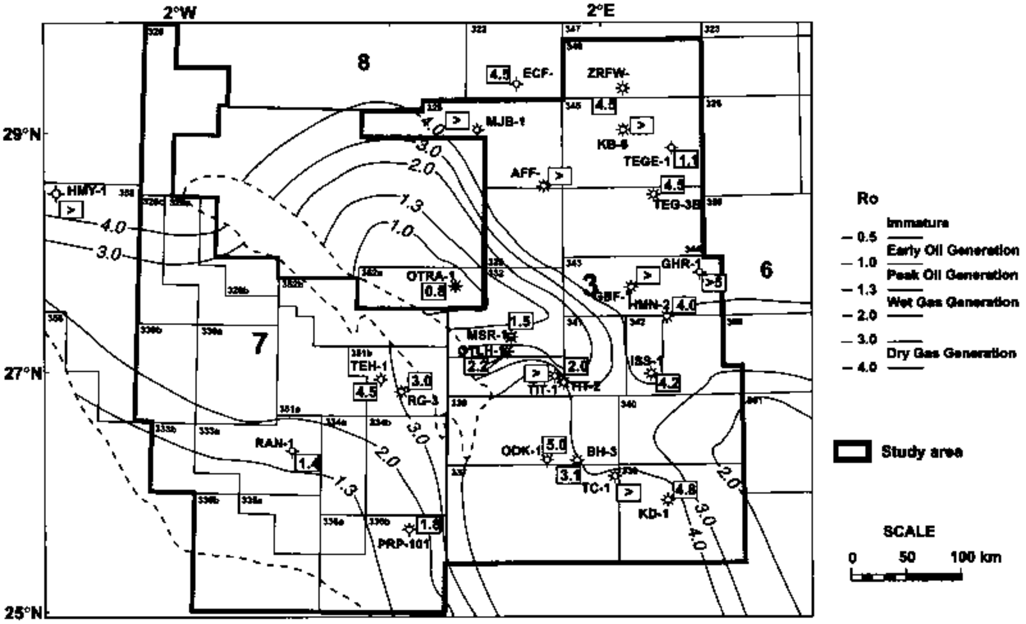

Fig. 26. Estimated maturity (R_0 equivalent) of Silurian hot shale.

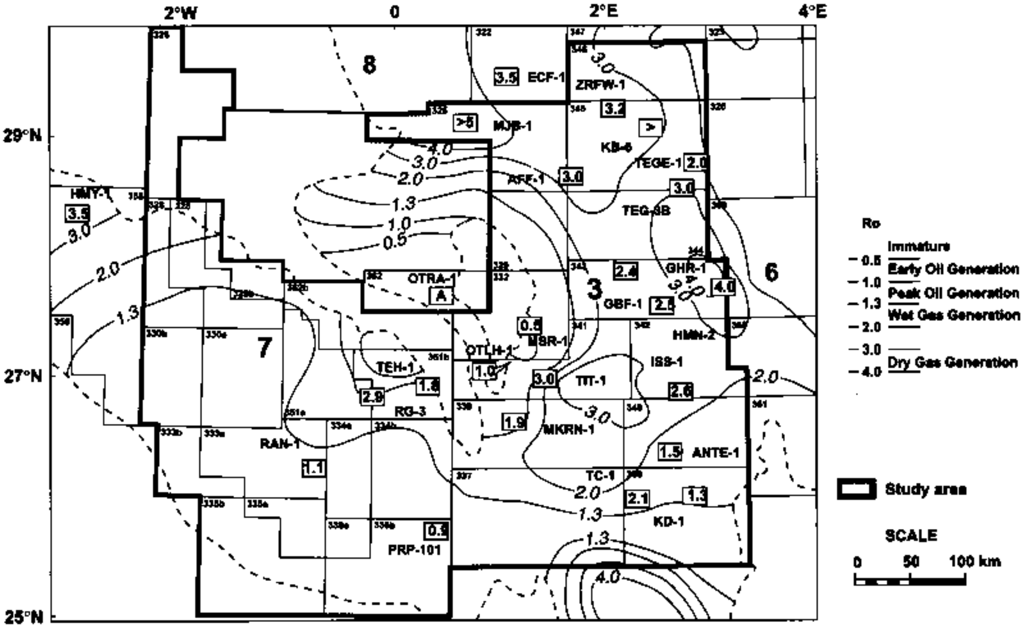

Fig. 27. Estimated maturity (R_0 equivalent) of Frasnian hot shale.

on the thermal histories derived from the analytical data.

As is to be expected, the Silurian hot shale is mature for dry gas generation throughout the area, with the exception of the Sbaa Basin and the centre of the Reggane Basin. In these cases, the admittedly limited data from OTRA-1 in the Sbaa Basin and from RAN-1 and PRP-101 in the Reggane Basin suggest that these areas lie within the oil window and wet gas window respectively. In the case of the Frasnian hot shale, a variety of states of maturity are suggested by the data. Some areas of the Ahnet Basin, particularly the north and extreme south, are mature for dry gas, with high levels of reflectance. On the western flank, however, and in the Sbaa and central Reggane Basins, the interval remains within the oil window.

