Palaeozoic petroleum systems of North Africa

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Abstract: The Palaeozoic petroleum systems of North Africa contain five large giant (> 1 billion barrels of oil equivalent) and 24 giant (> 250 million barrels of oil equivalent) oil and gas fields with total recoverable reserves discovered to date of more than 46 billion barrels of oil equivalent. This article presents a classification of these petroleum systems based upon their productivity and maturity. Productivity of each system has been estimated from the associated hydrocarbon reserves and maturity from an analysis of their geological history ranging from initial genesis to maturity, destruction and final extinction. Key factors controlling both productivity and maturity include hydrocarbon charge, style of drainage and entrapment, and intensity of post-entrapment tectonic, thermal and hydrodynamic destructive processes.

The regionally extensive Lower Silurian Tanezzuft Formation is the origin of 80–90% of Palaeozoic sourced hydrocarbons, with a further 10% from the Upper Devonian Frasnian shales, charging a number of intra-Palaeozoic and basal Triassic reservoirs. Triassic fluvial sands are the most important of these, hosting just over half of the total reserves, while Cambro-Ordovician and Lower Devonian F6 sandstone reservoirs are the second and third most significant, respectively.

Three categories of Palaeozoic petroleum systems have been identified:

(1) Mesozoic to early Tertiary charged systems with Triassic–Liassic shale and evaporite seals in the Mesozoic sag or 'Triassic' Basin of the northern Sahara Platform. These include > 78% of the total discovered reserves, with > 56% in the supergiants, Hassi R'Mel and Hassi Messaoud fields
(2) Mesozoic to early Tertiary charged systems with intra-Palaeozoic shale seals in basins of south and east of the Triassic Basin. These include > 18% of the total discovered reserves, mostly in the prolific Illizi Basin.
(3) Now largely extinct Palaeozoic charged systems with intra-Palaeozoic seals in basins of southwest Algeria and Morocco with 3% of discovered reserves.

The productivity of these systems varies considerably. Hassi R'Mel and Hassi Messaoud are classified as super-productive, located on the crests of broad Palaeozoic arches which encouraged extremely efficient lateral migration focusing, and a very high impedance entrapment style. Other petroleum systems within the Triassic Basin are of high productivity with somewhat less effective migration focusing and impedance characteristics. Because of a regional evaporite seal and minimal late stage modification, these systems are all preserved in a mature phase of evolution.

Basins south and east of the Triassic Basin are in various stages of destruction with variable productivities reflecting both less robust seals and post-entrapment modification by Austrian and mid-Tertiary uplift, tilting, remigration, spillage and freshwater flushing. The Illizi Basin is the least affected by these late stage destructive processes with some 15% of total discovered reserves still remaining.

The Palaeozoic charged systems of southwest Algeria and Morocco were largely destroyed by Hercynian, Austrian and mid-Tertiary deformation. Only the high relief Hercynian anticlines of the Ahnet–Gourara Basin retained their trapping integrity and still reservoir a very significant amount of gas. Apart from scattered hydrocarbon shows and a few small residual accumulations the other basins in this region now all appear to be extinct.

Since the first discovery in 1953, more than 1100 new field wildcat wells have been drilled to test the Palaeozoic basins of North Africa, with the discovery of more than 46 billion barrels of oil equivalent (BBOE) in over 300 separate pools. The hydrocarbon productivity of the petroleum systems within these basins varies widely from non-productive to extremely prolific. This paper

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attempts to define the key stratigraphic and structural variables which govern their differing productivity.

The North African Platform experienced a complex and polyphase history (Fig. 1). Initially part of a regionally continuous, clastic-dominated Gondwana passive margin, it was progressively segmented into broad forelands and intracratonic basins and swells during late Devonian to late Carboniferous collision with Laurasia. Uplift and erosional truncation of the deformed platform during late Carboniferous to early Permian was followed by a phase of rifting. This was succeeded by opening of the Tethyan seaway during the Mesozoic, when a regional transgression extended far south across the peneplaned Hercynian unconformity commencing in the late Permian and continuing through to the mid-Cretaceous. The Palaeozoic basins were buried beneath a Tethyan passive margin wedge of continental clastic deposits, evaporites and carbonates. During the later Cretaceous, the opening of the Atlantic seaway and change in relative plate motion between Africa and Eurasia were associated with periods of structural inversion, extension and development of local rift-associated depocentres on and along the flanks of the North African platform. Tertiary sedimentation was largely confined to the northern margin of the platform where the effects of collision between Africa and Eurasia were manifested in the Eocene through to the Miocene by Atlassic inversion and subsequent Maghrebian (Rif–Tellian) thrusting and nappe emplacement (Ziegler 1988). The influence of this compressional event extended back across the North African Platform with the development of a shallow foreland sag above the more inboard Palaeozoic basins and uplift of bounding highs, tilting and partial unroofing of those beyond.

Palaeozoic sourced hydrocarbon accumulations are widely distributed across the western part of the Saharan Platform, reservoired in various sandstones ranging from Cambro-Ordovician to basal Triassic in age. This review attempts to group these accumulations into discrete petroleum systems, each sharing a common generative area or pod of source rock and common reservoir(s) with broadly similar charging history (Magoon & Dow 1994). The more important systems have been described in a series of maps (Fig. 2), schematic cross-sections and critical element analyses, developed from the approach suggested by Demaison & Huizinga (1994) and Magoon & Dow (1994). These highlight the key stratigraphic and structural variables that appear to govern the distribution of oil and gas accumulations within each system, including source, reservoir and sealing facies, peak expulsion, preferred migration directions and post-charge modification such as basin tilting and flushing. Precise descriptive and analytical information is generally very limited and it was often not possible to constrain these variables directly. Instead, they were frequently inferred indirectly from regional structural and stratigraphic control. Critical uncertainties included the following:

(1) Defining generative areas or pods: although organic-rich Lower Silurian and Upper Devonian shales are now widely recognized as the primary source of Palaeozoic hydrocarbons in the region (Tissot *et al.* 1984; Daniels & Emme 1995) it was rarely possible to link reservoired oil or gas directly with discrete generative areas. These had generally to be inferred from the structural relationship between hydrocarbon accumulations and nearby source rocks.

(2) Critical period: because of the polyphase history of the region, source rocks within individual basins often experienced two periods of burial and maturation separated by significant uplift and unroofing. Consequently, it was frequently difficult to reconstruct the charge history with any precision. This was commonly extrapolated from structural history and the relationship between source, reservoired hydrocarbon maturities and time of trap formation.

(3) Migration drainage and entrapment style: sufficient stratigraphic information was available to define the more obviously important lateral migration conduits. Vertical migration conduits were inferred from the stratigraphic distribution of hydrocarbon accumulations and their relationship with lateral conduits, faults and erosional windows in intra-formational seals. Preferred migration drainage directions were then extrapolated from structural configuration. Entrapment style or impedance was estimated from the geometry of the primary conduit, seal continuity and structural complexity.

(4) Preservation time: the preservation time of each system was reconstructed from its structural history and relative timing between trap charge and late-stage events including uplift, tilting and hydrodynamic flushing.

(5) Relative importance of the stratigraphic and structural factors responsible for each system: although significant amounts of hydrocarbons must certainly remain to be discovered, exploration in the region is now at a fairly mature level and the reserves so far established for each system are considered at least a relative estimate of their ultimate productivity or efficiency in entrapping and retaining oil and gas. This in turn provides an independent and semi-

quantitative measure to compare the relative importance of the factors responsible for each system.

The analysis relied upon a wide variety of proprietary and published sources including Claret and Tempere (1967), Aliev *et al.* (1971), Bishop (1975), Chiarelli (1978), Hammuda (1980), Hamouda (1980*a*, *b*), Tissot *et al.* (1984), Van de Weerd & Ware (1994), Daniels & Emme (1995), Thomas (1995), Gumati *et al.* (1996), Macgregor (1996*b*). Many of the interpretations presented in this paper are dependent upon the accuracy of data and interpretations from a variety of published and proprietary sources. These were sometimes contradictory and required pragmatic selection and simplification. Wherever possible the final interpretations were constrained by independent evidence but geological inference and extrapolation were sometimes necessary and the resulting synthesis is inevitably rather speculative. Nevertheless, we believe this empirical approach proved adequate to measure and rank the relative importance of the critical variables which control the productivity of each system.

Tectono-stratigraphic evolution of the North African Platform

The North African Platform lies yoked between the African Shield in the south, with its Eglab, Hoggar, Tibesti, Jebel Awaynat and Nubian Precambrian massifs, and the Atlassic–Maghrebian fold belts and East Mediterranean Basin in the north (Fig. 2). The varied structural style of this platform is illustrated by a series of predominantly north–south schematic cross-sections, illustrating the Palaeozoic intra-cratonic basins of Morocco, Algeria and Libya, and the later Mesozoic sag and rift basins of eastern Algeria, Libya and Egypt (Figs 3–7). The underlying Precambrian basement evolved as part of Pangaea, formed from the collision and suturing of several cratons and intervening island arcs during the Pan-African orogeny. This subsequently evolved into a stable Gondwana and later Tethyan passive continental margin, interrupted by Hercynian deformation in the late Carboniferous, rifting during the Mesozoic and Atlassic-Maghrebian orogenesis in mid–late Tertiary. A widespread Hercynian unconformity divides the sedimentary cover into a lower Gondwana Super-Cycle of mildly deformed Palaeozoic clastic deposits and an upper Tethyan Super-Cycle of Mesozoic–Tertiary clastic deposits, evaporites and carbonates.

Gondwana Super-Cycle

During the early part of the Gondwana Super-Cycle, the North African Platform was blanketed by a regionally extensive succession of high-lati-

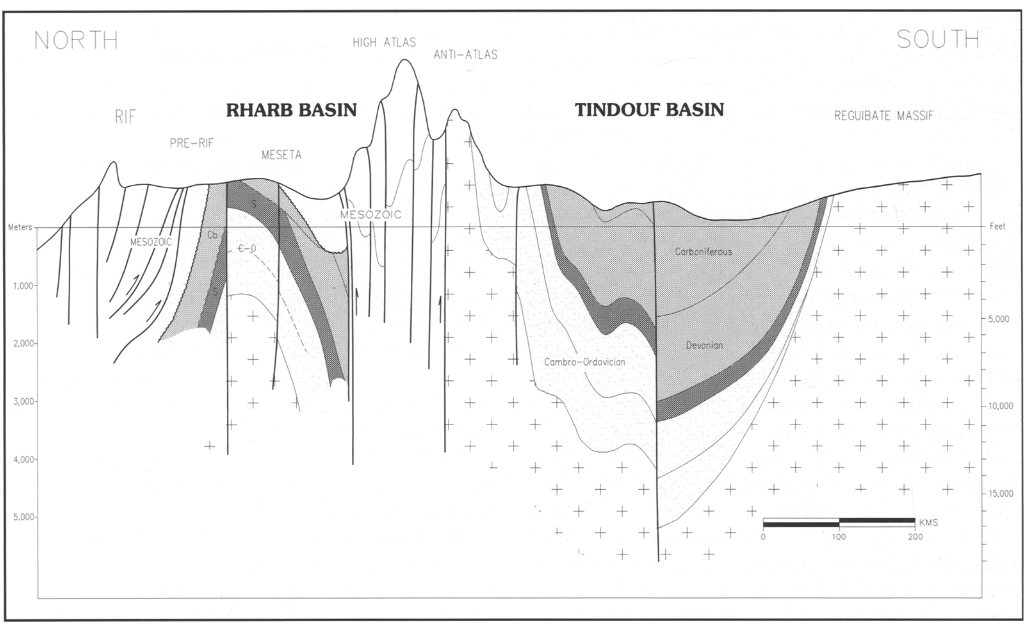


Fig. 3. Generalized structural cross-section across the Rharb and Tindouf Basins. (See Fig. 2 for location.) Partly adapted from Peterson (1986).

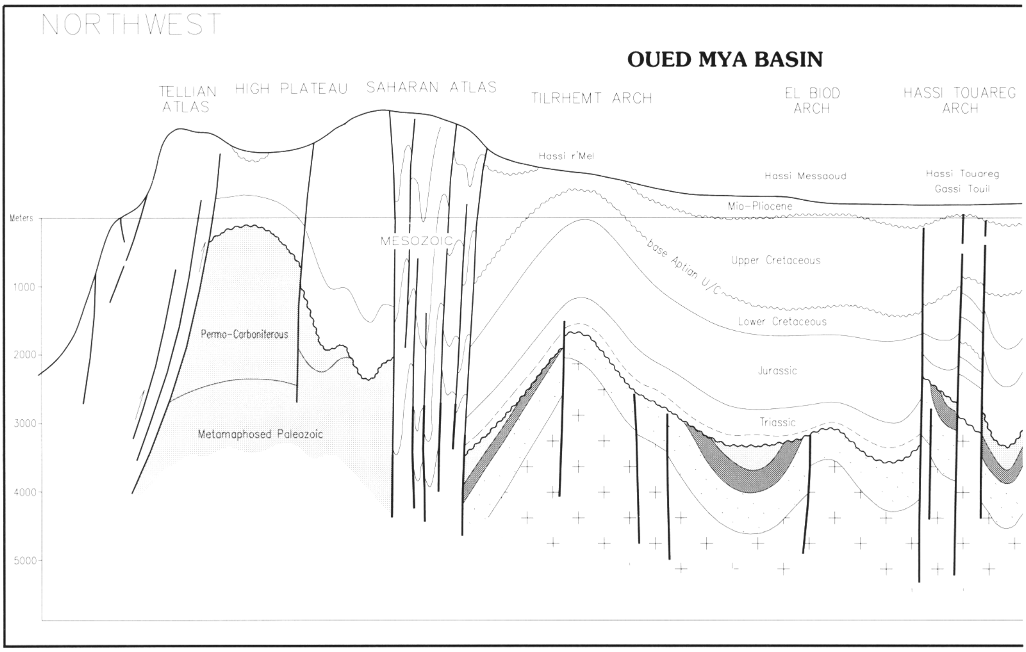


Fig. 4. Generalized structural cross-section across the Oued Mya and Illizi Basins. The Mesozoic foreland (1982).

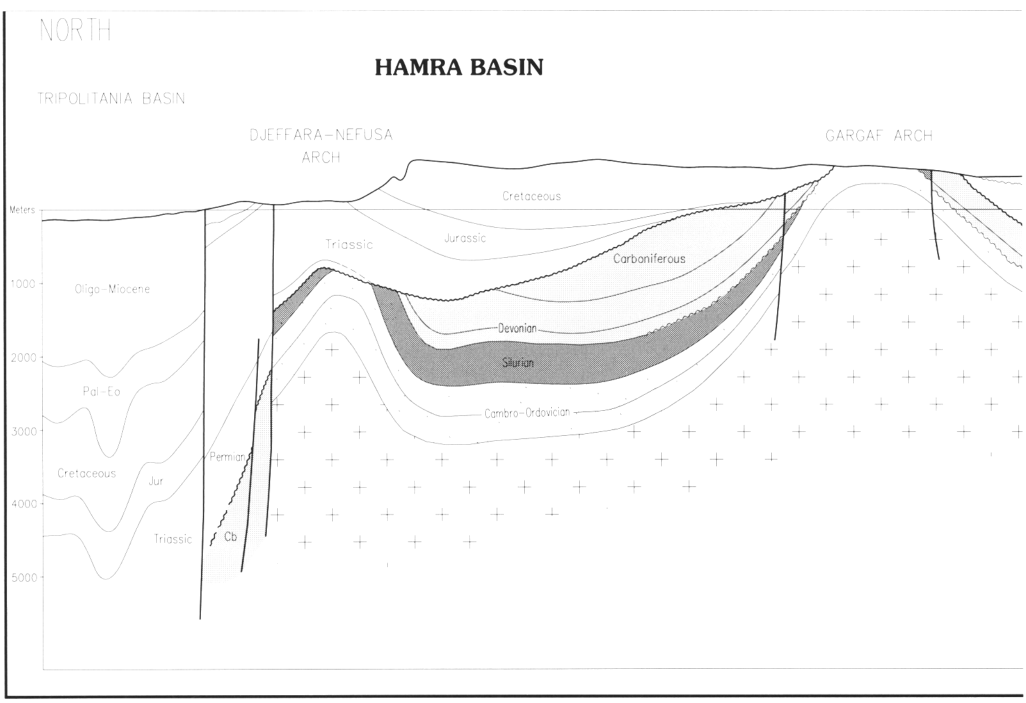
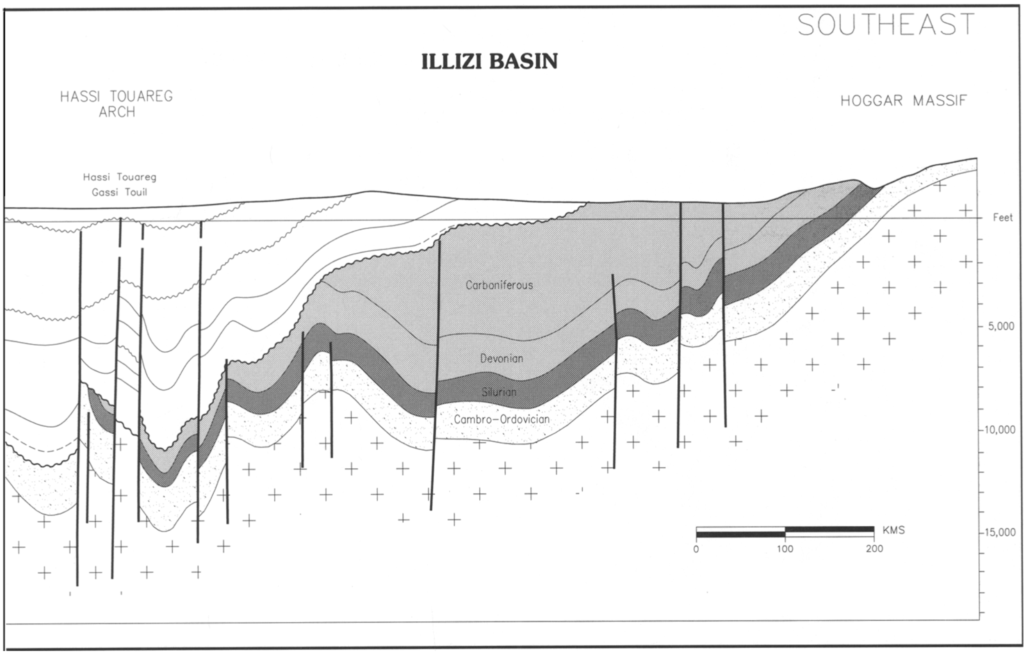
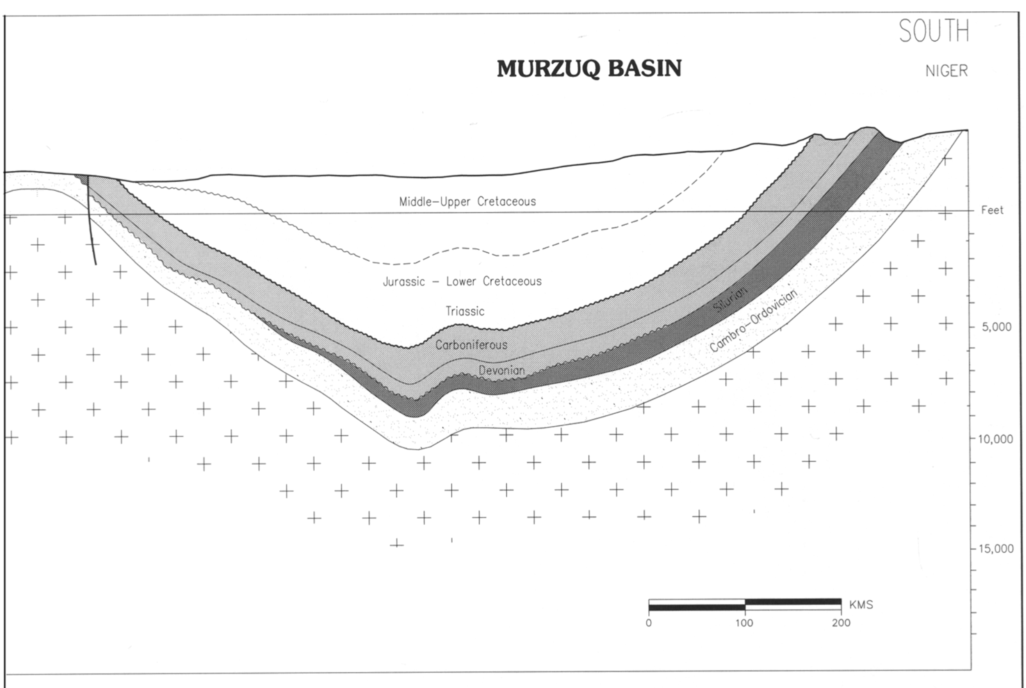


Fig. 5. Generalized structural cross-section across the Hamra and Murzuq Basins. (See Fig. 2 for location.) Partly



depocentre of the Saharan Platform is also illustrated. (See Fig. 2 for location.) Partly adapted from Peterson



adapted from Pallas (1980) and Peterson (1982).

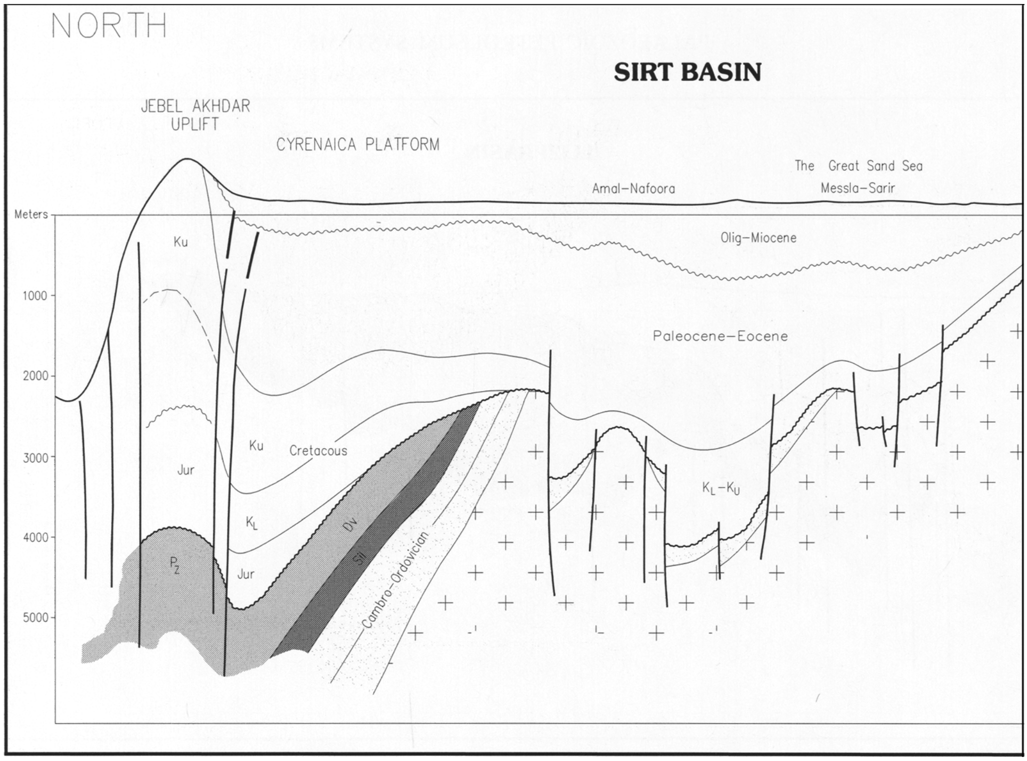


Fig. 6. Generalized structural cross-section across the Sirt and Kufrah Basins. (See Fig. 2 for location.) Partly

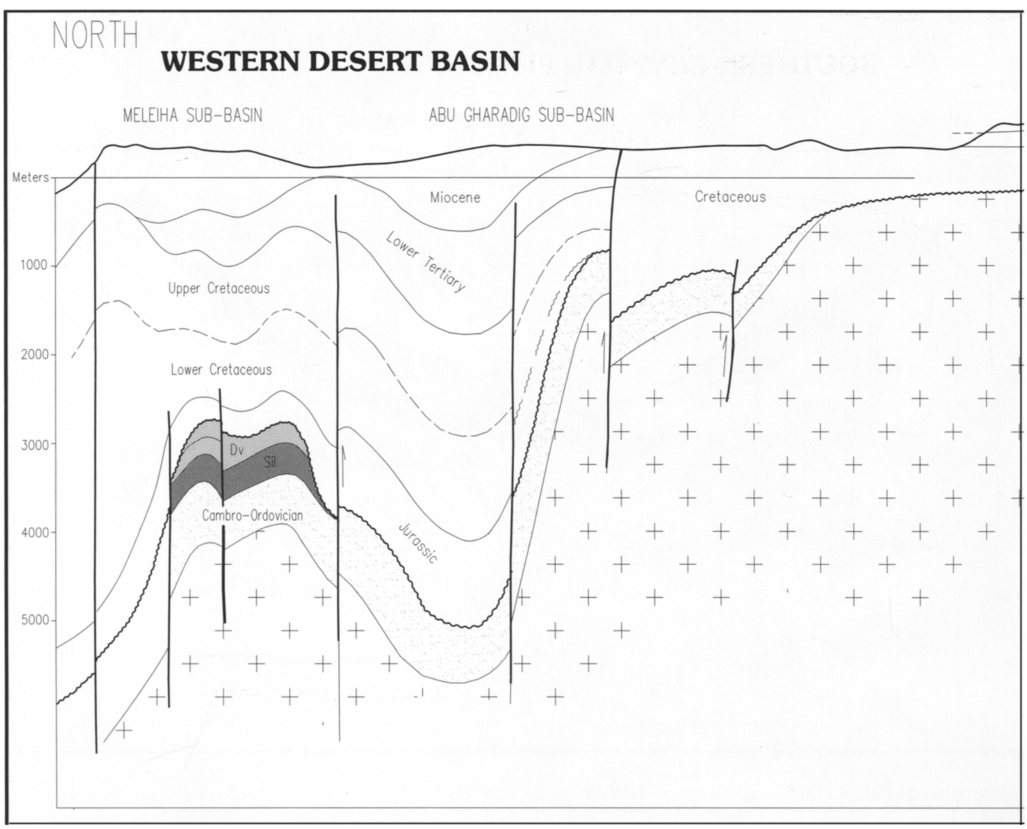
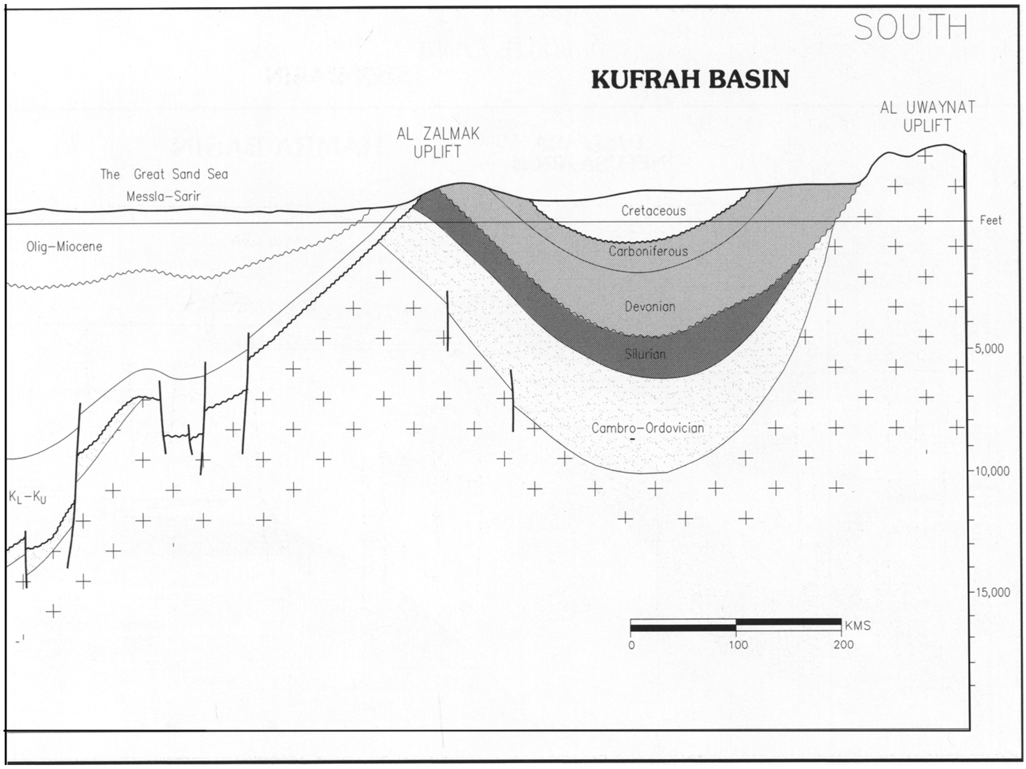


Fig. 7. Generalized structural cross-section across the Western Desert Basin and southern Egyptian platform. The (See Fig. 2 for location.) Partly adapted from Peterson (1982).



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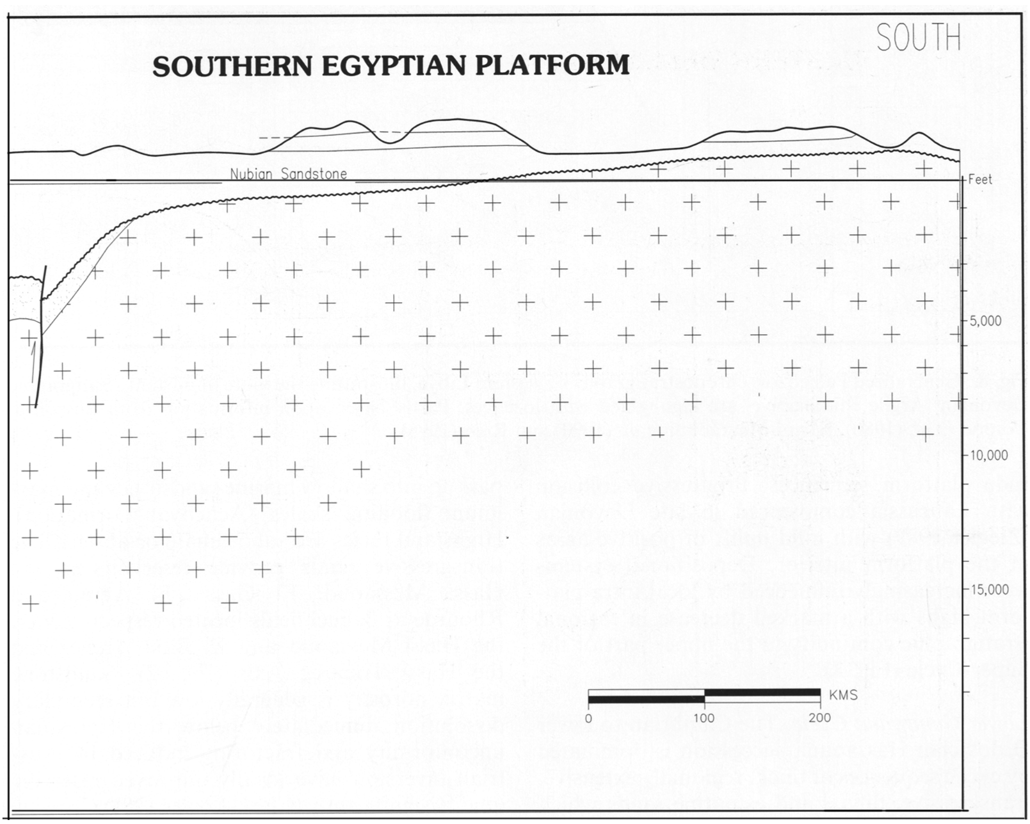


structure of the southern platform is weakly constrained and Palaeozoic sub-basins may underlie the Mesozoic.

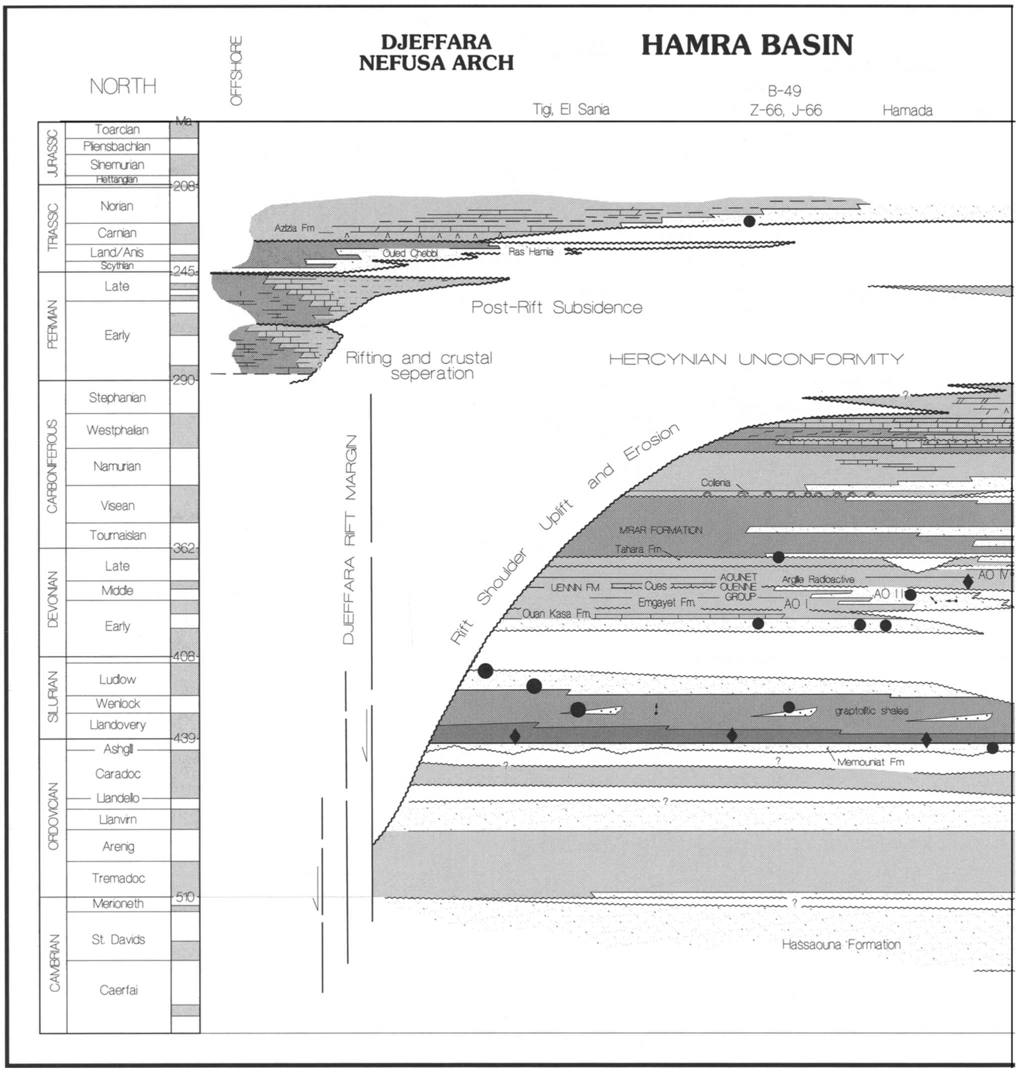


Fig. 8. Generalized Palaeozoic chronostratigraphy of western Libya, illustrating the more important stratigraphic Devonian 'Argile Radioactive' are highlighted with lozenges. Partly based upon information from Busson & Conrad *et al.* (1986), Kilani-Mazraoudi *et al.* (1990) and Rigo (1995).

tude platform sequences. Progressive collision with Laurussia commenced in late Devonian (Ziegler 1989) with mild uplift of positive areas in the platform interior. Depositional systems were increasingly influenced by local intra-platform highs with a marked decrease in regional stratigraphic continuity in the upper part of the Super-Cycle (Fig. 8).

Lower Gondwana Cycle. The Cambrian to lower Ordovician Hassaouna succession is dominated by cyclic sequences of thick, regionally extensive, transgressive, fluvial and estuarine sands which pass up into shallow marine sandstones and maximum flooding shales (Achebyat Formation). Highstand facies are subordinate or absent. The transgressive sands provide reservoirs in the Hassi Messaoud, El Gassi, El Agreb and Rhourde al Baguel fields located respectively on the Hassi Messaoud and El Biod Arches and the Hassi Touareg Axis (Fig. 2). Sandstone matrix porosity is generally low but secondary dissolution immediately below the Hercynian unconformity and fracturing induced by Austrian inversion have locally improved reservoir quality significantly (Clark-Lowes 1988; Crossley

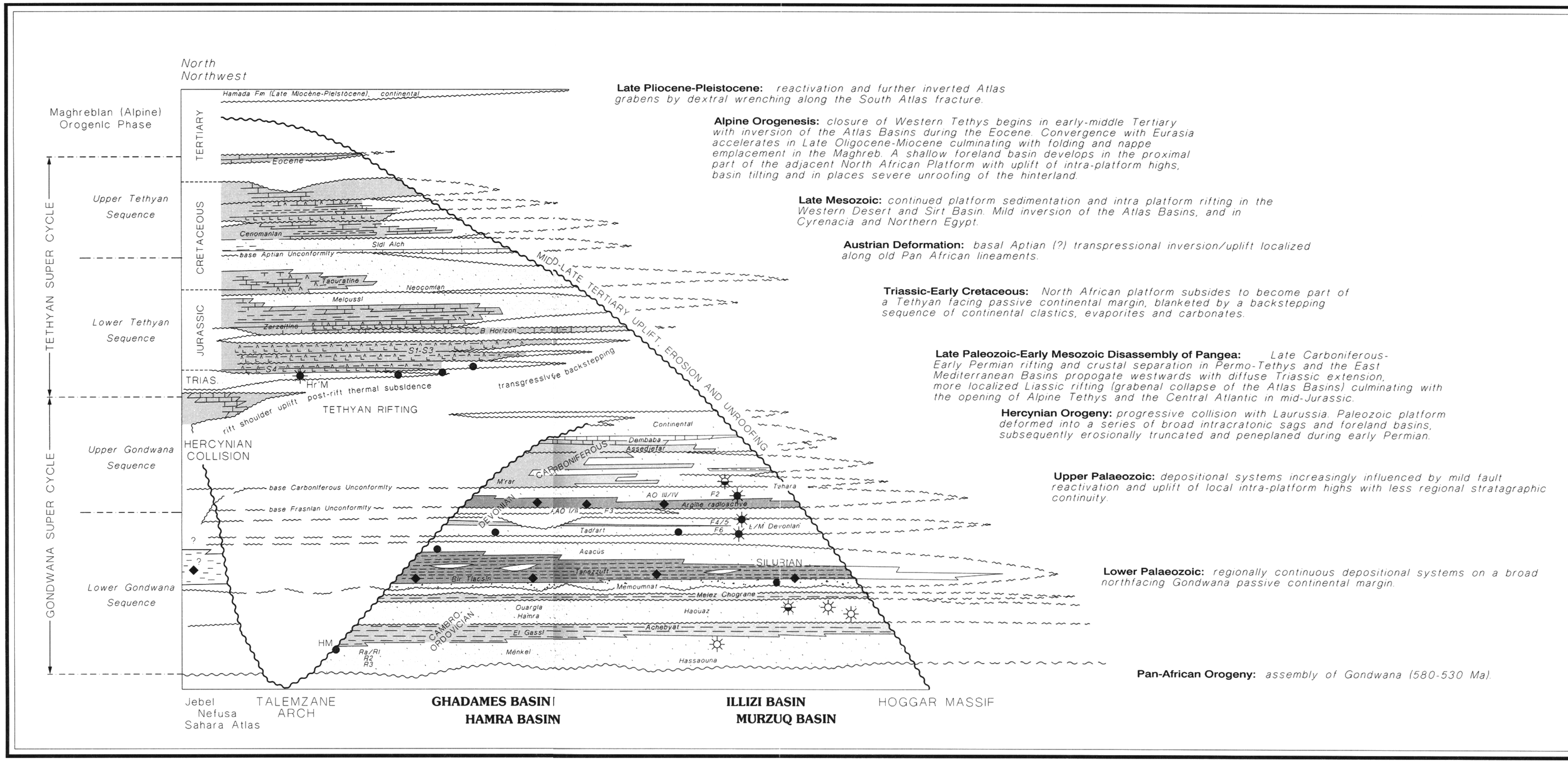


Fig. 1. Regional chronostratigraphic framework of the North African Platform, based upon the stratigraphic successions of eastern Algeria and western Libya. Large-scale stratigraphic cycles, and associated plate boundary tectonic events, and smaller-scale stratigraphic sequences and bounding unconformities are shown diagrammatically. The Lower Silurian Tanezzuft and Upper Devonian Frasnian source rocks are indicated by black lozenges, and the more important hydrocarbon reservoirs are highlighted by oil and gas symbols. AO I–AO IV represents the Middle and Upper Devonian Aouinet Ouenine formations of Western Libya. HR'M = Hassi R'Mel gas field, HM = Hassi Messaoud oilfield.

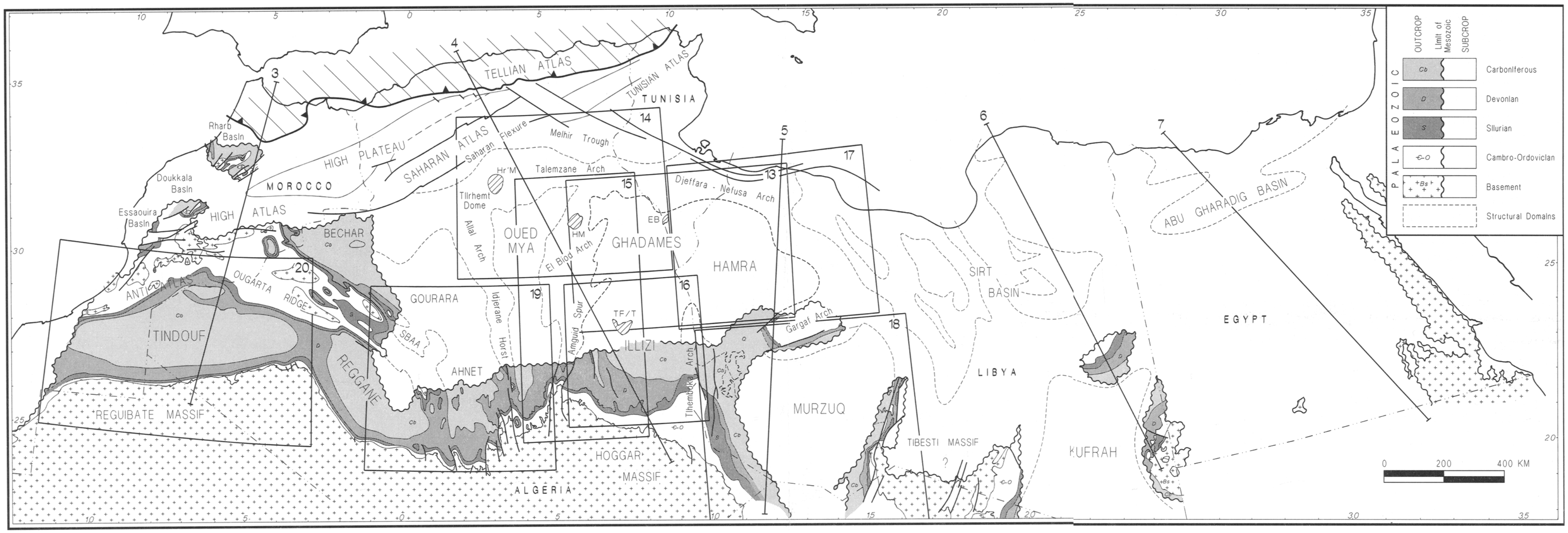
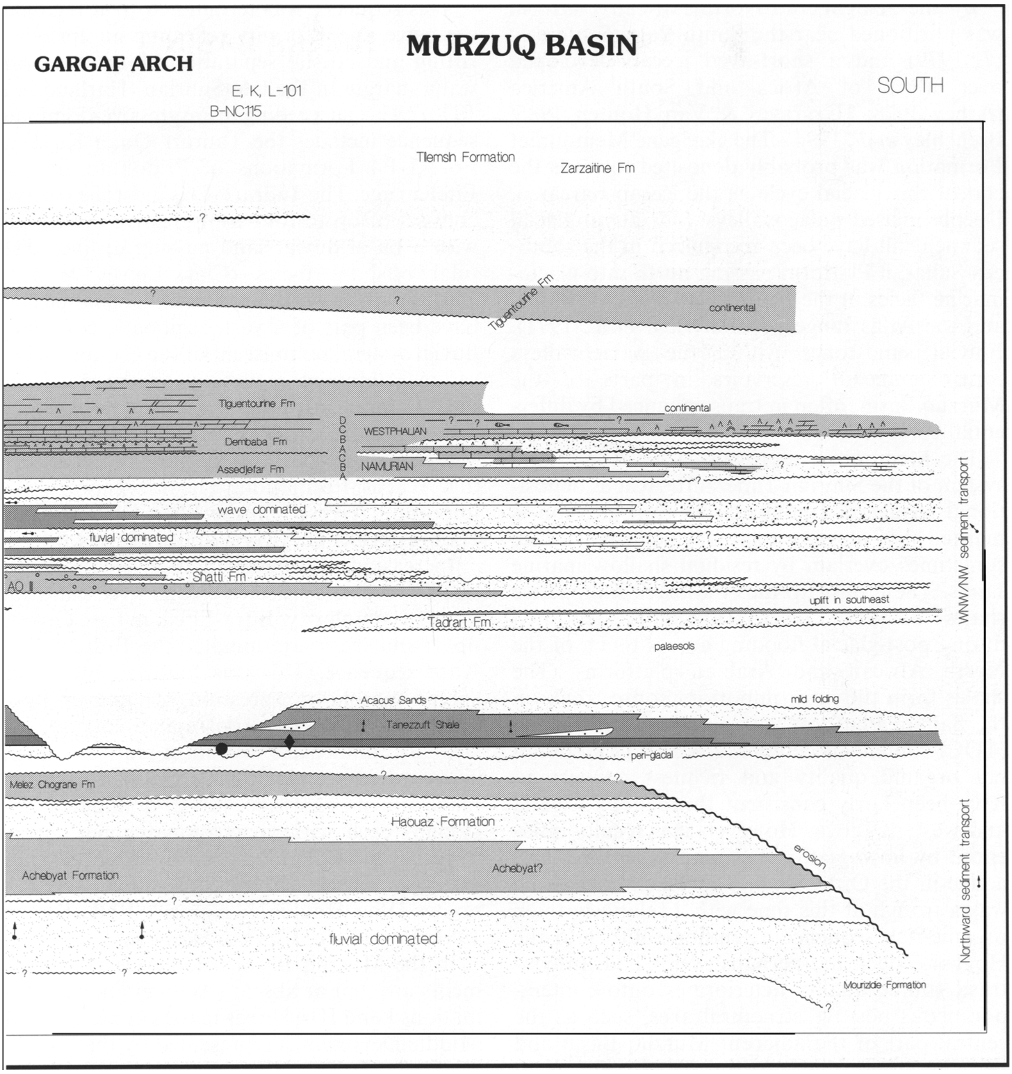


Fig. 2. Regional structural framework of North Africa, highlighting the main sedimentary basins and tectonic elements. These include the northeast–southwest aligned Atlas fault system extending into the Djeffara fault trend to the east. Basins or regions with high-productivity Palaeozoic petroleum systems include: the Tilrhemt Dome and Hassi R'Mel gas field (HR'M), the North Oued Mya Basin, the El Biod Arch with the Hassi Messaoud oilfield (HM), the Ghadames Basin and El Borma oilfield (EB), the Illizi Basin with the Tin Fouye–Tabankort field (TF/T) and the Gourara–Ahnet Basins. Basins with moderate- to low-productivity petroleum systems include the Sbaa, Hamra and Murzuq Basins. The Essaouira, Doukkala, Rharb, Tindouf, Bechar, Reggane and Kufrah Basins are marginal to non-productive. The location and figure numbers of structural cross-sections, petroleum system summary maps and critical elements analysis diagrams included in this paper are highlighted. Basement and Palaeozoic outcrops in the southern part of the region are shown by various shading. (Note: Arabic place-name transliteration usage is pragmatic and is that deemed to be most familiar and well established in English-language scientific literature.)



sequences and bounding unconformities in a simplified fashion. The organically-rich Tanezzuft Shales and Upper Burollet (1973), Massa & Beltrandi (1975), Jaeger *et al.* (1975), Bellini and Massa (1980), Fatmi *et al.* (1980),

& McDougall this volume; Djarnia & Fekerine this volume).