Figures 28–30 provide burial history curves for wells TEG-1 (Ahnet Basin), RG-3 (Reggane Basin) and OTRA-1 (Sbaa Basin). In the case of TEG-1 it is likely that Silurian and Devonian source rocks were probably sufficiently mature to have generated oil before the Hercynian event. During the Late Triassic event, they would have been heated through the gas window and any previously reservoired oil would have been cracked. On the less deeply buried flanks of the basin, however, for example at OTLH-1, maturity is somewhat less and it is possible that oil generation, particularly from Devonian source rocks, could have occurred in the relatively recent past. This is supported by the presence of oil shows in OTLH-1 and nearby wells.

The history of maturation for RG-3 is similar to that for TEG-1, although the overall maturity is rather lower. Evidence suggests that heating effects caused by the emplacement of intrusions are very localized and these have been excluded from the modelling.

Well OTRA-1, in the Sbaa Basin, indicates that the Silurian source rocks have not yet reached the gas window and reached a state of oil generation before the Hercynian event, since which time, maturity has not been significantly increased. Thus oil generated from these source rocks would have been available for expulsion and migration before Hercynian tectonism. It seems unlikely that these oils have remained entrapped in reservoirs since the Carboniferous, although this is not impossible. It seems more likely, however, that the oil currently found in the Sbaa Basin has been generated on the western flank of the Ahnet Basin in Mesozoic or later times and has migrated updip to the elevated Sbaa Basin.

It would seem therefore that the study area was affected by two principal phases of heating and hydrocarbon generation. The first, before Hercynian tectonism and uplift, involved heating because of simple burial. During this phase, liquid hydrocarbons were generated in the Sbaa, Reggane and deeper parts of the Ahnet Basin. The second phase, in Late Triassic times, elevated maturities to the gas window in deeper parts of the Ahnet and Reggane Basins, accompanied by cracking of previously reservoired oils. The Sbaa Basin was relatively unaffected by this heating event, and no significant increase in maturation took place. Generation of liquid hydrocarbons continued on the less mature flanks of the Ahnet Basin until relatively recently in geological time.

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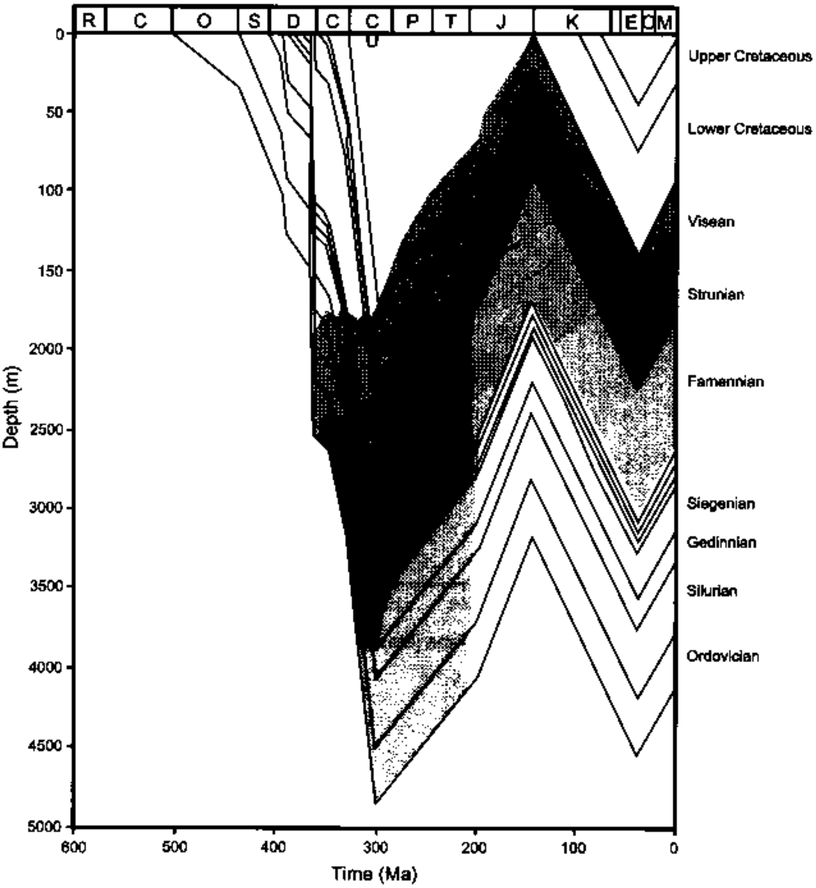

Fig. 28. Reconstructed burial history of well TEG-1.