Stacked regressive dominated sequences characterize the overlying Ordovician Arenig to Llandeilo Haouz Formation, typically with a thin basal transgressive lag passing up into marine graptolitic shales and coarsening-up delta front–delta top highstand sandstone facies (Vos 1981*a*). These generally have very low matrix porosity. The succeeding Llandeilian-Caradoc Melez Chograne shales extend across a wide area of the North African Platform, clearly represent a major flooding sequence, and may sometimes form a poor-quality source.

Unconformities interrupt the Ordovician succession at the base of the Haouz and Melez Chograne Formations. These reflect epeirogenic reactivation of heterogeneities in the underlying Pan-African basement. They tend to be local and confined to elongate intra-platform structural highs, with a generally pronounced NW–SE to N–S alignment. The most important include the Ougarta, Amguid–El Biod, Tihemboka, Gargaf, Calanscio–Al Uwaynat (Klitzsch 1981) and Al Uwaynat–Bahariyah (Keeley 1989) Arches of Algeria and Libya.

By the Ashgill, the North African Platform was positioned near the South Pole (Scotese *et al.* 1979) and a short-lived icecap developed over much of Africa and South America (Arbey 1978; Hargraves & Van Houten 1985; Brenchley *et al.* 1994). The glacigene Memouniat Formation was probably deposited towards the end of this glacial cycle as the icecap retreated. Deeply incised palaeovalleys with fluvio-glacial sediment fill have been recognized in the southern Saharan Platform passing north into glaciomarine facies in the Hamra and Tindouf Basins and the Atlas range beyond (Beuf *et al.* 1971). Fluvial sandstones within the palaeovalleys form significant reservoirs in parts of the Murzuq Basin, often in traps enhanced by differential compaction.

The Memouniat represents a basal lowstand system of the Silurian Tanezzuft–Acacus depositional sequence. Initial marine transgression is marked by an erosional ravinement surface sometimes overlain by residual shallow marine sands. These pass up into the black radioactive shales of the Lower Tanezzuft, deposited during post-glacial flooding across much of the North African and Arabian platforms. The shales form the most important source rock on the Sahara Platform with total organic carbon (TOC) content of between 2% and 17%. Original organic quality and richness appears to have been fairly consistent throughout Algeria and western Libya. However, it is locally influenced by intra-platform structural features first active in the Ordovician. The Tihemboka Arch was a trough at this time with a relatively thick organic-rich sequence extending south into the Hoggar, Niger and perhaps even Chad. In contrast, source quality deteriorates onto contemporaneous positive structural axes, such as the central part of the adjacent Murzuq Basin and perhaps across the ancestral Tibesti–Sirt Arch of central Libya (Klitzsch 1966). In the Kufrah Basin further to the southeast, the Tanezzuft is present, and although largely unknown, is reported to have some source potential (Keeley & Massoud this volume). In western Egypt, Silurian source potential is generally poor (Keeley 1989; Keeley & Massoud this volume).

Regional flooding of the North African Platform during early Llandovery (Berry & Boucot 1973; Bellini & Massa 1980) was followed by a pro-delta and delta top highstand system of the upper Tanezzuft and Acacus Formations which prograded northwards from late Llandovery to the Ludlow. Thin turbidite, shelf and distal delta sands of this sequence provide moderate- to poor-quality reservoirs in several western Libyan and Tunisian accumulations.

This sequence was terminated by a regionally extensive unconformity reflecting an episode of rifting and crustal separation along the Gondwana margin in the late Silurian (Harland *et al.* 1990). The succeeding transgressive-dominated sequence includes the Tadrart–Ouan Kasa and F6–F5–F4 Formations of Pridoli to Emsian–Eifelian age. The Tadrart–F6 sandstone reservoir consists of up to four transgressive cycles, each with a basal fluvial sand passing up into distal tidal offshore facies (Clark-Lowes & Ward 1991, Alem *et al.* this volume). This appears to have been part of a vast, regionally continuous fluvial system, reminiscent of the Cambrian Hassaouna, thinning regionally to the north and locally onto intra-platform structural arches. The sands were derived from a southeasterly source and are coarser than those of the underlying Acacus Formation. The F6–Tadrart is an important reservoir in the Illizi, Ghadames and Hamra Basins of Algeria and western Libya.

Increasing epeirogenic activity in the mid to late Devonian is reflected by an increase in stratigraphic complexity. Intra-Eifelian–base Givetian uplift and erosion terminated the Tadrart–Ouan Kasa sequence. This was followed by a widespread marine transgression, grading up into a series of stacked depositional cycles, each strongly influenced by intra-platform highs. These Middle and Upper Devonian cycles are made up of regressive, fluvial-dominated delta systems each with an erosional upper surface, in places incised and capped by extensive transgressive marine shales, limestones and iron oolites (Van Houten & Karasek 1981; Karasek 1981; Vos 1981*b*; Clark-Lowes 1988).

In the Murzuq Basin Middle Devonian sediments are thin or absent (Aouinet Ouenine Formations I and II) whereas in the Hamra Basin the Middle Devonian is represented by the Emgayet Formation. The Illizi–Ghadames equivalent comprises regressive sequences which form significant reservoirs in a number of the Illizi Basin fields (most notably the F3 sand; see Chaouchi *et al.* this volume).

Upper Gondwana Cycle. Mid to Upper Devonian intra-platform epeirogenic movements reflect the initial collision between Gondwana and Laurussia and progressive reassembly of Pangaea during the Late Palaeozoic. Deformation commenced along the northwestern promontory of the North African Platform and subsequently propagated eastwards to encompass the entire Atlas region by late Namurian. Foreland basins developed immediately south of this Mauretanide–Variscan orogenic belt, and major northwest aligned structural axes in the interior platform collapsed to be replaced by northeast-trending arches. The Tibesti–Tripoli (Brak–Ghanimah) and Calanscio–Al Uwaynat Arches subsided whereas the Tibesti–Sirt uplift became a dominant feature (Klitzsch 1971).

The basal Upper Devonian Frasnian unconformity reflects the most significant of the intra-Devonian epeirogenic movements, with clear evidence of deep erosional truncation over parts of the Ougarta and Gargaf Arches. A regional transgression followed during the Frasnian with the deposition of a widespread organic-rich shale, the 'Argile Radioactive', across much of the North African Platform. These shales, comparable with the basal Tanezzuft radioactive unit, are a major source rock in the Ghadames and Illizi Basins with TOC values ranging between 2% and 14%. Their distribution is less well defined elsewhere but they appear to have extended at least as far as the Western Desert of Egypt.

The overlying late Frasnian to early Tournaisian succession is dominated by relatively thin, cyclic, platform deltaic deposits of the upper Aouinet Ouenine (III and IV)–Ouenine–Shatti sandstone formations in Libya and the F2 sequence of the Illizi–Ghadames region. These sandstones and those of the overlying Tahara Formation (Karasek 1981) provide significant reservoirs in the Illizi and Hamra Basins.

Deltaic deposition dominated the Carboniferous across much of the North African Platform. Sedimentation patterns were strongly influenced by intra-platform highs and by the developing fold and thrust belt, with its associated flanking foreland basins, to the northwest. In the greater Ghadames area, Whitbread & Kelling (1982) interpreted the Visean M'rar Formation as a series of stacked fluvial-dominated deltaic cycles becoming more wave dominated upwards in the succession. This sequence was terminated in the early Namurian by a regionally widespread transgression and deposition of the Lower Assedjefar fluvio-deltaic systems tract. These deltaic deposits are overlain by marine shales and paralic algal stromatolitic limestones of the upper Assedjefar Formation above. Sandstones within this Lower Carboniferous succession form significant reservoirs in the Illizi and Ahnet Basins and to a lesser extent in the Ghadames–Hamra region. Clastic-dominated depositional systems transgressed southwards in the middle to late Carboniferous and gave way to shallow-marine carbonates and evaporites during the Westphalian (Dembaba Formation). By late Westphalian, the rising Hercynian orogenic belt had isolated the central and western Saharan Platform where sedimentation was dominated by continental sands and shales were deposited while carbonate platform deposition prevailed to the east.

Mauretanide–Variscan orogenesis culminated in the mid to late Westphalian with regional uplift and transpression in the Atlas and Anti-Atlas. The interior platform was deformed into a series of broad intracratonic sags, foreland basins, and intervening saddles and arches as far east as western Egypt. Intra-platform structural axes first established in the early Palaeozoic were once again uplifted. The Ougarta, Reguibate and El Biod Arches, and the Meharez and Oued Namous Domes all become strongly positive at this time, as did the Tilrhemt Dome and Dahar Arch (together forming the Talemzane Arch) and the Libyan Gargaf Arch. These were subsequently erosionally truncated and peneplaned during the early Permian to form the residual Palaeozoic basins now subcropping the Hercynian unconformity (Figs 9 and 10).

Tethyan Super-Cycle

With the disassembly of Pangaea in late Palaeozoic–early Mesozoic, the North African Platform became a broad Tethyan-facing passive continental margin (Wildi 1983; Ziegler 1988, 1989; Stampfli *et al.* 1991). A thick succession of Triassic to early Cretaceous sediments was deposited in a vast interior sag basin, the 'Triassic Basin' of eastern Algeria, southern Tunisia and western Libya. Mid to late Cretaceous sediments extend more widely across the Saharan Platform with major rift-related depocentres in the Sirt and Western Desert Basins of eastern Libya and Egypt. Lower Tertiary sedimentation was largely confined to the northern margins of the platform and by Mid-Tertiary Maghrebian orogenesis, and collision with Eurasia, brought the Super-Cycle to a close. The Mesozoic and Cenozoic tectonic and stratigraphic evolution of North Africa is discussed in this volume by Guiraud, Wilson & Guiraud and Macgregor & Moody.

Lower Tethyan Cycle. Late Carboniferous to early Permian rifting and crustal separation was the first step in the break-up of Pangaea with the opening of the Permo-Tethyan seaway and the East Mediterranean Basins (Stampfli *et al.* 1991). Synrift Permian clastics and reefal carbonates were deposited north of the Talemzane–Djeffara Arch (Rigo 1995; Rigby *et al.* 1979), while associated rift shoulder uplift shed continental Tiguentourine clastic deposits south onto the Saharan Platform. Rifting and crustal

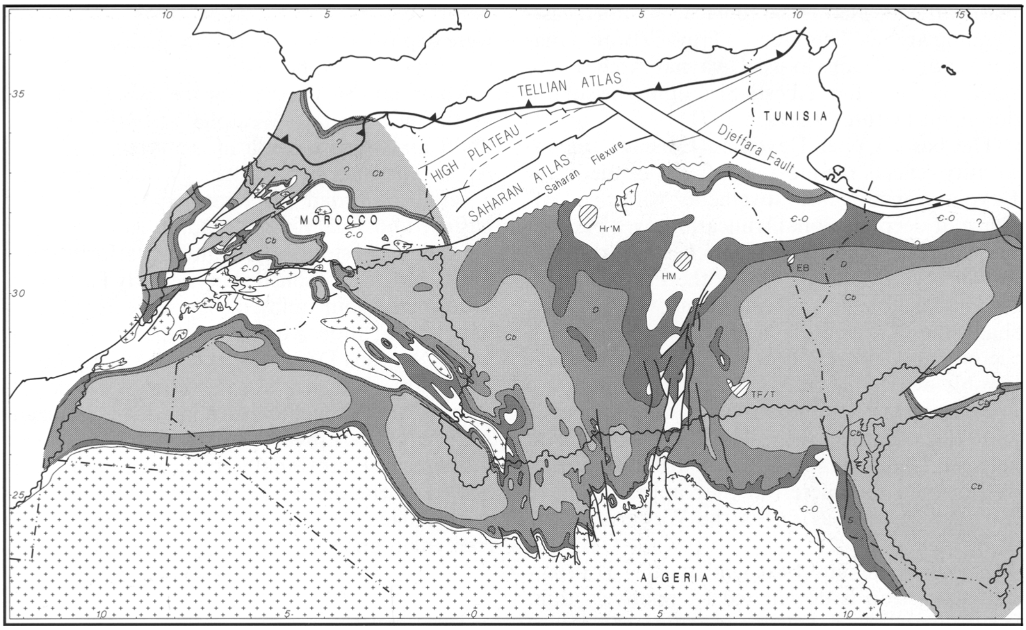


Fig. 9. Palaeozoic outcrop and subcrop distribution below the Hercynian unconformity. The present-day the Ougarta Ridge, Talemzane and Hassi Messaoud Arches, the Gargaf High and the Tibesti–Sirt Arch, modified distribution in the Algerian Atlas and north of the Djeffara fault trend is uncertain and not shown on this map.

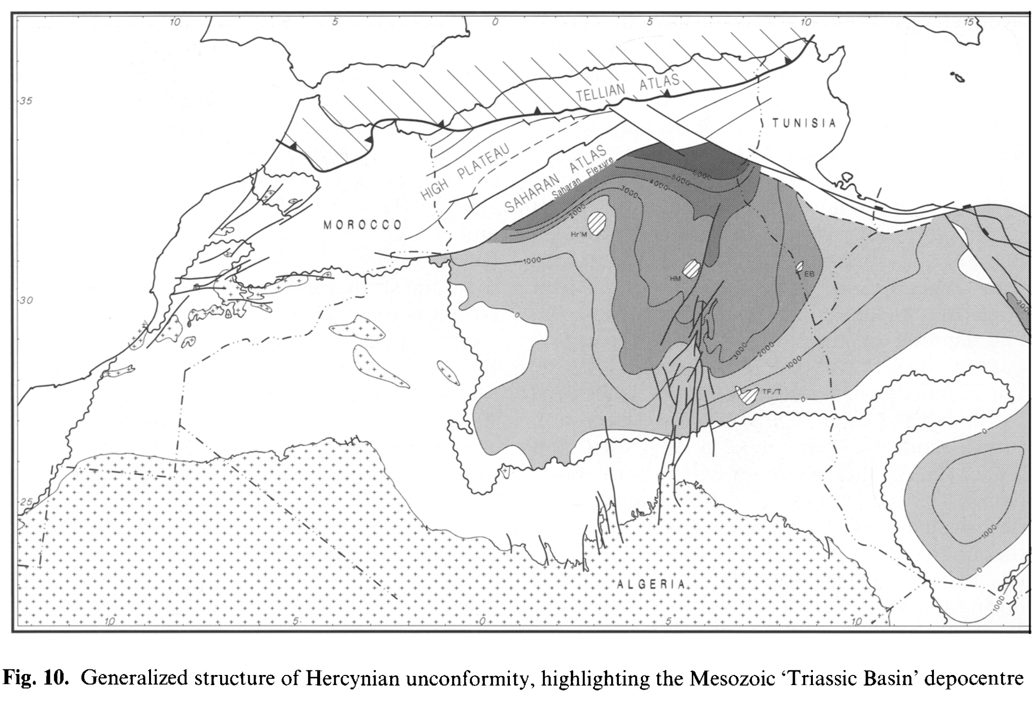
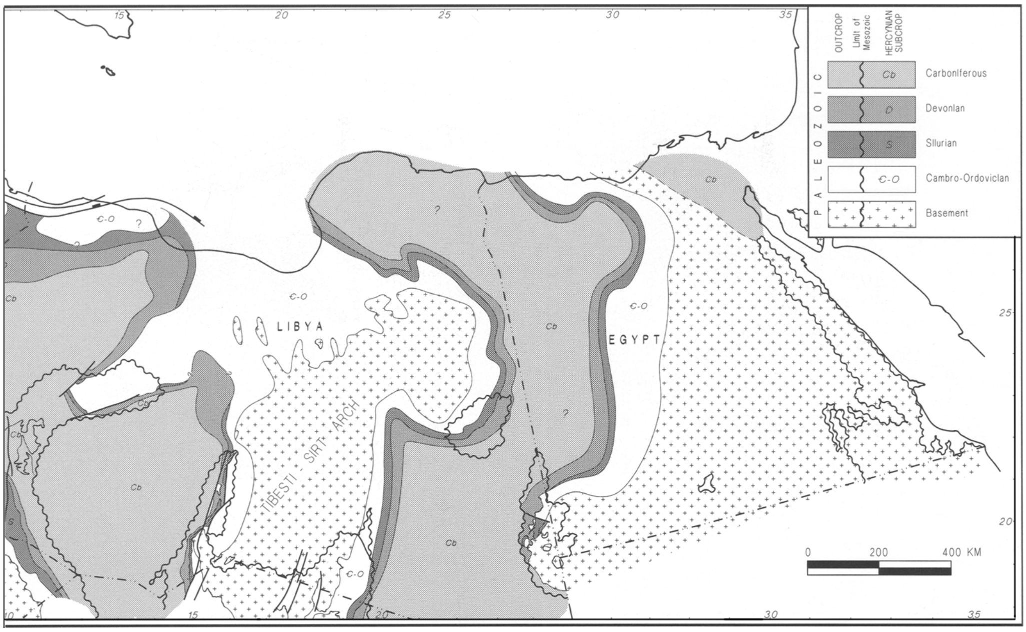
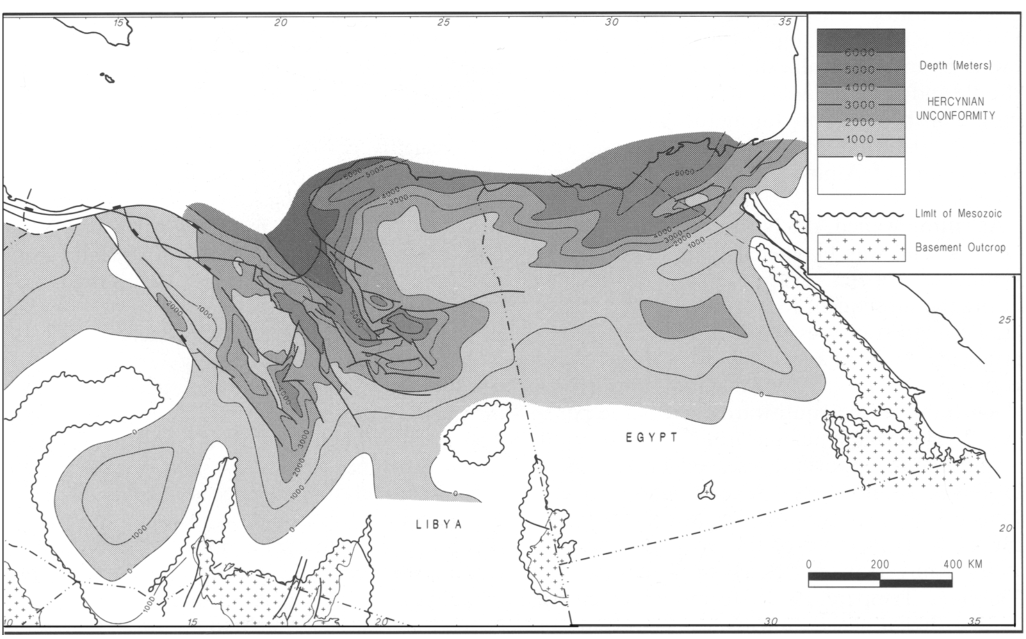


Fig. 10. Generalized structure of Hercynian unconformity, highlighting the Mesozoic 'Triassic Basin' depocentre



distribution of Palaeozoic basins on the North African Platform is a result of late Hercynian uplift and erosion of by later Mesozoic and early Tertiary subsidence associated with rifting and local transpression. Palaeozoic



of Algeria and Cretaceous rift basins of Libya and Egypt.

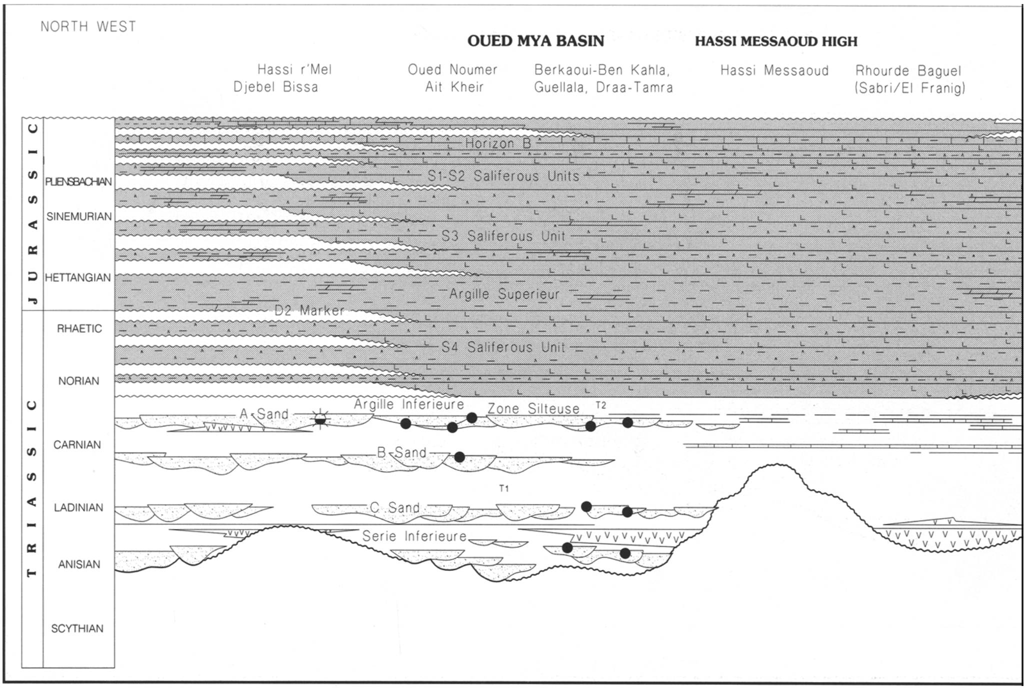


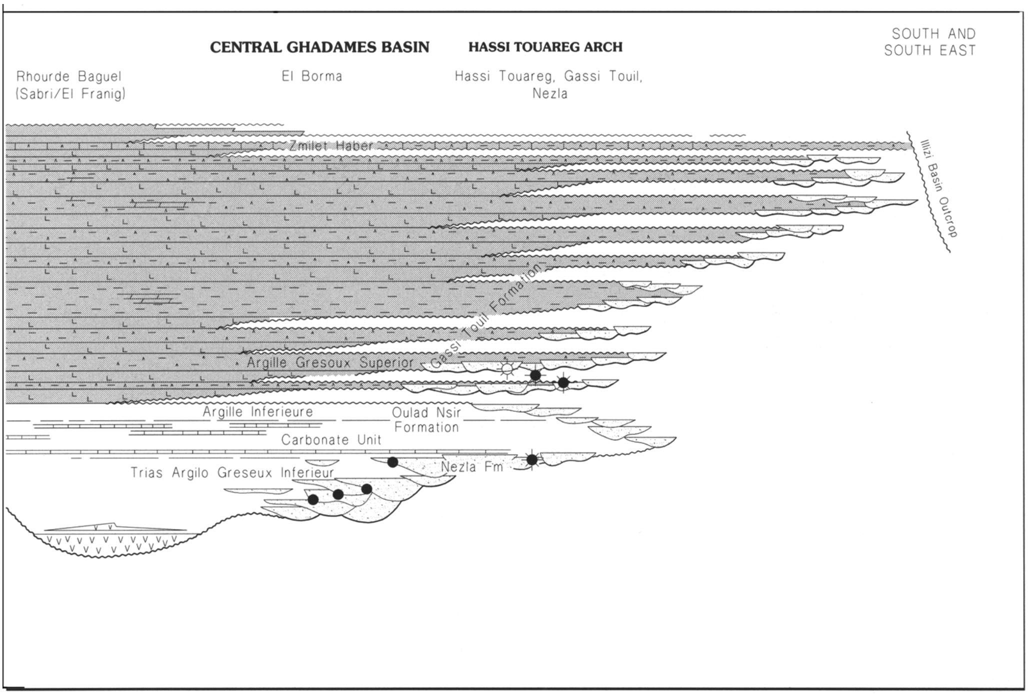
Fig. 11. Generalized lower Mesozoic chronostratigraphy of eastern Algeria. The diagram provides a tentative eastern Algeria and illustrates the diachronous relationship with the Hercynian unconformity surface and the consequently is very approximate. Partly based on information from Claret & Tempere (1967), Ali (1973), Assaad

stretching propagated westwards across the Mauretanide–Variscan orogen during the Triassic with diffuse crustal extension (Andrieux *et al.* 1989; Favre & Stampfli 1992). This was followed by more localized rifting in the High, Middle and Saharan Atlas and along the western margin of the platform during the early Jurassic. Crustal separation followed in mid-Jurassic with the opening of Alpine Tethys and the Central Atlantic.

As rifting waned, the North African Platform subsided and was blanketed by a succession of continental clastics, evaporites and carbonates during the subsequent Mesozoic (Fig. 11). Initial late Permian transgression from the East Mediterranean basin gave way to an extensive sequence of Triassic fluvial sands and shales which transgressed southwards across the peneplaned Hercynian unconformity. These now form the most important reservoir in the 'Triassic Basin' of northeast Algeria and southern Tunisia. The basal 'Triassic Argilo-greseux Inferieur' (TAGI) member of this sequence, and its lateral equivalent in the Hassi Touareg area (Claret & Tempere 1967), forms an extensive braided fluvial sheet sand over a large part of the Ghadames Basin passing laterally to the northwest, into shales and volcanic rocks. It grades upwards into mudstones, lacustrine carbonates and a second sandstone member, the 'Triassic Argilo-greseux Superieur' (TAGS) (Claret & Tempere 1967), laterally equivalent of the late Triassic S4 mudstones and salts (Ali 1973; Busson & Burollet 1973) (Fig. 11) to the north.

A roughly equivalent basal fluvial sand and shale sequence is developed to the northwest and north of the Hassi Messaoud Arch where it provides the reservoir for the north Oued Mya and Hassi R'Mel accumulations. Its precise stratigraphic relationship with the Ghadames sequence is unclear but it may be slightly older in part. The lower basal sand member (Unit C) is confined to erosional irregularities on the unconformity surface but the succeeding sand members (Units A and B) are more widespread, passing upwards into alluvial muds and evaporites of the upper Triassic S4 saline member.

This basal clastic sequence is strongly diachronous grading into Liassic sandstones and shales onlapping the Hercynian unconformity to the south and north into a thick cyclic succession of anhydrites, salts (S1, S2 and S3) and interbedded muds. The sandstones may represent highstand system tracts alternating with low stand evaporite precipitation and desiccation in



chronostratigraphic correlation of the more important basal Triassic sandstone reservoirs of the 'Triassic Basin' of overlying late Triassic–Liassic evaporite sequence. It is based upon very imprecise chronostratigraphic control and (1981), Megerisi & Mamgain (1980) and Bentahar & Ethridge (1991).

a broad alluvial basin, partially restricted from the open Tethyan seaway to the northeast.

Evaporite deposition had largely ended by the late Liassic and the Middle and Upper Jurassic is represented by a backstepping sequence of transgressive marine shales, carbonates and fringing deltaic sands. Regression followed in the Lower Cretaceous with a widespread deltaic system. This was terminated by an early Aptian phase of deformation developed in response to crustal separation and seafloor spreading in the South Atlantic (Guiraud & Maurin 1991; Guiraud 1992). Transpressional wrenching and uplift occurred along pre-existing Palaeozoic and Pan-African crustal heterogeneities with locally intense faulting and uplift. The north–south trending Amguid–Hassi Touareg structural axis was formed at this time and the Tihemboka Arch bounding the southeastern flank of the Illizi Basin and western Murzaq Basin experienced significant faulting and uplift.

Upper Tethyan Cycle. Platform sedimentation continued into the Upper Cretaceous. Intra-platform rifting was renewed in the Abu Gharadig Basin of Egypt and a phase of very rapid subsidence took place in the Sirt rift system during the Senonian. A change in relative plate motion (Savostin *et al.* 1986) between Africa and Eurasia at this time was reflected by mild inversion in the Atlas Basins, Cyrenaica and western Egypt. The platform subsequentially became relatively positive and only very thin successions of lower Tertiary sediments are present over much of the western North African Platform, at least partially as a consequence of later uplift and unroofing. Western Tethys began to close during the early to mid Tertiary with inversion of the Atlas Basin in the early Eocene (Courbouleix *et al.* 1981; Laville 1981; Van Stets & Wurster 1981; Vially *et al.* 1994), coincident with the initial collision of Africa and the Kabylie Block. Convergence with Eurasia accelerated during late Oligocene–Miocene, culminating in Maghrebian folding and nappe emplacement in northern Morocco, Algeria and Tunisia (Caire 1953; Wildi 1983)). A shallow foreland basin developed in the proximal part of the adjacent platform with fault reactivation, uplift of intra-platform highs, tilting and erosional unroofing of the intra-cratonic Palaeozoic basins in the region beyond. Further reactivation and uplift of the inverted Atlas Rift basins occurred during the late Pliocene–Pleistocene in response to dextral wrenching along the South Atlas fracture.

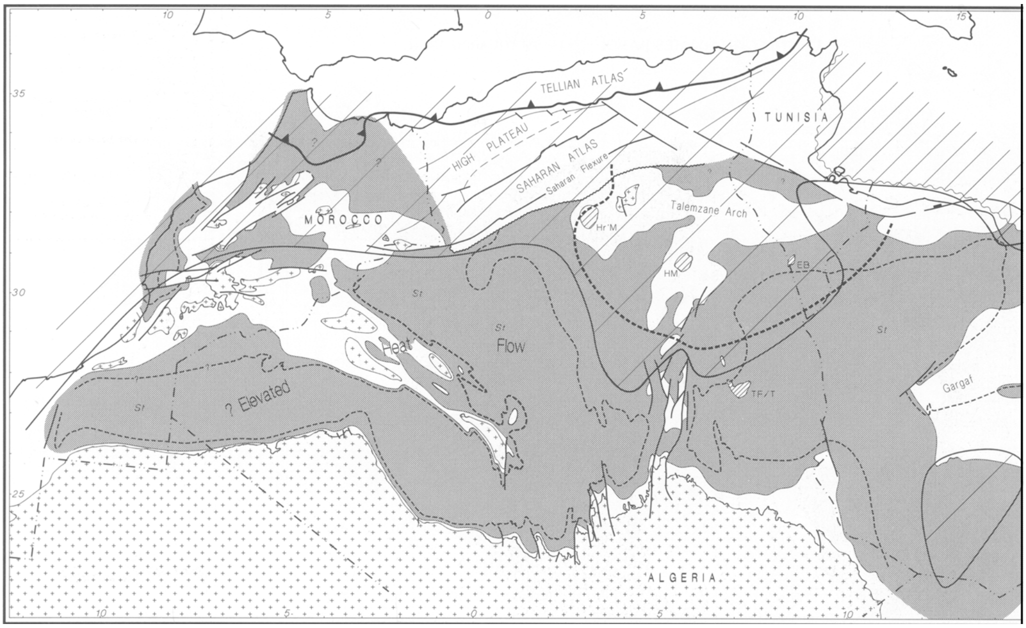


Fig. 12. Regional stratigraphic and structural controls governing the distribution of Palaeozoic petroleum evaporite seals and areas of significant post-Hercynian subsidence are highlighted. With the exception of the Illizi strong positive correlation with these three factors. Pre-Hercynian petroleum systems were probably active in the thus generated were largely dispersed by late Hercynian uplift and unroofing.

Palaeozoic petroleum systems

Introduction

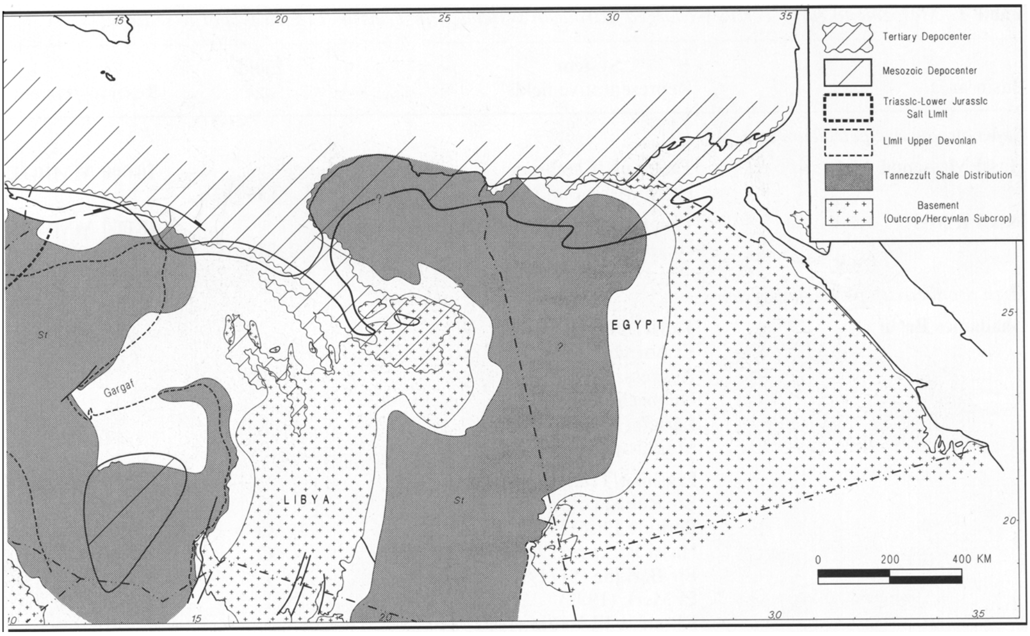
The most significant Palaeozoic-sourced petroleum accumulations of the North African Platform lie in Algeria and western Libya. Within this large area, there is a variety of discrete petroleum systems of widely different hydrocarbon productivity, reservoired in intra-Palaeozoic and basal Triassic sandstones and sealed by intra-Palaeozoic shales or late Triassic–Liassic evaporites. The regional stratigraphic and structural factors responsible for these systems are illustrated in Fig. 12 and include the following.

Distribution of Lower Silurian and Upper Devonian source rocks. Although shales within the Ordovician and Middle Devonian have some limited source potential, the Tanezzuft and Frasnian bituminous mudstones are overwhelmingly the most important Palaeozoic source rocks on the North African Platform. Both were deposited over a wide area of the platform during regional flooding events and their present distribution, preserved within Palaeozoic intra-cratonic depressions, is a result of gentle Hercynian deformation, uplift and erosion.

Presence of intra-Palaeozoic and basal Triassic fluvial sandstone reservoirs. Sandstone reservoirs occur throughout the Palaeozoic, and are of varying quality depending upon facies, age and post-depositional diagenesis. Basal Triassic reservoirs are best developed in the 'Triassic Basin' of Algeria and Western Libya onlapping onto the Hercynian unconformity to the south.

Distribution of intra-Palaeozoic and Triassic seals. Regionally developed shales are commonly developed throughout the Palaeozoic sequence. The Tanezzuft and Middle Devonian are the most significant of these, acting as primary seals for Cambro-Ordovician and Lower Devonian (F6) reservoired petroleum systems. They are limited to the intra-cratonic Palaeozoic depressions and eroded locally allowing migration into lower or higher reservoirs. The Trias–Liassic evaporite sequence provides the primary seal for the basal Triassic reservoired systems. It is confined to the 'Triassic Basin' on the northern part of the Saharan Platform, grading southwards into more proximal clastic facies.

Depocentres capable of maturing and generating hydrocarbons from the Tanezzuft and Frasnian source rocks. The Palaeozoic appears to have



systems. The distribution of the Silurian Tanezzuft and Upper Devonian Frasnian source rocks, Triassic–Liassic Basin, which lacks Triassic reservoir and seal, all the high-productivity Palaeozoic systems of North Africa show a western and southwestern Palaeozoic basins, partly in response to regionally elevated heat flow. Hydrocarbons

thickened regionally towards the west and southwest before Hercynian uplift and erosion, with more rapidly subsiding depocentres developed locally. The Tanezzuft and Frasnian Shales achieved very high maturities in places, as a consequence of increased overburden and regionally elevated heat flow associated with Hercynian igneous activity. Very significant amounts of oil and gas were generated at this time. However, much of this was subsequently dissipated with Hercynian unroofing and residual gas accumulations were only preserved locally. The exhumed basins were never buried deeply enough again to renew generation and much of the western part of the North African Platform is unprospective as a result.

Virtually all the currently active petroleum systems in the region are directly associated with the Mesozoic sag basin ('Triassic Basin') of eastern Algeria.

Migration conduits. Regional continuity of the intra-Palaeozoic and basal Triassic sandstones and seal facies encouraged sometimes very long distance lateral migration and dispersion within the mildly deformed basinal areas. However, fault-related vertical migration is important locally along intra-basinal structural axes and bounding highs, reactivated during the Cretaceous.

Presence of adequate hydrocarbon traps. A wide variety of trapping closures were formed on the Saharan Platform at different times. These range from tight anticlinal folds of the Ahnet Basin to the broad regional domes of Hassi Messaoud and Hassi R'Mel, formed during the Hercynian deformation, to the very high relief wrench fault structures and very subtle low-relief closures of the Ghadames and Oued Mya Basins formed by Austrian and possibly later deformation.

Post-charge dispersal processes. Mid to late Tertiary plate margin orogenesis was responsible for significant uplift and local erosion of the Saharan Platform. This was particularly severe in the south where regional tilting and unroofing encouraged meteoric invasion with increased water flow through intra-Palaeozoic and Triassic aquifers. Mature petroleum systems affected by this late-stage event, were partially and sometimes completely dispersed by spillage, remigration and flushing.

It is the varying effect of these factors upon the petroleum systems in the region that is responsi-

Table 1. *Mesozoic to early Tertiary-charged petroleum systems with Triassic–Liassic evaporite seals*

Basin/area	System Representative fields	Field size	Reserves/system
Super-productive petroleum systems			
Hassi Messaoud Arch	**Tanezzuft/Cambrian**		**10 000 MMBOE**
	Hassi Messaoud (1956)	LG	
Hassi R'Mel	**Tanezzuft/Triassic**		**18 000 MMBOE**
	Hassi R'Mel (1956)	LG	
High productivity petroleum systems			
Ghadames Basin	**Tanezzuft/Triassic**		**750 MMBOE**
	El Borma (1964)	G	
	Keskessa (1969)	S	
	Debbech (1979–81)	S	
	Larich (1979–81)	S	
	Makhrouga (1979–81)	S	
	Frasnian/Triassic		**+2250 MMBOE**
	Bir Rebaa complex (1990)	G	
	Berkine East (1994)	G	
	Hassi Berkine (1994)	G	
	Bir Berkine (S) (1993)	L	
	El Merk (1993)	L	
	Rhourde El Krouf (1992)	L	
	Wadi el Teh (1976)	M	
	Ech Chouech	S	
	Chouech Essaida	S	
Oued Mya Basin	**NE Tanezzuft/Triassic**		**1080 MMBOE**
	Haoud Berkaoui (1965)	G	
	Guellala (1969)	G	
	Ben Khalala (1966)	G	
	Haniet El Beida (1978)	M	
	Draa El Temra (1971)	M	
	N'Goussa (1975)	M	
	NW Tanezzuft/Triassic		**120 MMBOE**
	Oued Noumer (1969)	M	
	Ait Kheir (1971)	S	
El Biod Arch	**Tanezzuft/Cambrian**		**630 MMBOE**
	El Agreb (1960)	G	
	Zotti (1959)	L	
	El Gassi (1958)	L	
Amguid–Hassi Touareg Axis	**Tanezzuft/Triassic (South)**		**2550 MMBOE**
	Rhourde Nouss (1962)	LG	
	Hamra (1959)	G	
	Rhourde Chouff (1963)	L	
	Rhourde Adra (1964)	L	
	Tanezzuft/Triassic (Central)		**950 MMBOE**
	Gassi Touil (1961)	G	
	Brides (1964)	G	
	Hassi Touareg (1960)	L	
	Hassi Chergui (1963)	S	
	Tanezzuft/Cambro-Ordovician (North)		**870 MMBOE**
	Rhourde El Baguel (1963)	G	
	Nezla (1960)	L	
	Messdar (1967)	M	

Notes to Table 1. Petroleum systems are grouped according to their relative productivity and representative fields are listed by size with their discovery date indicated. Approximate total estimated ultimately recoverable reserves are given for each system based upon existing discoveries, and are therefore a minimum amount. Additional discoveries and improved recoveries may increase these figures considerably. A field with significant reserves in secondary reservoirs may be listed under more than one petroleum system. The boundary between the Illizi–Ghadames and the Hamra Basins is taken along the boundary between Libya and Algeria–Tunisia save for D1-52 (Alrar extension) and the giant A1 NC169/Alwafa (adjacent to Alrar), which are taken as part of the Illizi Basin. The division adopted in this table between systems with either Mesozoic or Palaeozoic seals is difficult to apply to the Amguid–Hassi Touareg multiple-reservoir systems. For simplicity, these systems are grouped together on the basis that a salt seal is present within this province. MMBOE, million barrels of oil equivalent; bbls, barrels; LG, large giant fields (recoverable reserves greater than 1000 MMBOE); G, giant fields (greater than 250 MMBOE); L, large field (greater than 100 MMBOE); M, medium-sized field (greater than 25 MMBOE); S, small field (less than 25 MMBOE). The conversion factor used for gas was 5.8 billion cubic feet gas = 1 MMBOE. The definition of a giant field varies widely but the one used here is consistent with Macgregor & Moody (this volume).

ble for their wide range in productivity, from extremely prolific to non-productive or extinct. Each of these systems is reviewed in the following section and the relative influence of the controlling factors is examined in more detail. Emphasis is placed upon the high-productivity petroleum systems, while moderate to non-productive systems are described in less detail. However, a fuller account is given of one of the non-productive or extinct basins, the Tindouf Basin to provide a more complete perspective.

Hydrocarbon productivity was estimated very approximately from reserves so far discovered in each system as listed in Tables 1–3. Inevitably these will increase with new discoveries and enhanced recovery techniques but nevertheless they do provide a relative and semi-quantitative measure, sufficient to permit a general comparison of each system.

The main characteristics of the petroleum systems identified are tabulated in Table 4 and described in the following section. This review is based upon information displayed in the accompanying diagrams constructed from both published sources (cited in the figure captions) and proprietary data/interpretations. Definitions of field size (large giant, giant, medium) referred to in the text and tables are given in the footnotes to Table 1.

Mesozoic to early Tertiary charged systems with Triassic–Liassic seals

Ghadames Basin.

The Ghadames Basin forms part of a broad intra-cratonic Palaeozoic depression east of the Hassi Touareg structural axis and south of the Talemzane Arch (Figs 2 and 13). It plunges northwards unconformably beneath a thick Mesozoic wedge of clastics, carbonates and evaporites which provide reservoir and seal for a number of large accumulations (Van de Weerd & Ware 1994; Echikh this volume). Recent exploration has proven it especially prolific, with reserves of over 3 BBOE and potential for significantly more (Table 1; Macgregor this volume). Much of this is concentrated in the central and northeastern part of the basin in generally subtle low-relief structures. Although it has not been possible to differentiate oils reservoired in the area into discrete families (Daniels & Emme 1995), the regional stratigraphic architecture of the basin suggests the presence of two petroleum systems defined by the relative contribution of the Tanezzuft and Frasnian source rocks. These subcrop the Hercynian unconformity to the west and north, charging basal Triassic sands below Upper Triassic to Liassic shale and evaporite seals. A shaly basal Triassic facies limits the effectiveness of the Tanezzuft in the northwest, separating a Tanezzuft sourced–Triassic reservoired system to the northeast and a Frasnian–Triassic system in the central part of the basin. Regional dip at the unconformity level encouraged long distance, lateral migration through the basal Triassic sands towards the south and east, where the sealing facies grade into continental clastic deposits and both systems are limited by water washing, flushing and dispersion to the surface (Fig. 13).

Tanezzuft–Triassic petroleum system. The Tanezzuft Shale in the Ghadames area ranges in thickness from less than 200 m to over 500 m, thinning over the Ahara Arch and to the northeast. The organically richest interval is a basal 30 m radioactive unit with as much as 17% TOC of predominantly type I–II kerogen (Daniels & Emme 1995). Although the deepest part of the Palaeozoic depocentre is now very mature, it is unlikely to have contributed much to the Triassic petroleum system because of the intervening Devonian and Carboniferous. Instead this was charged by the section immediately below the unconformity, either directly

Table 2. *Mesozoic to early Tertiary-charged petroleum systems with intra-Palaeozoic shale seals*

Basin/area	System Representative fields	Field size	Reserves/system
High productivity petroleum systems			
Illizi Basin	**Lower Tanezzuft/Cambro–Ordovician (I)**		**1500 MMBOE**
	Zarzaitine (1957)	LG	
	Tin Fouye–Tabankort (1961)	LG	
	Edjeleh (1956)	G	
	Alwafa (1991)	G	
	Ohanet (1960)	L	
	Tiguentourine (1956)	M	
	La Reculee (1957)	M	
	Dome a Collenias–Ouan Taredert (1958)	S	
	Upper Tanezzuft/Lower Devonian (II)		**3500 MMBOE**
	Zarzaitine (1957)	LG	
	Tin Fouye–Tabankort (1961)	LG	
	Alrar (1960)	G	
	Edjeleh (1956)	G	
	Alwafa (1991)	G	
	Dimeta Ouest (1979)	G	
	Tin Zemane (1981)	G	
	Stah (1971)	G	
	Timedratine (1961)	L	
	Mereksene (1974)	M	
	Tiguentourine (1956)	M	
	Acheb (1963)	M	
	Dome à Collenias/Ouan Taredert (1958)	S	
	Frasnian/Upper Devonian–Carboniferous (III)		**2000 MMBOE**
	Zarzaitine (1957)	LG	
	Alrar (1960)	G	
	In Amenas Nord (1958)	G	
	Edjeleh (1956)	G	
	Dimeta Ouest (1979)	G	
	Stah (1971)	G	
	Ohanet (1960) (Lower Devonian reservoir)	L	

The petroleum systems and their representative fields are listed as in Table 1. Abbreviations as in Table 1.

from the subcropping shale, or more diffusely through Upper Silurian–Lower Devonian and Cambro-Ordovician sands on either side and vertically via nearby faults and fractures. Peak expulsion is estimated to have occurred during the later Cretaceous and early Tertiary.

The basal Triassic clastic unit, TAGI, is a regionally extensive sheet sand, discontinuous or absent in the northwest and thickening south and east to over 100 m. Porosities range from 17 to 20% and permeabilities between 100 and 450 mD (Boudjema 1987). It formed an excellent conduit and, once charged, encouraged lateral migration towards the southwest for distances of 50 kms and occasionally up to 100 km. Structural relief is very gentle at the unconformity level, with minor perturbations capable of focusing significant amounts of migrating hydrocarbons. The El Borma field is an exception because of its unique position on the culmination of a broad regional high. Although Ghenima (1995) and others have argued that this was charged from the Devonian, its position structurally downdip from the Frasnian subcrop, suggests the Tanezzuft as a more likely source. Elsewhere, accumulations are small in low-relief features draped over deeper Palaeozoic structures. Such traps were especially sensitive to mid–late Tertiary tilting associated with uplift of the Djeffara–Nefusa Arch. Scattered oil and gas shows, and some possible residual oil columns are common in the area, suggesting that pre-existing accumulations may have spilled some or all of their entrapped hydrocarbons during uplift, perhaps accounting for the small size of the fields characteristic of the area. The system is estimated to reservoir 750 MMBOE of which 700 MMBOE. is in El Borma.