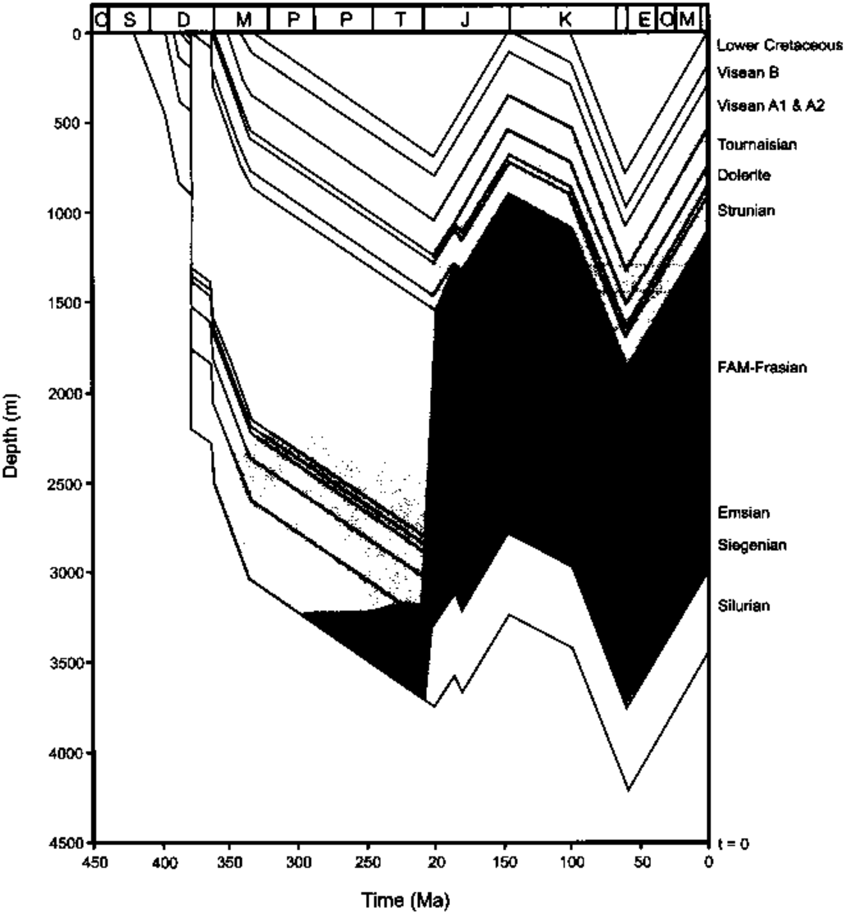

Fig. 29. Reconstructed burial history of well RG-3.

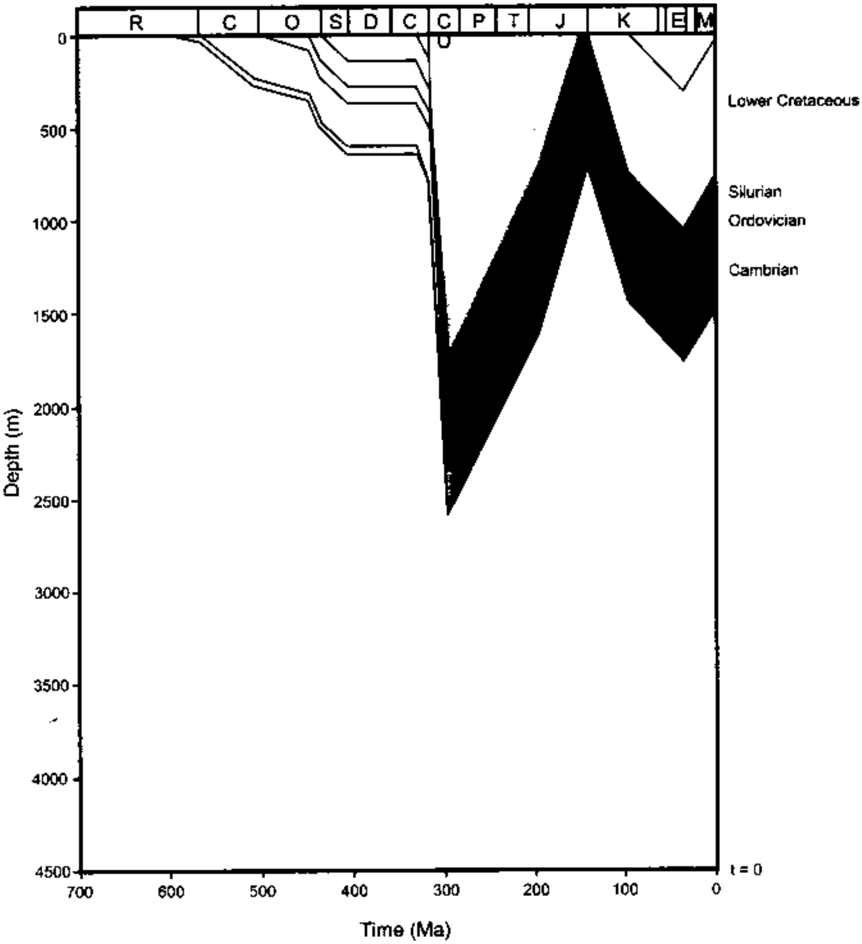

Fig. 30. Reconstructed burial history of well OTRA-1.