Frasnian/Triassic Petroleum System. The Frasnian source rock ranges from less than 25 m to

Table 2. *Continued*

Basin/area	System Representative fields	Field size	Reserves/system
High productivity petroleum systems (continued)			
	Mereksene (1974)	M	
	Tiguentourine (1956)	M	
	El Adeb Larache (1958)	M	
Moderate to low productivity systems			
Hamra Basin	**(North) Tanezzuft/Acacus**		**65 MMBOE**
	NC 100 discoveries (1982–1986)	M	
	Bir Tlacsin (1959)	S	
	Tigi (1961)	S	
	Es Sania (1961)	S	
	(Central) Tanezzuft/Devonian		**250 MMBOE**
	Gazeil (A-1-26) (1959)	M	
	NC005A (O66-Z) (1961)	M	
	O26-Q-001 (Q-1-26) (1965)	M	
	NC007-AA (1981)	M	
	North Gazeil (1960)	S	
	Kabir (1979)	S	
	(South) Tanezzuft/Lower Devonian		**635 MMBOE**
	El Hamra Pools (1960–1962)	G	
	Emgayet (1959)	M	
	O66-LL (1962)	M	
	O66-E (1960)	S	
Murzuq Basin	**Tanezzuft/Cambro–Ordovician**		**600 MMBOE**
	NC 115 discoveries		
	(including Murzuq Field) (1984)	G	
	NC 101 discoveries (1984)	L	
	NC 174 discovery (1993)	S	
Extinct systems			
Kufrah Basins	Immature–marginally mature and flushed		

greater than 100 m in thickness, displaying similar lateral variations to the Tanezzuft. Values of up to 8–14% TOC of oil-prone type I–II kerogen have been reported in a basal radioactive interval, with quality improving to the north. Its maturity generally mirrors the Silurian but at slightly less elevated levels. As in the case of the Tanezzuft, the overlying Triassic sands were probably charged most efficiently from the section immediately below the unconformity, both directly from the subcropping shale and more diffusely through Devonian sands on either side. Because of their relatively higher porosities, this process may have been more efficient than was the case for the Tanezzuft–Triassic system. Furthermore, the Frasnian subcrop lies some distance southeast from the shaly basal Triassic facies responsible for the reduced effectiveness of the Tanezzuft and was ideally positioned to charge the overlying conduit. Perhaps most importantly, a series of fault splays extending northeast from the Hassi Touareg structural axis across the central part of the basin promoted vertical migration through the Carboniferous, directly into Triassic traps above. Two Triassic fluvial sands are present in the area, the basal TAGI and the overlying TAGS reservoirs. As in the Tanezzuft–Triassic system, these encouraged long distance lateral migration towards the southeast. Most of the larger accumulations in the system occur in very low relief traps, a relatively short distance updip of the Frasnian subcrop. This apparent concentration may reflect more efficient local migration focusing by subtle perturbations at the Triassic sand level. As regional structural relief above the unconformity is extremely gentle, these would have become less effective with increasing distance from the subcrop, tending to disperse hydrocarbons widely towards the southeast. Unlike the

Table 3. *Palaeozoic-charged petroleum systems with intra-Palaeozoic shale seals*

Basin/area	System Representative fields	Field size	Reserves/system
Productive systems			
Ahnet/Gourara Basins	**Tanezzuft/Devonian (Cambro–Ordovician)**		**1250 MMBOE**
	In Salah (1958)	G	
	Krechba (1957)	G	
	Teguentour (1973)	L	
	Hassi Moumene (1990)	L	
	Hassi M' Sari (1990)	L	
	Gour Mahmoud (1989)	M	
	Garet El Guefoul (1991)	M	
	Djebel Berga (1953)	M	
	Tit (1956)	S	
Sbaa Basin	**Tanezzuft/Devonian (Cambro–Ordovician)**		**100 MMBOE**
	Hassi Sbaa (1980)	M	
	Oued Tourhar (1991)	M	
	Hassi Ilatou (1983)	S/M	
	Azzene (1959)	S	
	Frasnian/Devonian (Carboniferous)		**50 MMBOE**
	Hassi Sbaa (1980)	M	
	Hassi Ilatou (1983)	S/M	
	Decheira (1987–89)	S	
Extinct systems			
Tindouf Basin	Extremely high maturity—exhumed and flushed		
Reggane Basin	Extremely high maturity—exhumed and flushed		

The petroleum systems and their representative fields are listed as in Table 1. Abbreviations as in Table 1.

Tanezzuft–Triassic system, the Frasnian-sourced accumulations were largely unaffected by mid–late Tertiary tilting and retained their trap integrity to the present time. As a consequence, the system is extremely prolific, with approximately 2250 MMBOE discovered so far and the probability of more to be found.

A number of relatively small Palaeozoic accumulations are also present in the area. The Devonian F6 sand is perhaps the most important reservoir with significant reserves in the Tin Zemane and Bir Rebaa fields. These were probably charged by fault-controlled migration vertically upwards from the Silurian. In contrast, the small Cambro-Ordovician Ain Romana pool was presumably charged by downloading from the basal radioactive member of the Tanezzuft.

Northern Oued Mya–Hassi R'Mel–Hassi Messaoud Province.
The greater Oued Mya Basin is an elongate Palaeozoic cratonic sag, west of the El Biod–Amguid axis, lying unconformably beneath a northeasterly thickening wedge of Mesozoic sediments (Figs 2 and 14). The central and southern part of the basin is unproductive but the northern arm is fairly prolific, with a number of fields reservoired in basal Triassic sandstones sealed by late Triassic evaporites. The super-giant Hassi R'Mel and Hassi Messaoud accumulations lie to the northwest and southeast on flanking Lower Palaeozoic arches (Table 1).

In the northern Oued Mya Basin, the Devonian source rock interval has been entirely removed by Hercynian erosion and all the fields in the province have been charged by Tanezzuft shales still preserved within the basin. Four distinct petroleum systems can be identified, two in the northern Oued Mya limited by deteriorating reservoir updip to the south, and the Hassi R'Mel and Hassi Messaoud systems situated on broad regional structural highs. A fifth petroleum system, the El Biod system, is also included here although it is not certain from which area it received its charge (Figs 14a and 15a).

Tanezzuft–Triassic (NE Oued Mya) system. The Tanezzuft Shale subcrops the Triassic over much of northeast Oued Mya, in an ideal position to charge the overlying sands (Hamouda 1980*a*,*b*). A 20–70 m basal radioactive unit is the richest part organically of the shale, with an average 3–12% of oil-prone kerogen. Accurate reconstruction of its thermal history is difficult because of the uncertain amount of Hercynian erosion. However there is little evidence of significant pre-Hercynian generation and peak oil expulsion is estimated to have occurred during the late Cretaceous to early Tertiary.

The overlying basal Triassic sequence is composed of several stacked fluvial sands interbedded with shales and volcanic rocks (Ali 1973). Porosities range from between 11 and 15% and permeabilities from 130 to 150 mD. Shale and volcanic interbeds acted as intra-formational seals locally but are sufficiently discontinuous to allow migration up into higher sands, while gentle regional dip encouraged long distance lateral migration to the northwest and southeast. Within the central part of the depression, migration was more locally focused along low-relief northeast–southwest trending structural highs. These first developed during a mid-Cretaceous deformational episode and were sometimes enhanced by mid-Tertiary reactivation. Subtle culminations along these axes now provide traps for a series of stacked accumulations culminating with the Hassi Berkaoui field to the south.

Hydrocarbon expulsion from the Tanezzuft source was almost certainly terminated by Miocene uplift and unroofing with little further post-uplift burial capable of renewing generation. Structural readjustment at this time was very gentle and apart from some possible local spillage and remigration, the fields appear to have retained their trapping integrity to the present. The petroleum system is of moderate to high productivity with 1080 MMBOE reserves.

Tanezzuft–Triassic (NW Oued Mya) petroleum system. A number of relatively small oil and gas accumulations occur clustered together in low-relief closures on the northwestern flank of the Oued Mya Basin. The hydrocarbons are reservoired in Triassic sands resting unconformably upon the Cambro-Ordovician and were clearly charged by long distance lateral migration from subcropping Tanezzuft Shale, 20–40 km to the southeast. There is a greater proportion of gas in this system compared with the northeast Oued Mya, reflecting their differing charge history. The area was strongly influenced by the growth of the Hassi R'Mel culmination during the later Mesozoic, when expulsion and migration from the subcropping source rock to the southeast was at its peak. Subtle changes of dip on an otherwise very gentle regional surface may have induced significant changes in preferred migration direction, perhaps responsible for the later charging of the northwestern fields at a time of more elevated source maturity. Only some 120 MMBOE are attributed to this system. It is not clear whether this reflects limited trap size or volume, or relatively ineffective migration focusing.

Hassi R'Mel petroleum system. The Hassi R'Mel gas field lies on the culmination of the broad regional Talemzane Arch, flanked by the Benoud Trough–Atlas Foredeep to the north and the northern Oued Mya depression to the southeast (Magloire 1970). Hydrocarbons are reservoired in three basal Triassic sands (A, B and C) below upper Trias and Liassic evaporites (Hamel 1990). Reservoir continuity is variable, particularly in the lower two sands, reflecting both erosional topography on the unconformity surface and local facies changes. Porosities range up to 20–22% with permeabilities as high as several darcies (Magloire 1970).

The area was part of a southeasterly dipping monocline in the Jurassic and it was only later in the Cretaceous, after the subsidence of the Benoud and Oued Mya basins that the modern closure developed. During the subsequent later Cretaceous and early Tertiary it formed the culmination of a very gently deformed arch, ideally positioned to focus hydrocarbons migrating updip from two large fetch areas to the north and southeast. It is this combination of circumstances which is responsible for its enormous size.

Although predominantly gas, the accumulation includes an oil rim with greater than 300 MMBOE reserves. Subtle changes in the geochemical character of this oil across the field suggest northwesterly migration from the Oued Mya Basin. In contrast, the gas appears to have come from very mature Tanezzuft and possible Upper Devonian source rocks in the Benoud Trough on the northern side of the Talemzane Arch. The system reservoirs 18 000 MMBOE almost entirely within the Hassi R'Mel field itself with a few very small flanking accumulations.

Hassi Messaoud petroleum system. The Hassi Messaoud oil field lies on the culmination of a regional, north–south trending Palaeozoic arch, buried unconformably beneath basal Triassic silts, clays and evaporites (Balducchi & Pommier 1970; Bacheller & Peterson, 1991). Hydrocarbons are reservoired in Cambrian Ra Unit sandstones which subcrop the unconformity in the area of the field. There is also minor production from the R2 unit just below. These sands are usually impermeable and their quality has only been enhanced locally in the Hassi Messaoud area by weathering during Hercynian erosion and exposure. The reservoir is layered, with a

Table 4. *North African Palaeozoic petroleum systems; summary of key factors controlling productivity*

Productivity	Area/basin	Systems	Stage	Trap Style	Trap Age
Mesozoic–Early Tertiary charge; Mesozoic evaporite or shale seal					
Super	Tilrhemt Dome	Tanezzuft/Triassic	Late Mature	L, A	Aust?
	Hassi Messaoud	Tanezzuft/Cambrian	Early Mature	L, A	Herc
High	Ghadames Basin	Tanezzuft/Triassic	Early Mature	L, F	Aust
		Frasnian/Triassic	Early Mature	L, F	Aust
	North Oued Mya Basin	NE Tanezzuft/Triassic	Early Mature	M, F	Herc/Aust
	El Biod Arch	Tanezzuft/Cambrian	Early Mature	L, F	Herc
	Amguid Hassi Touareg Rhourde Chouff	Tanezzuft/Triassic	Late Mature	H, F	Aust
	South Hassi Touareg	Tanezzuft/Triassic	Late Mature	H, F	Aust
	North Hassi Touareg	Tanezzuft/Cambro–Ordovician	Late Mature	H, F	Aust
Mod	North Oued Mya Basin	NW Tanezzuft/Triassic	Early Mature	L, F	Herc/Aust
Mesozoic–Early Tertiary Charge; Palaeozoic shale seal					
High	Illizi Basin	Lower Tanezzuft/ Cambro–Ordovician	Early Destructive	M, F	Herc/Aust
		Upper Tanezzuft/ Lower Devonian	Early Destructive	M, F	Herc/Aust
		Frasnian/Upper Devonian (Cb)	Early Destructive	M, F	Herc/Aust
Mod–low	Hamra Basin	(North) Tanezzuft/Acacus	Early Destructive	M. F	Herc/Aust
		(Central) Tanezzuft/Devonian	Early Destructive	L, F	Herc
		(South) Tanezzuft/Devonian	Late Destructive	L, F	Herc
	Murzuq Basin	Tanezzuft/Cambro–Ordovician	Late Destructive	L	Herc
Extinct	Kufrah Basin	Tanezzuft/Cambro–Ordovician	Extinct	L	Herc?
Palaeozoic charge; Palaeozoic shale seal					
High	Ahnet-Gourara	Tanezzuft/Lower Devonian (Є-O)	Late Destructive	H, A	Herc
Mod–low	Sbaa Basin	Tanezzuft/Devonian (Є-O)	Late Destructive	M, F	Herc
		Frasnian/Devonian (Cb)	Late Destructive	M, F	Herc
Extinct	Tindouf Basin	Tanezzuft/Lower Devonian (Є-O)	Extinct	M, F	Herc
	Reggane Basin	Tanezzuft/Lower Devonian	Extinct	M, F	Herc

Three groups of Palaeozoic-sourced petroleum systems are recognized on the North African Platform: (1) Mesozoic-charged systems with Triassic evaporite seals, (2) Mesozoic-charged systems with intra-Palaeozoic seals and (3) Palaeozoic-charged systems with intra-Palaeozoic shale seals. The key factors governing their productivity are tabulated. The relative effectiveness of each petroleum system can be estimated approximately from the total recoverable reserves (in oil equivalent) reservoired within it. This is a minimum number and may increase with future discoveries and increased recovery efficiencies. Notes: (a) trap style refers to the general structural relief and

Migration drainage	Peak oil expulsion	Phase oil–gas	Impedance	Entrapment style	Post-charge modification	Reserves (MMBOE)
L	K_u–T	Gas >> oil	HI	Ex salt seal large domal closure	Miocene tilting and remigration of oil	18,000
L	K_u–T	Oil >> gas	HI	Ex salt seal large domal closure	Minor Miocene uplift	10,000
L >> V	K_m–T	Oil >> gas	MI	Ex salt seal moderate structure	Minor freshwater flushing	750
L > V	T	Oil >> gas	MI	Ex salt seal moderate structure	Minor freshwater flushing	2250
V > L	K_u–T	Oil >> gas	MI	Gd volcanic seal moderate structure	Minor Miocene uplift	1080
V + L	K_u–T	Oil >> gas	HI	Ex shale seal moderate structure	Minor Miocene uplift	630
V	J–K_L	Gas >> oil	MI	Gd salt seal intense structure	Miocene uplift: Mio–Pliocene subsidence	2550
V	J–K_L	Gas > oil	MI	Gd salt seal intense structure	Miocene uplift: Mio–Pliocene subsidence	950
V + L	J–K_L	Oil > gas	MI	Gd salt seal intense structure	Miocene uplift: Mio–Pliocene subsidence	870
L	K_u–T	Oil > gas	LI	Ex salt seal major structure	Miocene tilting and remigration of oil	120
L + V	T_R–T Pre-Herc?	Gas > oil	MI	Gd shale seal moderate structure	Tertiary tilting, spillage, remigration, freshwater flushing	1500
L + V	T_R–T Pre-Herc?	Oil > gas	MI	Gd shale seal moderate structure	Tertiary tilting, spillage, remigration, freshwater flushing	3500
L + V	K_L–T	Oil ≈ gas	MI	Gd shale seal moderate structure	Tertiary tilting, spillage, remigration, freshwater flushing	2000
V > L	K_L–T	Oil >> gas	LI	F shale seal minor structure	Major Tertiary tilting, spillage, remigration, freshwater flushing	65
L	K_L–T	Oil >> gas	LI	F shale seal minor structure	Tertiary tilting, spillage, remigration, freshwater flushing	250
L > V	K_L–T	Oil >> gas	LI	F shale seal minor structure	Major Tertiary tilting, spillage, remigration, freshwater flushing	635
L	K_u–T	Oil >> gas	MI	Ex shale seal minor structure	Tertiary uplift, spillage remigration, freshwater flushing	600
L?	T?	Oil?	LI	P shale seal minor structure	Tertiary uplift, spillage remigration, freshwater flushing	–
V	Herc	Gas >> oil	HI	Gd shale seal major structure	Hercynian uplift, thermal event; Tertiary uplift	1250
V	Herc	Oil >> gas	MI	Gd shale seal moderate structure	Hercynian uplift, Tertiary flushing	100
V	Herc	Oil >> gas	MI	F shale seal moderate structure	Hercynian uplift, Tertiary flushing	50
V + L	Herc	Gas >> oil	LI	F shale seal moderate structure	Hercynian uplift, thermal event; Tertiary uplift	–
V	Herc	Gas >> oil	LI	F shale seal moderate structure	Hercynian uplift, thermal event; Tertiary uplift	–

character of the traps where relief is indicated as high (H), moderate (M) or low (L), and further qualified as being either anticlinal (A) or faulted (F); (b) important trap-forming orogenic phases are indicated as Hercynian (Herc) and Austrian (Aust); (c) migration drainage is indicated as vertical (V) or lateral (L); (d) the critical period of peak oil generation is estimated; (e) the impedance of each petroleum system is indicated as high (HI), moderate (MI) or low (LI), and further qualified by the intensity of structural deformation and the general lithology and nature of the seal (Ex, excellent; Gd, good; F, fair; P, poor).

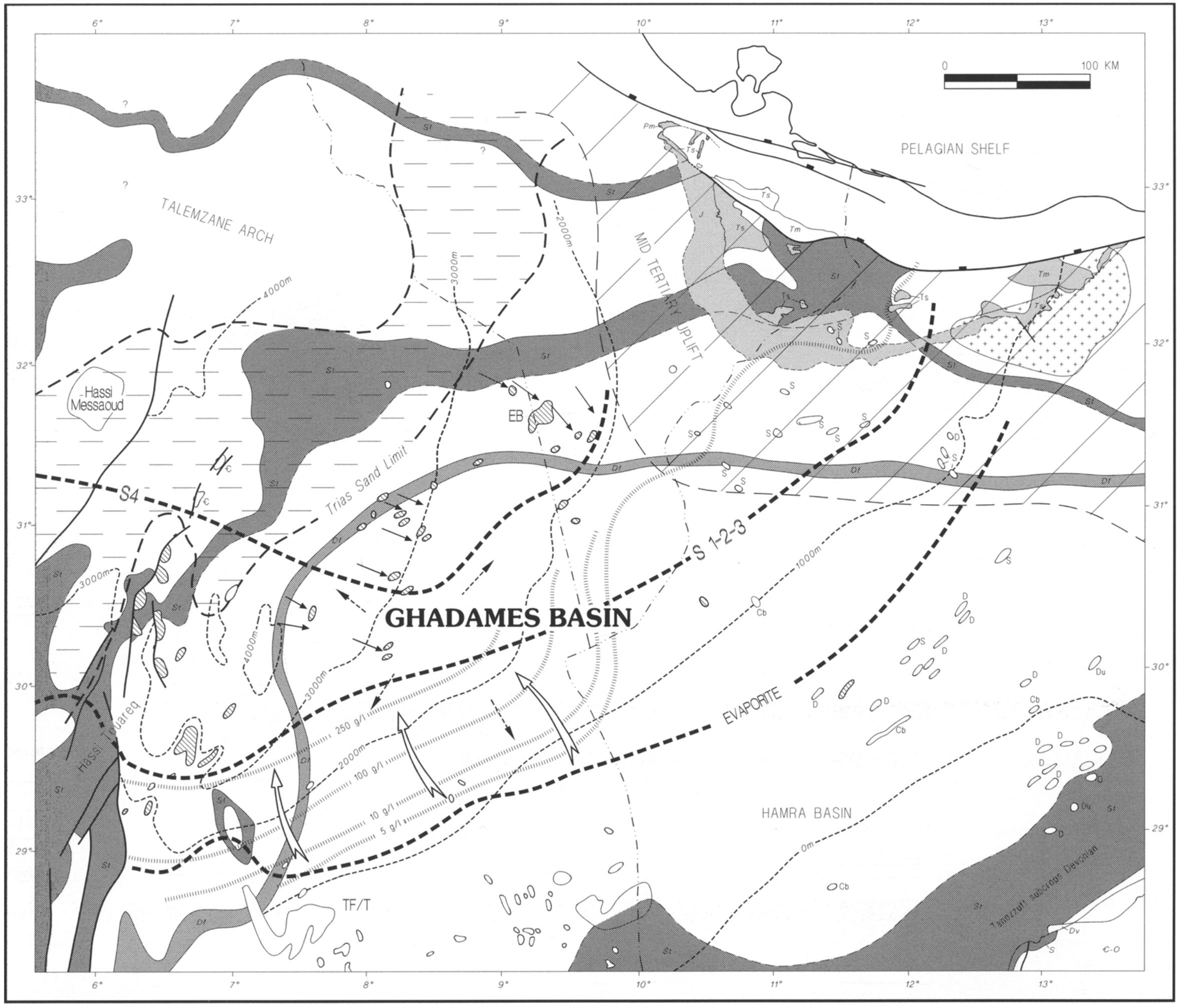


Fig. 13. **(a)** Ghadames Basin petroleum systems summary map (see Fig. 2 for location). Two petroleum systems are recognized in the Ghadames area reservoired in Triassic sands, one in the central part of the basin charged by Frasnian shales and a second to the northeast charged by the Tanezzuft. The subcrop of the Tanezzuft and Frasnian source rocks to the Hercynian unconformity is highlighted and preferential migration directions within the Triassic sandstone conduit are indicated by arrows (see depth contours on Hercynian unconformity). Oil and gas accumulations reservoired in the Triassic are shown by a hachured pattern. The systems are limited by basal Triassic shale facies to the northwest, and loss of Triassic–Liassic evaporite seals by lateral facies change to the south. Preferential intra-Palaeozoic migration directions are indicated by broken arrows. Late-stage meteoric invasion and freshwater flushing from the south are suggested by open arrows and isosalinity contours (after Chiarelli 1978). (Refer to the legend for further detail.) Partly based on information from Bishop (1975), Sonatrach (1979), Hamouda (1980), Bentaher & Ethridge (1991), Emme & Sunderland (1991), van de Weerd and Ware (1994), Daniels & Emme (1995), Gauthier *et al.* (1995).

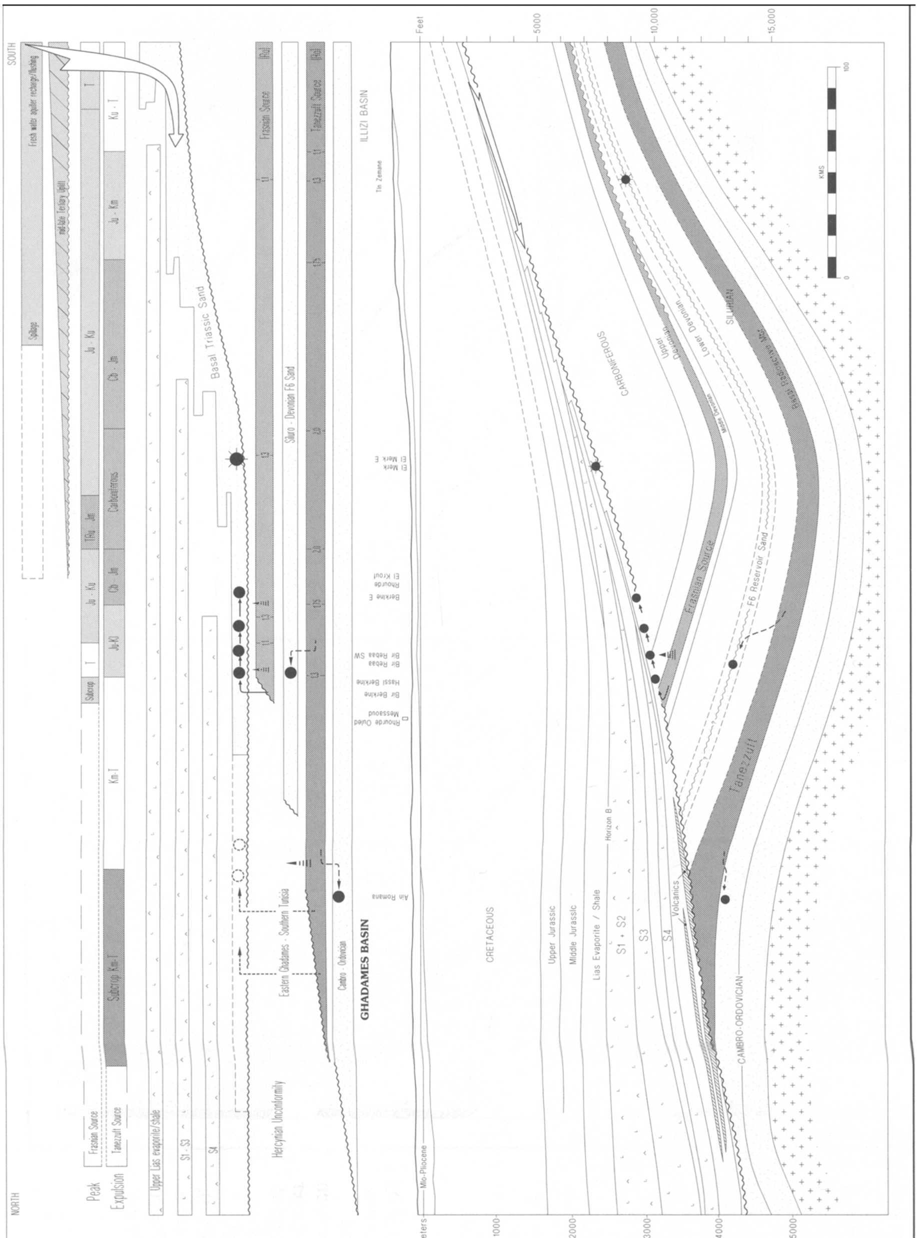


Fig 13. (**b**) Critical elements analysis for Ghadames Basin petroleum systems, illustrating the spatial relationship and relative timing of critical structural, stratigraphic and thermal variables controlling hydrocarbon distribution in the basin and highlighting their relative timing. Although Tanezzuft and Frasnian sources matured early within the deepest part of the Palaeozoic basin, most of the hydrocarbons reservoired in the two systems were probably generated later from the subcropping shales directly into overlying Triassic conduits and via porous units above and below. The main phase of charging is estimated to have started in mid-Cretaceous with short to long distance, high-impedance lateral migration towards the southwest. Prospectivity decreases to the south with the loss of seal and late Tertiary meteoric invasion. (Refer to the legend for more detail.) It should be noted that petroleum system data from out of the line of section are displayed with dashed lines.

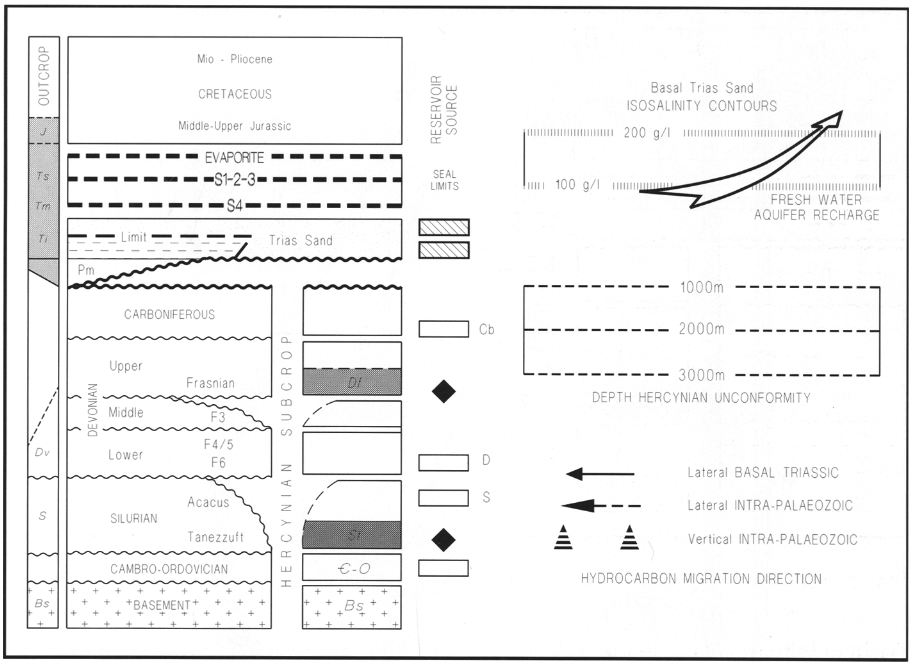


Fig 13. Legend. Ghadames Basin petroleum systems. Schematic stratigraphy (divided into outcrop map notation on left and subcrop notation on right), illustrates main source rocks (lozenge symbols) and main reservoir rocks (rectangles), the reservoir of the primary play being hachured.

thin impermeable cap at the unconformity surface passing down into sands with variable porosities and permeabilities ranging between 2 and 11% (average 8%) and 0 to 1000 mD.

The field was charged by long distance migration from Tanezzuft Shale in the Oued Mya Basin (Bacheller & Peterson 1991). With few structural barriers, migration was very efficiently focused by the Hassi Messaoud Arch, first through Triassic sands and then perhaps along the weathered unconformity surface towards the crest of the structure where these pass into shales. Basal Triassic incised sand-filled fluvial channels may have enhanced this process significantly. The field was unaffected by mid-Cretaceous deformation and later Tertiary uplift and erosion, with little or no subsequent loss of trap integrity. Some 10 000 MMBOE are reservoired in the accumulation.

El Biod petroleum system. The El Agreb, Zotti and El Gassi oil fields are clustered together to form a second discrete petroleum system further south along the Hassi Messaoud Arch (Figs 14a, and 15). They are similar to the Hassi Messaoud field, with Cambrian reservoirs and a Triassic shale and silt seal (Ali 1975). Charging may have been southwards by spillage from Hassi Messaoud or more laterally from Tanezzuft Shale preserved in a separate Palaeozoic depression immediately to the east. Approximately 630 MMBOE are reservoired in the three accumulations.

North Talemzane Arch. Four oil and gas condensate fields (including Sabri and El Franig) have been discovered in southern Tunisia, on the northern flanks of the Talemzane Arch (Cunningham 1988; Rigo 1996). One is reservoired in basal Triassic sands and sealed by shales and evaporites, and the others are reservoired within fractured Ordovician sandstones unconformably beneath Triassic shales. All four accumulations were clearly sourced from mature Tanezzuft shales which subcrop the Hercynian unconformity in the immediate area. Although they are very small they are significant, proving the presence of an active petroleum system(s) on the north side of the Arch. It is possible that further exploration may extend the system to the west although it is limited in the east by the Djeffara–Nefusa Uplift (Rigo 1996).

Amguid Spur–Hassi Touareg Axis.

The Amguid Spur–Hassi Touareg Axis is a complex north-plunging ridge of en echelon horsts and faulted anticlines, bounded by the El Biod Arch and Oued Mya Basin to the west and the

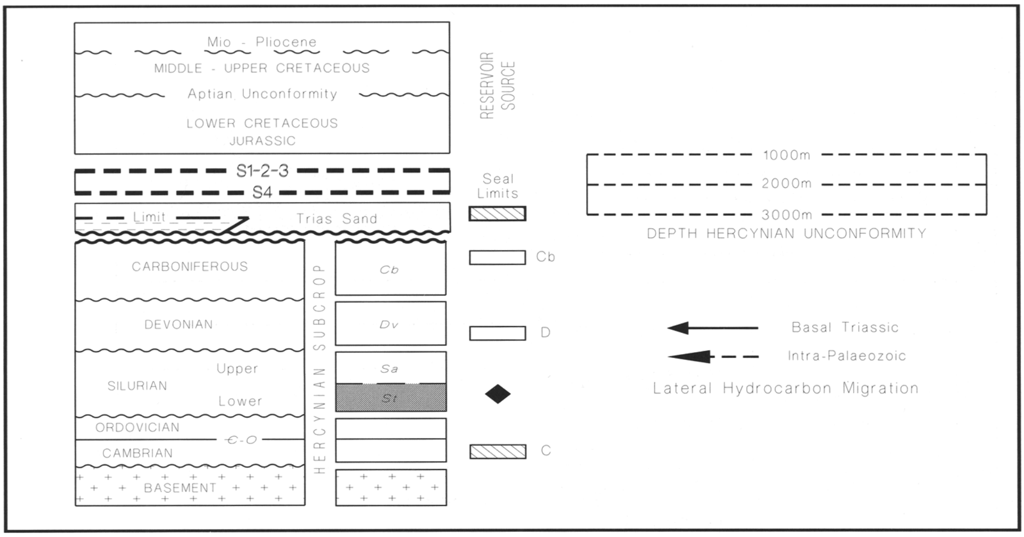


Fig. 14. Legend. North Oued Mya, Hassi R'Mel and Hassi Messaoud-El Biod Arch petroleum systems.

Ghadames Basin in the east (Figs 2 and 15). The ridge developed during the mid-Cretaceous Austrian phase of transpressional wrench deformation and very pronounced high relief structural traps were formed at this time. These reservoir large gas, gas condensate and oil accumulations in Triassic and fractured Palaeozoic sands, sealed by overlying and across-fault shales and evaporites (Table 1). The accumulations were charged by Tanezzuft Shale from a depocentre flanking the eastern side of the axis. Peak oil expulsion maturities were reached before mid-Cretaceous deformation over much of this depression and the Austrian-aged traps were charged later with gas and gas condensate and lesser amounts of oil as maturities increased during the later Cretaceous and early Tertiary. Unlike petroleum systems in the neighbouring basins, large displacement faulting encouraged vertical migration, and multiple stacked reservoirs are common. In some parts of the Hassi Touareg trend faulting has been too severe, offsetting reservoir against Cretaceous sands and limiting trap volume.

Three petroleum systems can be distinguished, a Tanezzuft–Cambrian one to the north and two Tanezzuft–Triassic systems along the southern part of the Hassi Touareg Axis and southeast in the Rhourde Chouff area (Figs 2 and 15).

Rhourde Chouff Tanezzuft–Triassic petroleum system. There are several large gas condensate and oil accumulations on the Rhourde Chouff structural alignment reservoired in basal Triassic sands. These occur within high-relief Austrian aged structural traps charged by relatively long distance lateral migration from the north and perhaps by vertical migration via faults from the underlying Tanezzuft. The southern boundary of the system is defined by the stratigraphic limit of the Triassic–Liassic evaporite seal. It reservoirs some 2550 MMBOE.

South Hassi Touareg Tanezzuft–Triassic petroleum system. The southern Hassi Touareg accumulations are trapped within very high relief mid-Cretaceous fault blocks. Hydrocarbons are reservoired in two stacked basal Triassic fluvial sands charged by vertical and short distance lateral migration from subcropping Tanezzuft Shale nearby. The reservoir sand grades into alluvial silts, shales and mudstones immediately to the north, which define the limit of the system (Claret & Tempere 1967).

The combined reserves of the accumulations within this system are only 950 MMBOE despite the very large structures, because effective trap volume has been limited by across fault seals.

Tanezzuft–Cambro-Ordovician petroleum system. Two oil and gas fields, Messdar and Rhourde El Baguel, are located along the northern part of the Amguid Spur–Hassi Touareg ridge, trapped within wrench-generated horst blocks. In contrast to the accumulations further south, the hydrocarbon phase in both fields is dominated by oil (with subsidiary gas), reservoired in fractured Cambrian sandstones. The stratigraphic architecture of the area surrounding the two fields suggests they were charged by long distance lateral migration immediately

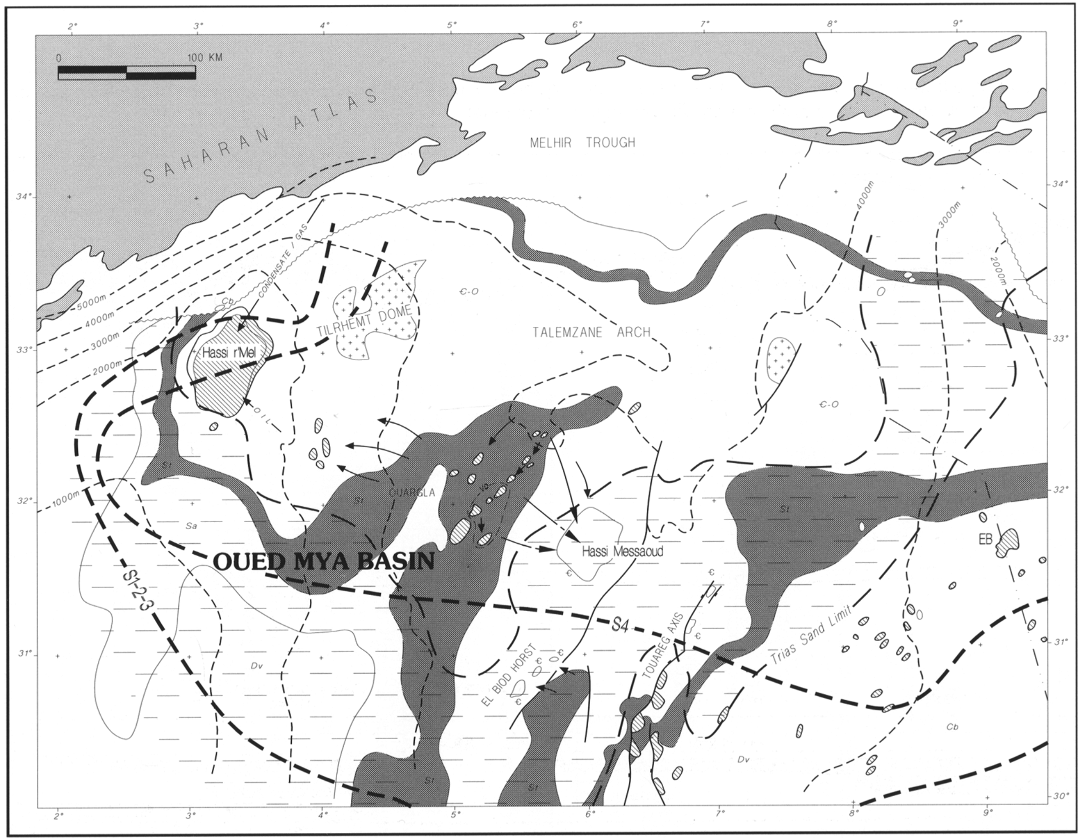


Fig. 14. **(a)** North Oued Mya, Hassi R'Mel and Hassi Messaoud–El Biod Arch petroleum systems (See Fig. 2 for location). Five petroleum systems are recognized in the northern Oued Mya Basin and adjacent areas: (1) the northeastern Oued Mya Basin system with basal Triassic reservoirs charged directly from unconformably underlying Tanezzuft Shale, (2) the northwestern Oued Mya System with Triassic reservoirs charged by long distance lateral migration from the southeast, (3) Hassi R'Mel gas field with a Triassic sandstone reservoir charged by gas and condensate from the northern Benoud Trough and oil from the southeast in late Cretaceous–early Tertiary, (4) the Hassi Messaoud oilfield with a weathered Cambrian reservoir sealed by Triassic shales unconformably above and charged by long distance migration from the Oued Mya Basin and (5) the El Biod system with Cambrian reservoirs charged by a Tanezzuft depression to the east or possibly by spillage from the Hassi Messaoud accumulation (Fig. 15b). A group of fields in southern Tunisia on the northern margin of the Talemzane Arch demonstrates the existence of another, poorly known petroleum system(s). The Tanezzuft subcrop within the northern Oued Mya Basin is highlighted and the stratigraphic limits of the Triassic reservoir sandstone and overlying sealing evaporite units are indicated. The distribution of a Triassic volcanic and shale sequence which forms an intraformational seal in the northeastern part of the Oued Mya Basin is also shown. (Refer to the legend for more detail.) Partly based on information from Balducchi & Pommier (1970), Magloire (1970), Aliev *et al.* (1971), Ali (1973), Ali (1975), Hamouda (1980*a*), Hamouda (1980*b*), Assaad (1981), Bacheller & Peterson (1991), Benamrane *et al.* (1993) and Yahi and Khatir (1995).

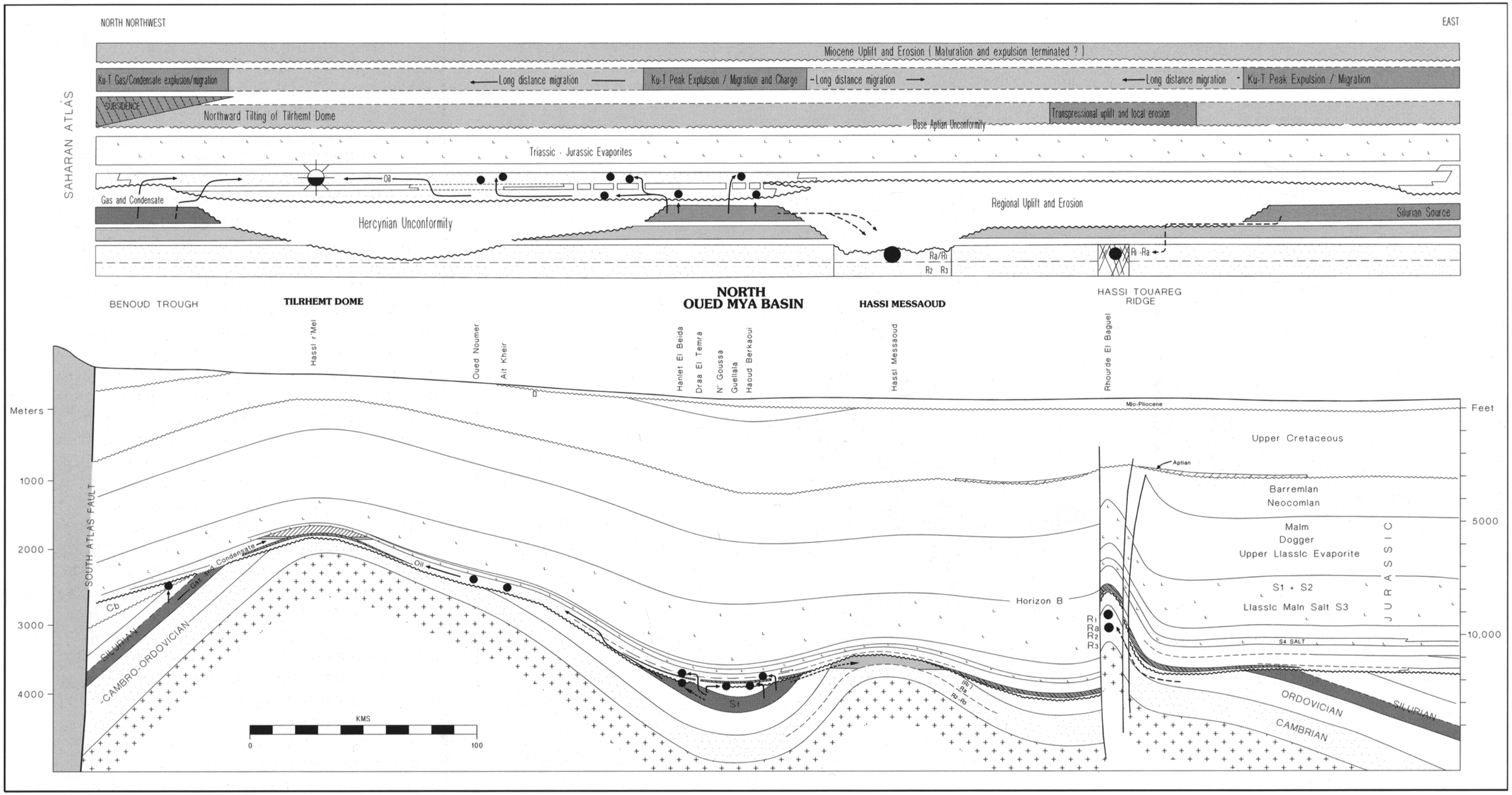


Fig. 14 (**b**) Critical elements analysis for North Oued Mya, Hassi R'Mel and Hassi Messaoud–El Biod petroleum system, illustrating the spatial relationship and relative timing of key structural, stratigraphic and internal factors controlling hydrocarbon distribution in the area. The five systems recognized in this area were all charged by high-impedance short to long distance lateral migration with only a minor component of vertical migration.

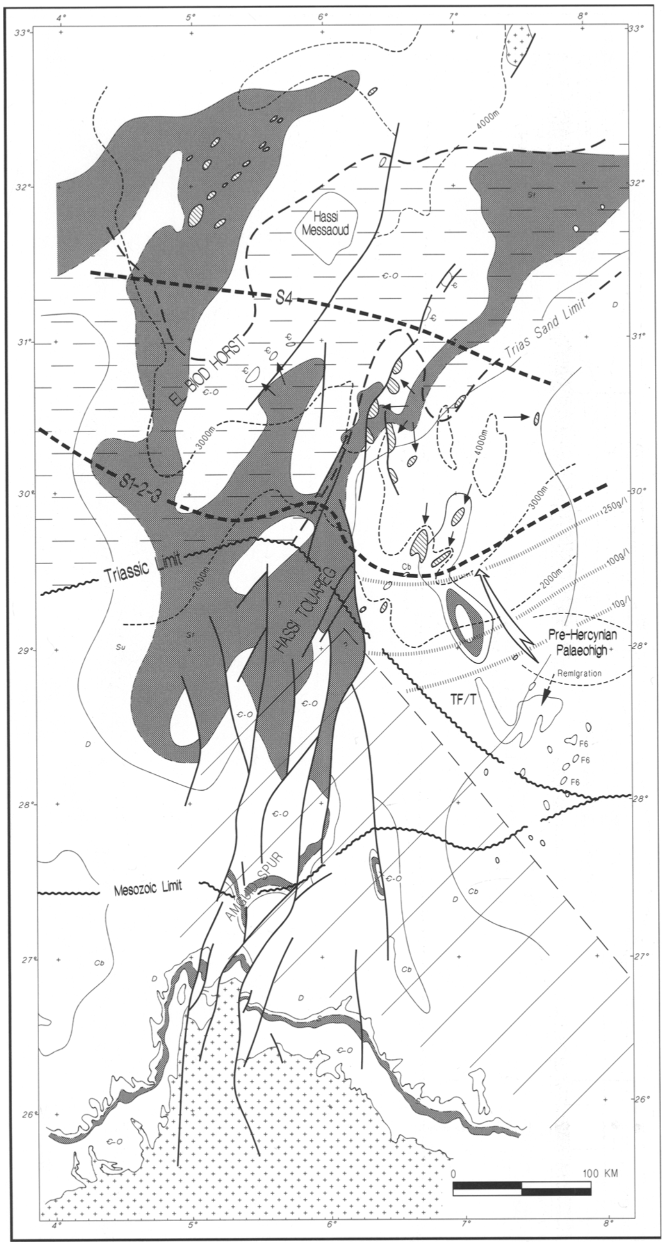


Fig. 15. (**a**) Amguid–Hassi Touareg Ridge petroleum systems summary map (see Fig. 2 for location). Three petroleum systems are recognized along the mid-Cretaceous (Austrian) Amguid–Hassi Touareg Ridge, all in high-relief structural traps sealed by overlying and across-fault Triassic and Jurassic shales and evaporites. These are (1) a southern Triassic reservoired system on the Rhourde Chouff Alignment (140 km NW of TF/T) charged by subcropping Tanezzuft Shale to the north and locally by vertical migration from the Silurian below, (2) a Triassic reservoired system along the southern part of the Hassi Touareg horst complex charged locally by Tanezzuft Shale and (3) a Cambrian reservoired system along the northern part of the Hassi Touareg axis (Fig. 14b). The north–south trending mid-Cretaceous ridge with its bounding faults is shown schematically. Triassic sandstone reservoir and evaporite seals limits are highlighted. Triassic reservoired oil and gas fields are indicated with a hachured pattern and postulated migration directions are indicated with arrows. (Refer to the legend for more detail.) Partly based on information from Claret & Tempere (1967), Aliev *et al.* (1971) and Ali (1975).

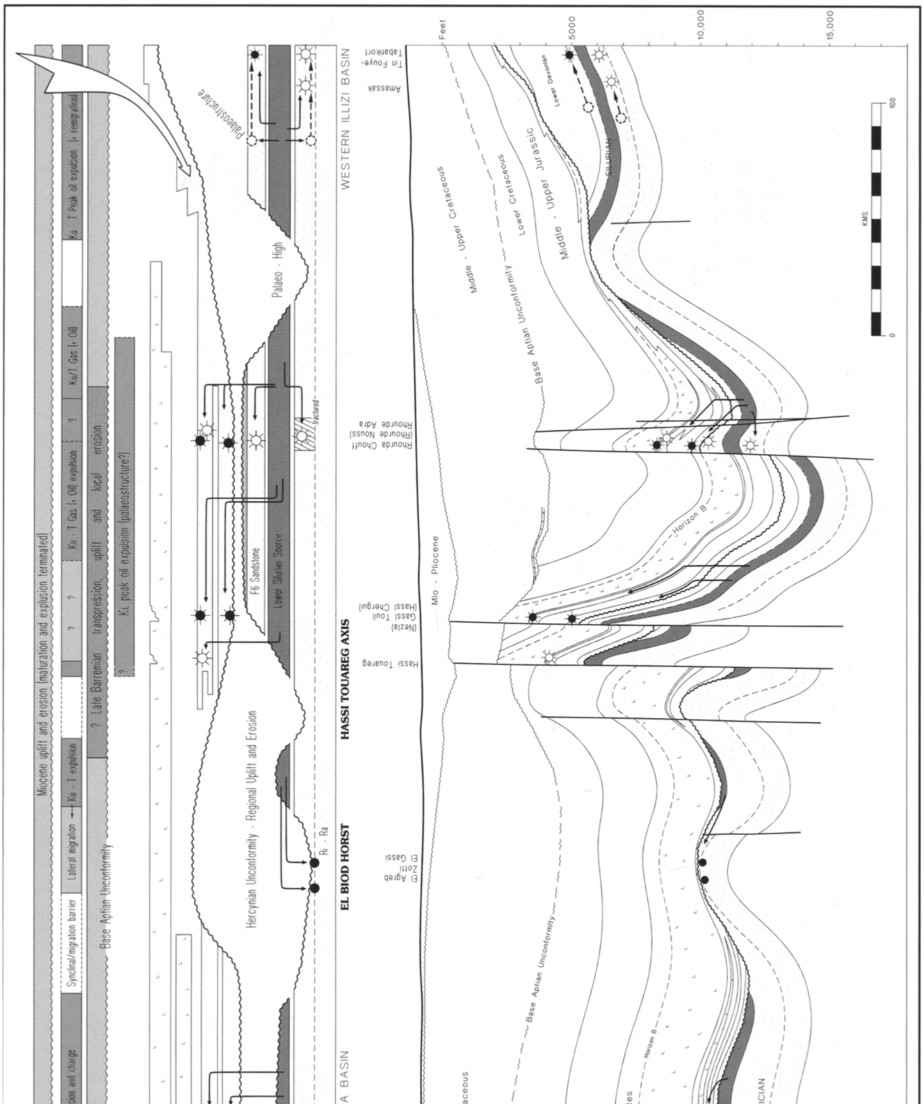


Fig. 15 (**b**) Critical elements analysis for Amguid–Hassi Touareg Ridge petroleum systems, illustrating the spatial relationship and relative timing of key structural, stratigraphic and thermal variables controlling hydrocarbon distribution along the Amguid–Hassi Touareg structural ridge (adapted from Claret & Tempere (1967)). Burial history analysis suggests that peak oil generation occurred before the mid-Cretaceous transpressional deformation responsible for the structural axis, and traps formed at that time were subsequently charged by high-maturity gas and oil in later Cretaceous and early Tertiary. The southern two systems were charged by lateral migration from subcropping Tanezzuft source rocks to the east with significant vertical migration locally up trap bounding faults (and underlying Tanezzuft). The northern system was charged by long distance lateral migration from the east along the unconformity surface and perhaps thin sands above. Preferred migration directions are indicated.

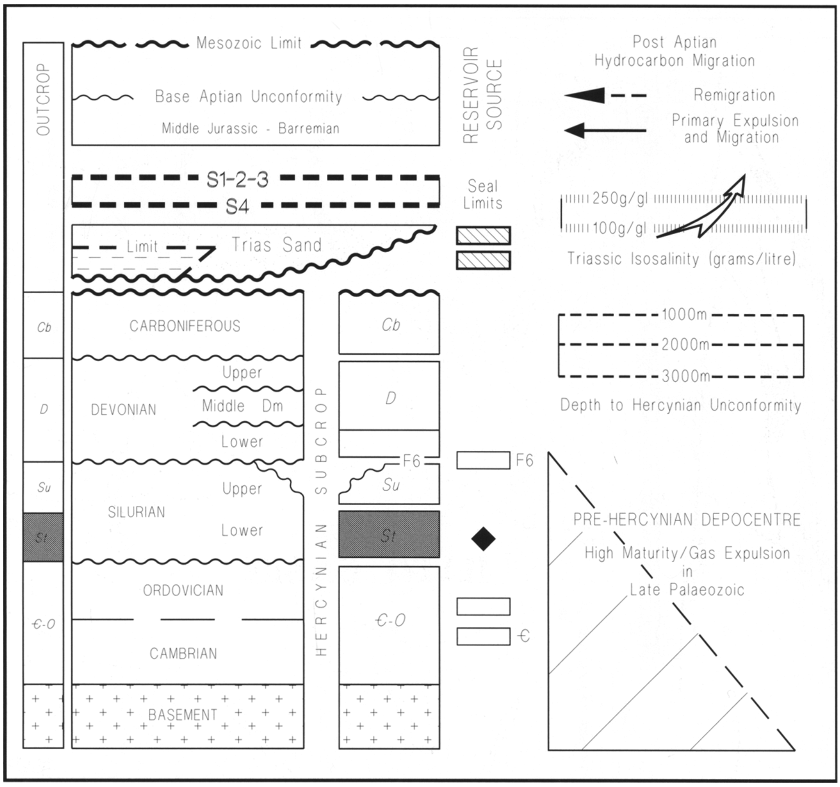


Fig. 15. Legend. Amguid–Hassi Touareg Ridge petroleum systems.

along the Hercynian unconformity surface, from Tanezzuft Shale some distance to the east. The system appears to be trap limited, with only 870 MMBOE reserves discovered so far.

Mesozoic to early Tertiary charged systems with Palaeozoic shale seals

Illizi Basin.

The Illizi Basin (Figs 2 and 16) forms the southern part of a broad intra-cratonic Palaeozoic depression extending over the greater Ghadames–Hamra region. It is flanked by the Amguid Spur to the west and the Tihemboka Arch to the east. The Palaeozoic crops out to the south towards the Hoggar Massif and plunges north below a thin unconformable Mesozoic cover. Its northern boundary is generally defined as the proximal limit of the Liassic evaporite sequence.

The basin is extremely prolific with eight fields of over 250 MMBOE and total reserves of approximately 7 BBOE (Table 2). As in the Ghadames area to the north, the Tanezzuft and Frasnian source rocks are both preserved in the basin, charging fluvial, estuarine and shallow marine sandstone, ranging from Cambro-Ordovician to Carboniferous in age (Chiarelli 1978; Tissot *et al.* 1984; Van de Weerd & Ware 1994; Daniels & Emme, 1995). Interbedded marine shales provide seals of varying effectiveness. The area is only very gently deformed and regional stratigraphic continuity tended to encourage long distance lateral migration. However, vertical migration was important locally through erosional windows in intra-formational shale seals, and also in proximity to the Tihemboka Arch, where faulting was more common.

The basin experienced a long but relatively simple history, punctuated by Hercynian, Austrian and mid–late Tertiary deformational events. During the Palaeozoic, a thick sequence of sediments accumulated in a depocentre immediately southwest of the modern basin (Tissot *et al.* 1984). Tanezzuft shales within this depocentre achieved very high maturities (+1.75% *R*o) before the Hercynian and generated large

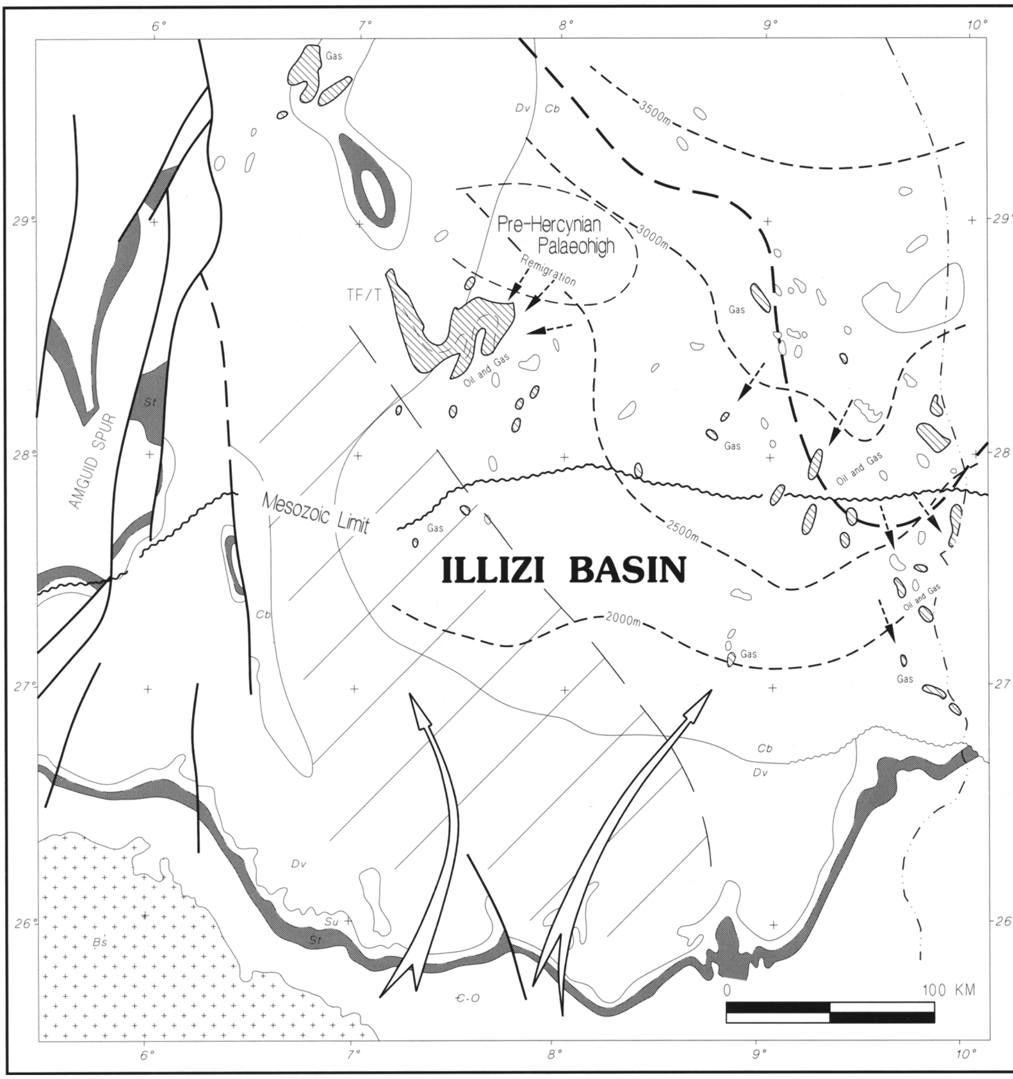


Fig. 16. (**a**) Illizi Basin: Lower Silurian/Cambro-Ordovician Petroleum System I (see Fig. 2 for location). Three active and one extinct petroleum systems are recognized in the Illizi Basin: (1) a late Palaeozoic system charged from a depocentre to the southeast and subsequently dispersed during Hercynian (and Austrian) uplift and unroofing, (2) a Cambro-Ordovician system (System I) charged by the Lower Tanezzuft, (3) a Lower Devonian reservoired system (System II) charged by Upper Tanezzuft Shale and (4) an Upper Devonian–Lower Carboniferous reservoired system (System III) charged by Frasnian shales, from the northeastern depocentre and flanking areas to the northeast. The outcrop and Mesozoic subcrop of the Lower Tanezzuft source rock responsible for System I are indicated. Cambro-Ordovician oil and gas accumulations are highlighted with a hachured pattern and preferred lateral migration directions are shown by dashed arrows. The estimated present-day oil–gas maturity transition within the Mesozoic depocentre is shown by a dashed line and the exhumed pre-Hercynian depocentre southwest of the basin is indicated by diagonal lines. Source rocks in this area are thought to have charged palaeo-highs on the adjacent platform which subsequently remigrated into new structures after Austrian uplift and tilting. Late-stage meteoric invasion and flushing from the south is suggested by open arrows. Partly based on information from Chiarelli (1978), Tissot *et al.* (1984), van de Weerd & Ware (1994) and Gauthier *et al.* (1995).

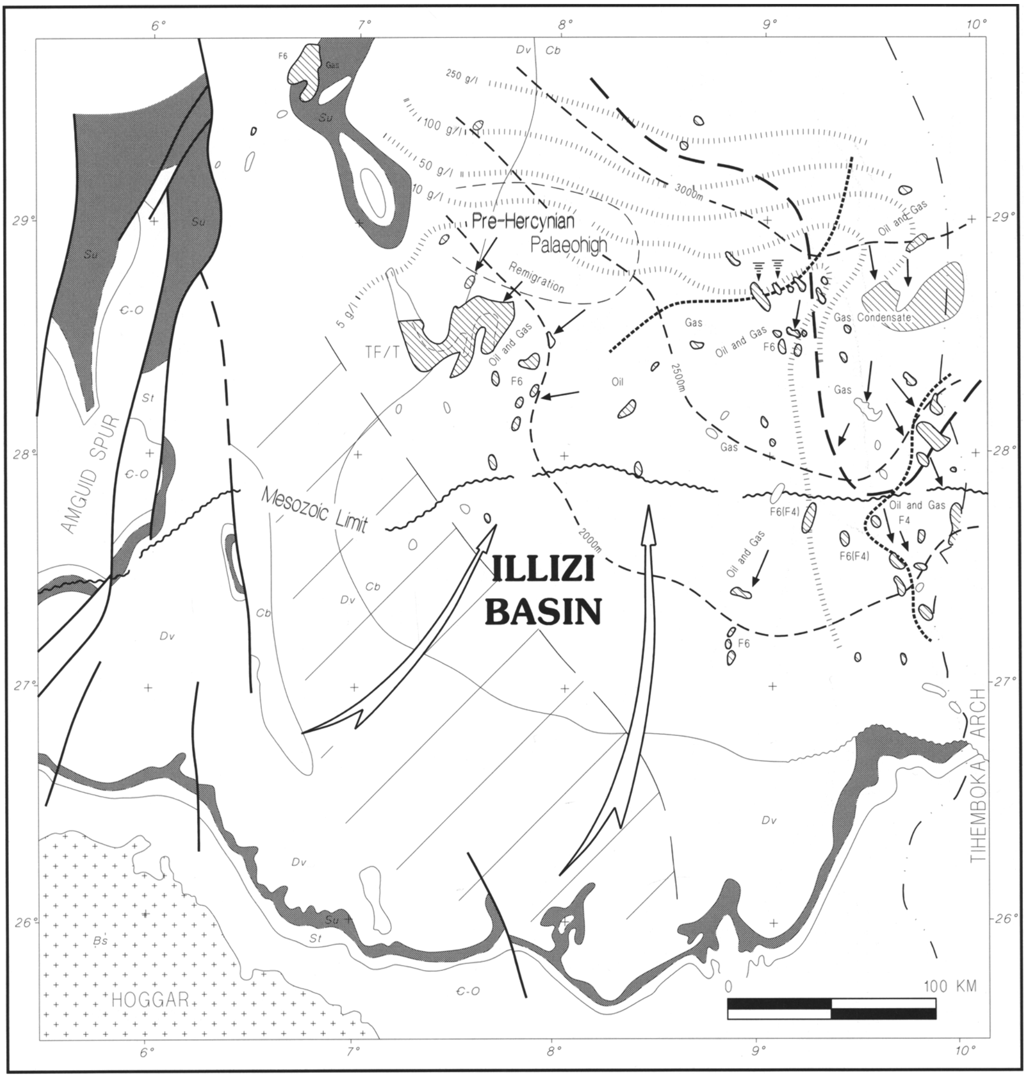


Fig. 16 (**b**) Illizi Basin: Silurian/Lower Devonian F6–F4 Petroleum System II (see Fig. 2 for location). The outcrop and Mesozoic subcrop of the upper Tanezzuft source rock responsible for this system is indicated. Lower Devonian accumulations are highlighted with a hachured pattern and preferred lateral migration directions are shown by arrows. Erosional windows in the F6 shale seal allowing upward migration into F4 reservoirs on the Talemzane Arch and downward migration of Frasnian oil into F6 reservoirs in the Ohanet area are outlined by short dashed lines. The estimated present-day oil–gas maturity transition is shown with a long dashed line. The exhumed pre-Hercynian depocentre is shown by diagonal lines and possible remigration from Palaeozoic charged palaeo-accumulations into later post-mid-Cretaceous closures are indicated (after Tissot *et al.* (1984)). Late Tertiary meteoric invasion and flushing from the south is suggested by open arrows and F6 Sand isosalinity contours (after Chiarelli (1978)).

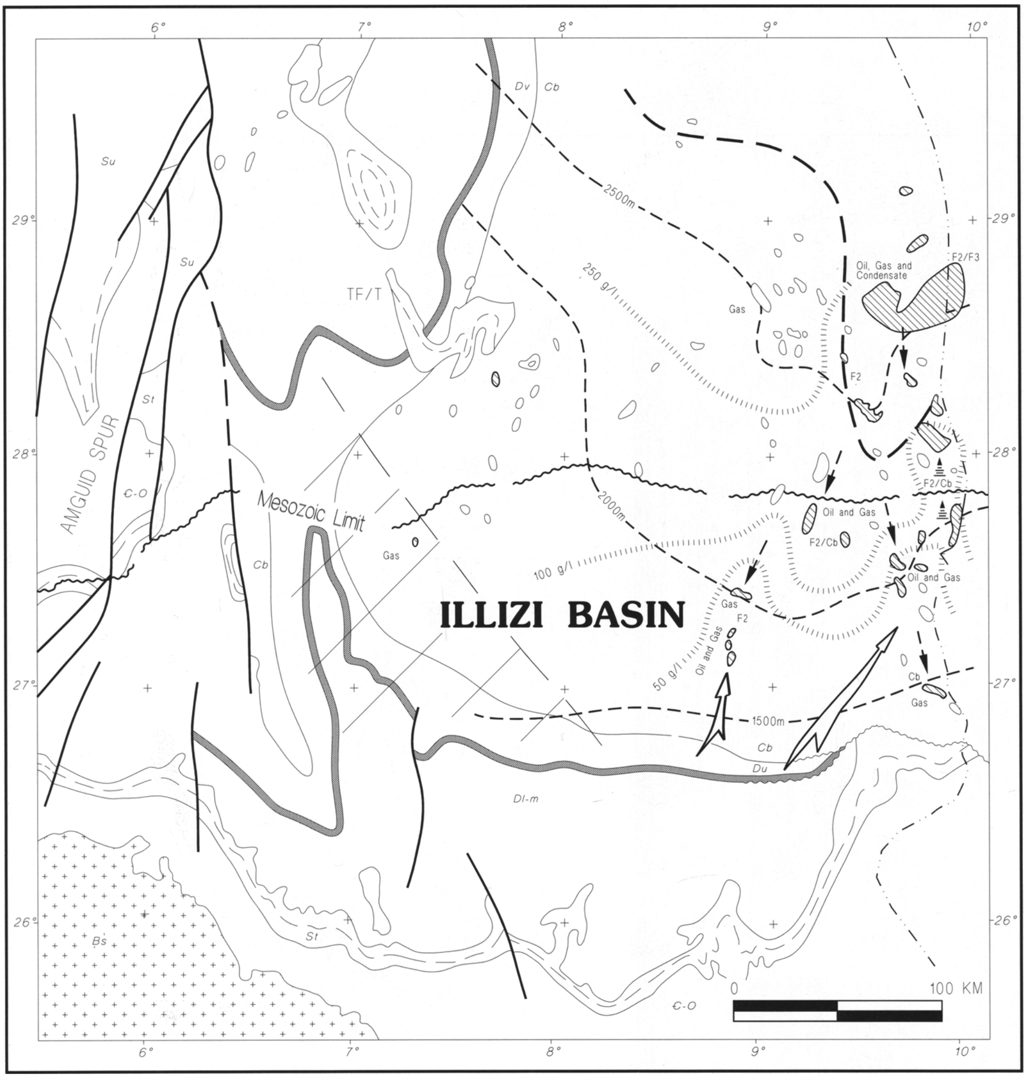


Fig. 16. (c) Illizi Basin: Frasnian/Upper Devonian to Lower Carboniferous System III (Figure 2 for location). The outcrop and Mesozoic subcrop of the Frasnian source rock responsible for the Upper Devonian-Carboniferous system is indicated. Upper Devonian/Lower Carboniferous accumulations are highlighted by a hachured pattern and preferred lateral and vertical migration directions are shown by dashed arrows. Late Tertiary meteoric invasion and flushing from the south is suggested by open arrows and Upper Devonian isosalinity contours (after Chiarelli (1978)). (Refer to the legend for more detail.)

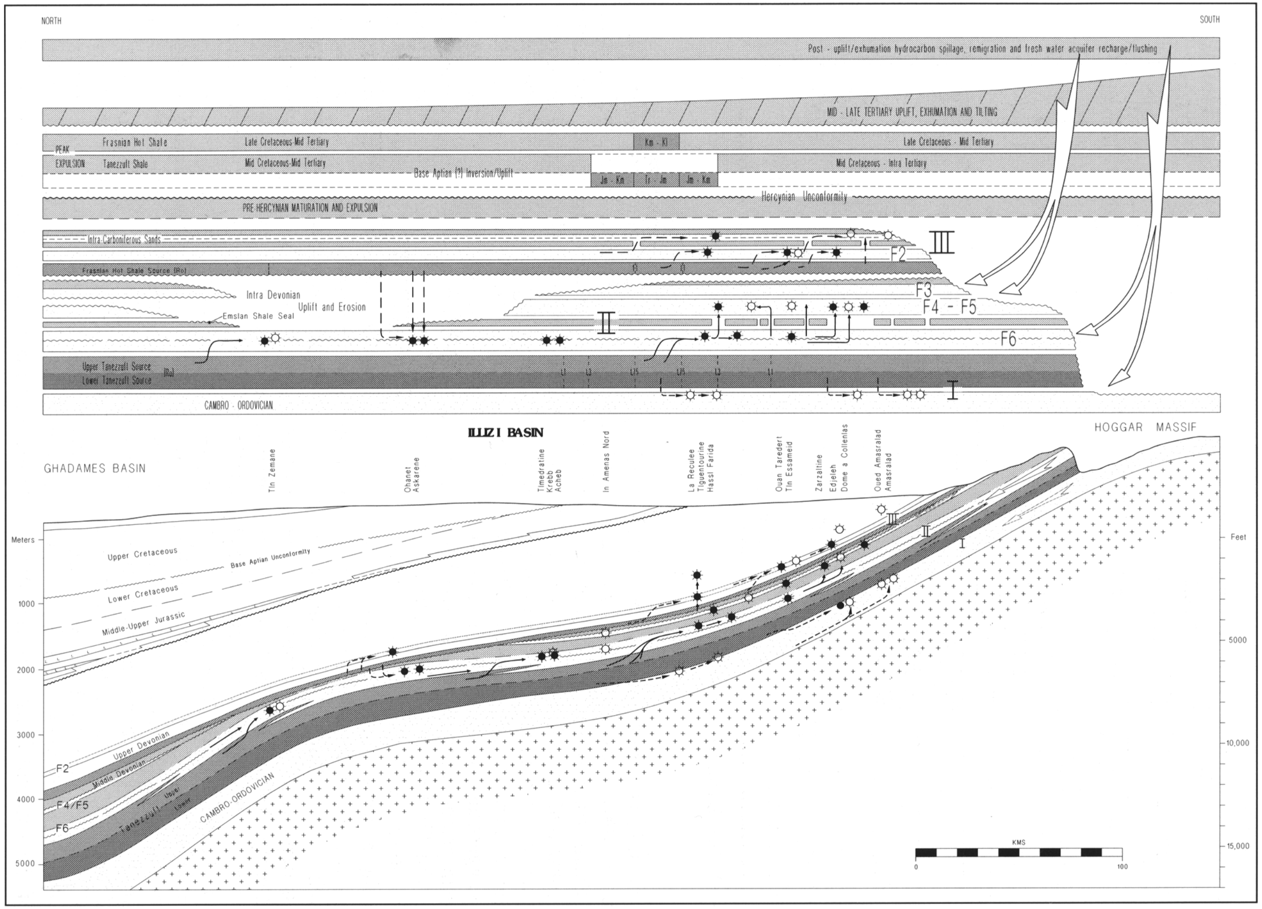


Fig. 16 (**d**) Critical elements analysis for Illizi Basin petroleum systems, illustrating the spatial relationship and relative timing of critical structural, stratigraphic and thermal variables controlling hydrocarbon distribution in the Illizi Basin. Generation and expulsion from the Tanezzuft and Frasnian source within the Mesozoic depocentre started in the north and moved progressively south during the Cretaceous and early Tertiary. Preferred short to long distance moderate-impedance migration directions are indicated.

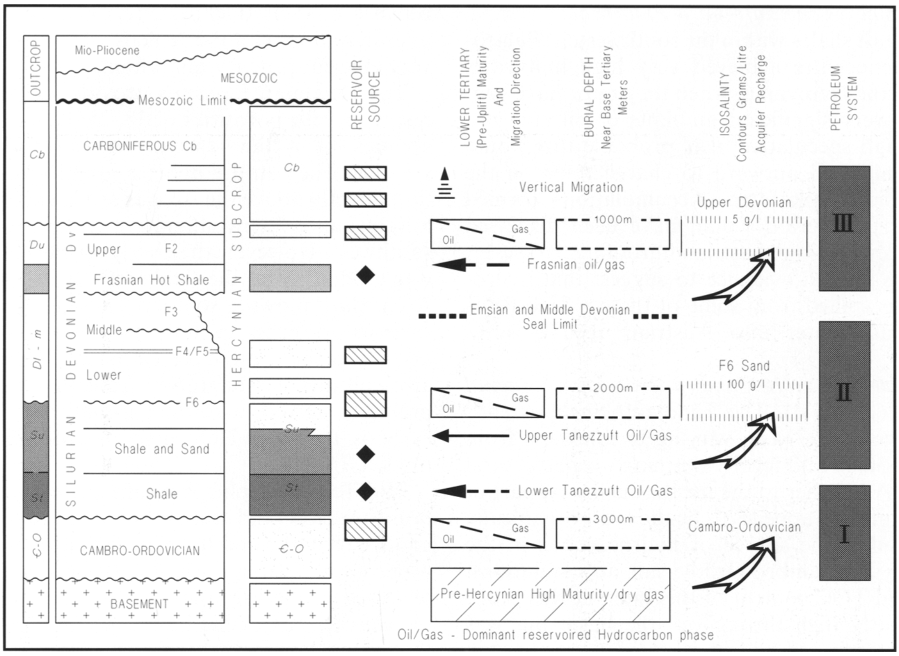


Fig. 16. Legend. Illizi Basin petroleum systems.

volumes of oil and gas, which must subsequently have migrated northeast towards the central part of the Illizi Basin. Expulsion was terminated by Hercynian uplift and unroofing, and hydrocarbons generated at this time were largely dissipated. However there is some evidence (Tissot *et al.* 1984) suggesting a very significant amount may have been preserved in a large palaeo-high just north of the Tin Fouye–Tabankort field.

During the Mesozoic, the Illizi Basin gradually subsided to the north and a second depocentre developed to the northeast along the flank of the Tihemboka Arch. Tanezzuft and Frasnian shales in this depocentre become mature in the Jurassic and early Cretaceous, first to the north and then progressively southwards. Oil and gas generated in the depocentre migrated out to charge low-relief structural closures on the flanking platform, while gentle regional structural axes encouraged longer distance migration, along the Tihemboka Arch to the south and west towards the Tin Fouye–Tabankort area. Austrian deformation followed with uplift and unroofing of the Amguid Spur, Hoggar Massif and southern Tihemboka Arch. The north Tin Fouye–Tabankort palaeostructure was tilted out of closure at this time, and may have spilled entrapped hydrocarbons southwards to charge the Tin Fouye–Tabankort field and flanking structures (Tissot *et al.* 1984).

Generation continued during the later Cretaceous and early Tertiary with increasing amounts of gas migrating from the Mesozoic depocentre to the northeast, whereas the exhumed southwestern Palaeozoic depocentre remained inactive. Many of the deeper reservoirs were partially and sometimes completely gas flushed at this time (Macgregor 1996*a*,*b*), and oil and gas remigrated far to the south. Generation was terminated by regional mid-Tertiary uplift, unroofing and northward tilting. Renewed hydrodynamic flow and freshwater recharge followed with flushing, spillage and partial dissipation of entrapped hydrocarbons (Chiarelli 1978). However, this destructive phase so far appears to have been gentle and most accumulations remain only slightly to moderately affected.

As a result of this polyphase history, a number of petroleum systems developed in the basin at different times. Tissot *et al.* (1984) identified three families of reservoired oil, which they correlated with the lower and upper Tanezzuft (Lower Acacus) and Frasnian shales. The two Silurian sourced oils are very similar and differ only in their maturity (Daniels & Emme 1995). However, their distribution and stratigraphic position justifies the distinction. Based upon this oil–source correlation, it is possible to distinguish three petroleum systems still active in the basin and one extinct one as follows:

Extinct Tanezzuft–intra-Palaeozoic system. Tanezzuft shales within the southwestern Palaeozoic depocentre achieved very high maturities before the Hercynian, when they must have generated very significant amounts of oil and gas. Although speculative, it is probable this would have migrated outward to charge traps on the surrounding platform. Accumulations formed during this period would have been dispersed by Hercynian and Austrian unroofing. However, there is limited evidence to suggest that hydrocarbons spilled from some of these palaeo-fields remigrated later into Austrian aged closures nearby.

Lower Tanezzuft–Cambro-Ordovician System I (Fig. 16a and d). The Tanezzuft Shale extends over the entire basin varying in thickness from 200 to 500m and locally thinning over structural highs. As further to the north, the lowest part of the formation appears to be the most organically rich and is the source of hydrocarbons in the underlying Cambro-Ordovician accumulations. Original TOC content of this interval was probably fairly high throughout the basin but was subsequently reduced in areas of more elevated maturities. It now varies from less than 2% in the east rising to 4% in the north and 8% in the west (Daniels &Emme 1995). Maturities range from 1.1% *R*o equivalent in the central part of the basin to 1.75% *R*o in the southwest and northeast. Local very high maturities are associated with laccolith intrusions (Daniels & Emme 1995).

As well as a source, the Tanezzuft provides an excellent regional seal for underlying Cambro-Ordovician sandstone reservoirs (porosities 7–14% and permeabilities up to 250 mD). Although of rather poor quality, their regional continuity has encouraged long distance lateral migration to the west, southwest and south along the flank of the Tihemboka Arch during later Mesozoic and early Tertiary. Pools in the Tin Fouye–Tabankort area were partially charged by high-maturity oil and gas spilled from pre-Hercynian traps during the Austrian deformational event. Charge and migration ceased with mid-Tertiary uplift and unroofing to be followed by freshwater aquifer recharge and flushing from the south. The system is very prolific, with some 1500 MMBOE reserves.

Tanezzuft–Lower Devonian F6, F4 System II (Fig. 16b and d): Hydrocarbons in the Lower Devonian F6 and F4 sands were sourced from the upper part of the Tanezzuft Shale and perhaps interbedded shales within the overlying Acacus Formation. Although inferior in quality compared with the rich basal member of the Tanezzuft, they form a very prolific source rock because of their thickness, regional extent and interdigitation with the Acacus which facilitated very efficient primary migration.

The Devonian F6 sands provide an excellent reservoir with porosities of 18–25% and permeabilities of a few darcies (Alem *et al.* this volume). Their stratigraphic continuity and position directly above the Acacus sands encouraged long distance lateral migration to the west and southwest. However, the overlying F6 shale seal was eroded along the flanks of the Tihemboka Arch, thus allowing southerly migrating hydrocarbons to pass up into F4 reservoir sands above. Further west in the Tin Fouye–Tabankort area, oil and gas migrating from the northeast probably mixed with higher-maturity hydrocarbons from pre-Hercynian palaeo-accumulations.

Mid-Tertiary uplift brought primary migration to a close and was followed by very active aquifer recharge and flushing. Fresh to brackish water and strong hydrodynamic flow are observed in the F6 sands across a large area in the central part of the basin. Accumulations in that area were strongly affected. Both Chiarelli (1978) and Alem *et al.* (this volume) have suggested that the Tin Fouye–Tabankort accumulation is trapped hydrodynamically. Alternatively it may represent an originally structurally trapped accumulation now in the first phases of flushing and destruction. The petroleum system is extremely prolific, with 3500 MMBOE reserves.

Frasnian to Upper Devonian–Carboniferous System III (Fig. 16c and 16d): The Frasnian shales extend across the central and northeastern part of the basin, outcropping to the south and subcropping the Mesozoic to the west. They vary in thickness between 25 and 110 m thinning locally onto structural highs. Organic carbon content ranges from less than 2% in the southeast to 4–6% in the north and west. The kerogen is predominantly oil prone (although a mixed kerogen facies becomes more dominant to the southeast). Present-day maturities increase northwards from 1.1 R_0 in the central part of the basin to 1.3 R_0 in the northeastern depocentre.

Peak oil expulsion is timed at early Cretaceous to mid-Tertiary and has charged overlying reservoirs in the Upper Devonian and Lower Carboniferous including the F2 sands, Tahara Sandstone and sands interbedded with the M'rar Formation. Porosities in the F2 reservoir typically range from 15 to 22% with permeabilities of 50–300 mD. The overlying Tahara and Carboniferous sandstones have rather poorer reservoir quality.

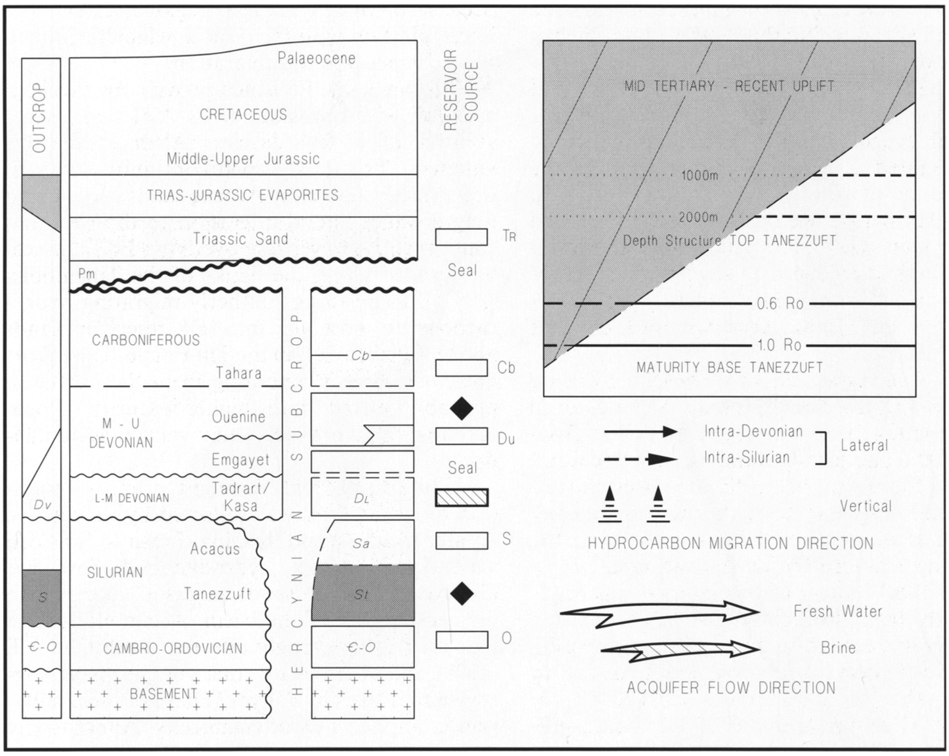


Fig. 17. Legend. Hamra Basin petroleum systems.

Migration was dominantly lateral, southwards along low-relief structural axes. There also appears to have been a significant vertical component of migration through Austrian aged faults on the flank of the Tihemboka Arch. To the north of the basin, a local erosional window in the Middle Devonian shales allowed the Frasnian source to charge F6 reservoirs in the Ohanet area (Tissot *et al.* 1984) and F3 sands at Alrar (Chaouchi *et al.* this volume).

As in the other sytems, mid-Tertiary uplift and unroofing appears to have terminated primary migration and charging. However hydrodynamic flushing was less severe than in the underlying F6 sands, perhaps because of lower stratigraphic continuity and proximity to the Tihemboka Arch. The system is very prolific, with total reserves of approximately 2000 MMBOE.

Hamra Basin.

The Hamra Basin (Figs 2 and 17) forms the eastern extension of the greater Ghadames intra-cratonic Palaeozoic sag, buried beneath a north thickening wedge of Mesozoic clastics, carbonates and evaporites (Gumati *et al.* 1996; Echikh this volume). The basin is only moderately productive, with 950 MMBOE reserves in a large number of small to very small accumulations (Table 2). These all appear to have been sourced from the Tanezzuft Shales with perhaps only a minor contribution from the largely immature Upper Devonian Ouenine Formation. The Tanezzuft is thickly developed in the central part of the basin, subcropping the Mesozoic in the north on the Djeffara–Nefusa Arch, and the Lower Devonian Tadrart sands in the south, on the flanks of the Gargaf High. Peak oil expulsion is timed at late Cretaceous to early Tertiary, charging a number of sandstone reservoirs ranging in age from Cambro-Ordovician to Triassic.

Mid-Tertiary uplift of the Nefusa and Gargaf Arches had a very profound effect upon hydrocarbon accumulations within the basin. Tilting and pervasive meteoric invasion and flushing which occurred at this time are probably responsible for the small field size characteristic of the basin. Oil and gas fields are clustered in three areas, representing discrete petroleum systems, each with slightly different charge histories (Fig. 17).

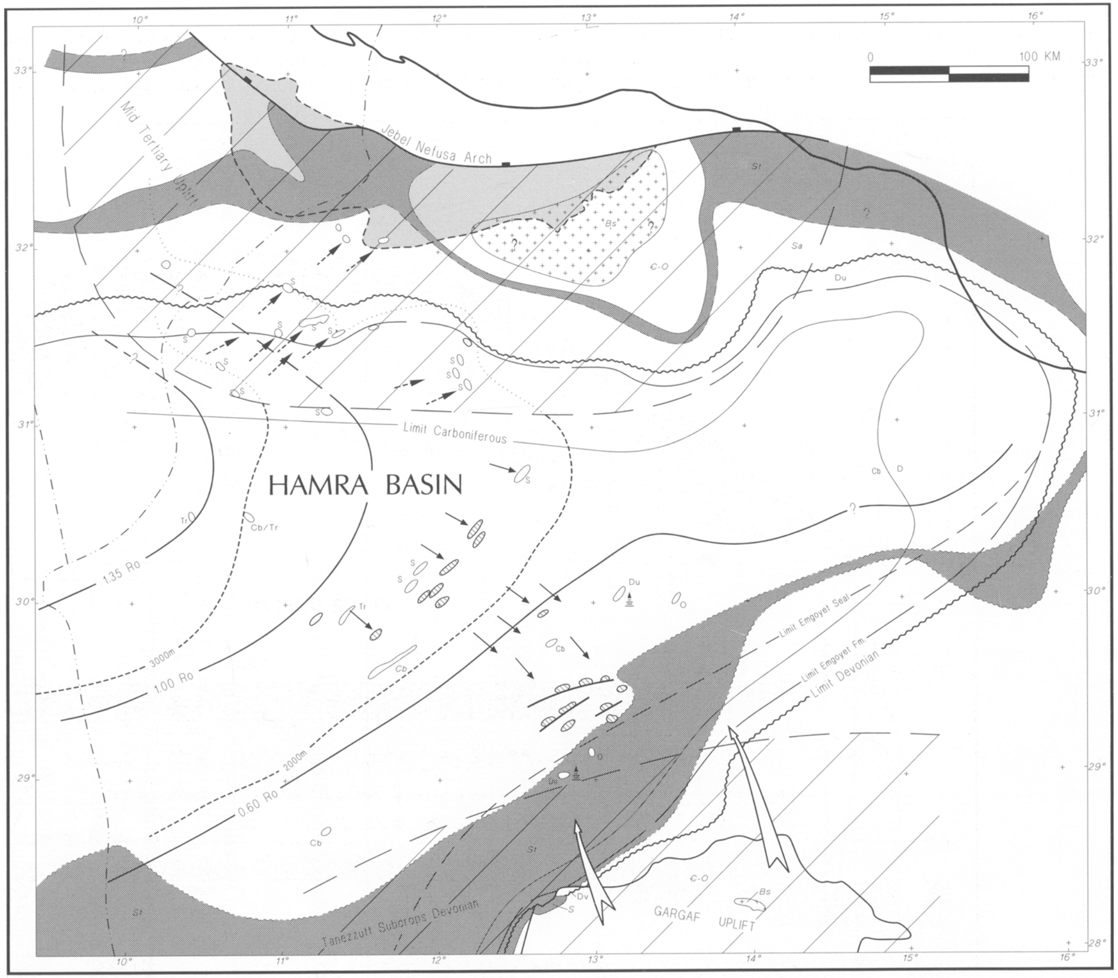


Fig. 17. **(a)** Hamra Basin petroleum systems (see Fig. 2 for location). Three broadly defined petroleum systems are recognized in the Hamra Basin: (1) in the north, a system reservoired by Upper Silurian Acacus sands (and occasionally in Lower Devonian sandstones) in small fault and unconformity traps charged by Tanezzuft Shale, (2) a second system in the central part of the basin reservoired in Acacus and Lower Devonian sandstones (with some vertical leakage into Lower Carboniferous sandstones) and (3) a southern system with Lower Devonian reservoirs charged by long distance migration from Tanezzuft Shale to the north. The Lower Devonian shale seal (Emgayet Formation) is increasingly sandy towards the south and allowed migration up into overlying sands and ultimately to the surface. Minor downloading of Tanezzuft hydrocarbons into Cambro-Ordovian reservoirs also occurred locally. The distribution of the Tanezzuft source rock subcrop is highlighted. In the north, subcrop is to the Permian Bir Jaja Shale and Triassic; to the south, subcrop is to the Devonian. Preferred migration directions (lateral and vertical) are shown by small arrows. Areas of mid-Tertiary uplift and unroofing are shown by diagonal lines; late Tertiary meteoric invasion and flushing by open (fresh) and hachured (brackish) arrows (adapted from Pallas 1980). Small Triassic accumulations in the west–central part of the basin were probably sourced by long distance migration from Frasnian source rocks to the west. (Refer to the legend for more detail. Partly based upon information from Bishop (1975), Hammuda (1980), Pallas (1980), Gumati *et al.* (1996).

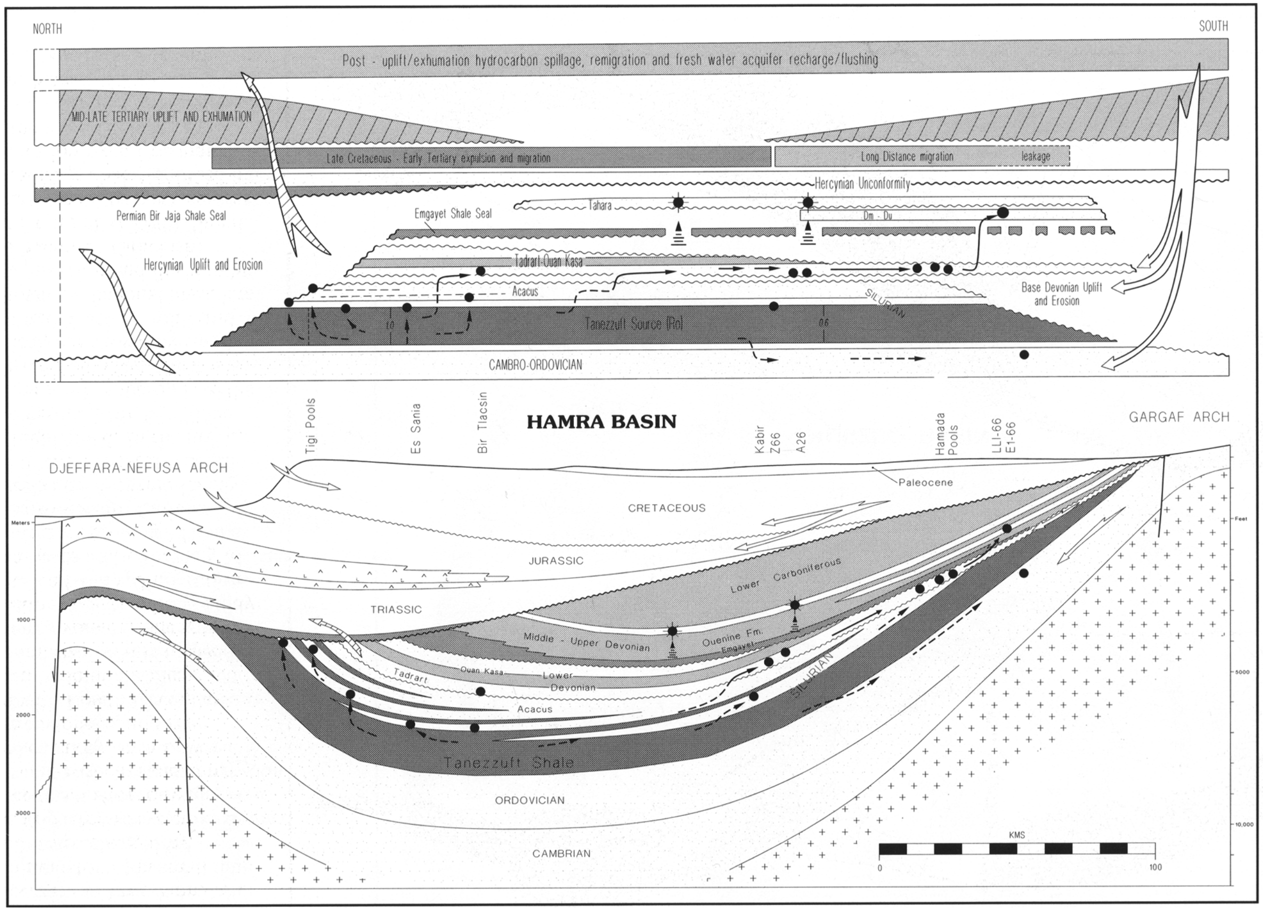


Fig. 17. (**b**) Critical elements analysis for Hamra Basin petroleum system, illustrating the spatial relationship and relative timing of key stratigraphic, structural and thermal factors controlling hydrocarbon distribution in the Hamra Basin (adapted in part from Pallas (1980)). Preferred migration directions from the Tanezzuft into the Acacus and Lower Devonian Tadrart sands above are indicated by arrows. Meteoric invasion and fresh to brackish water hydrodynamic flow which followed mid-Tertiary uplift and unroofing is shown by open hachured arrows.

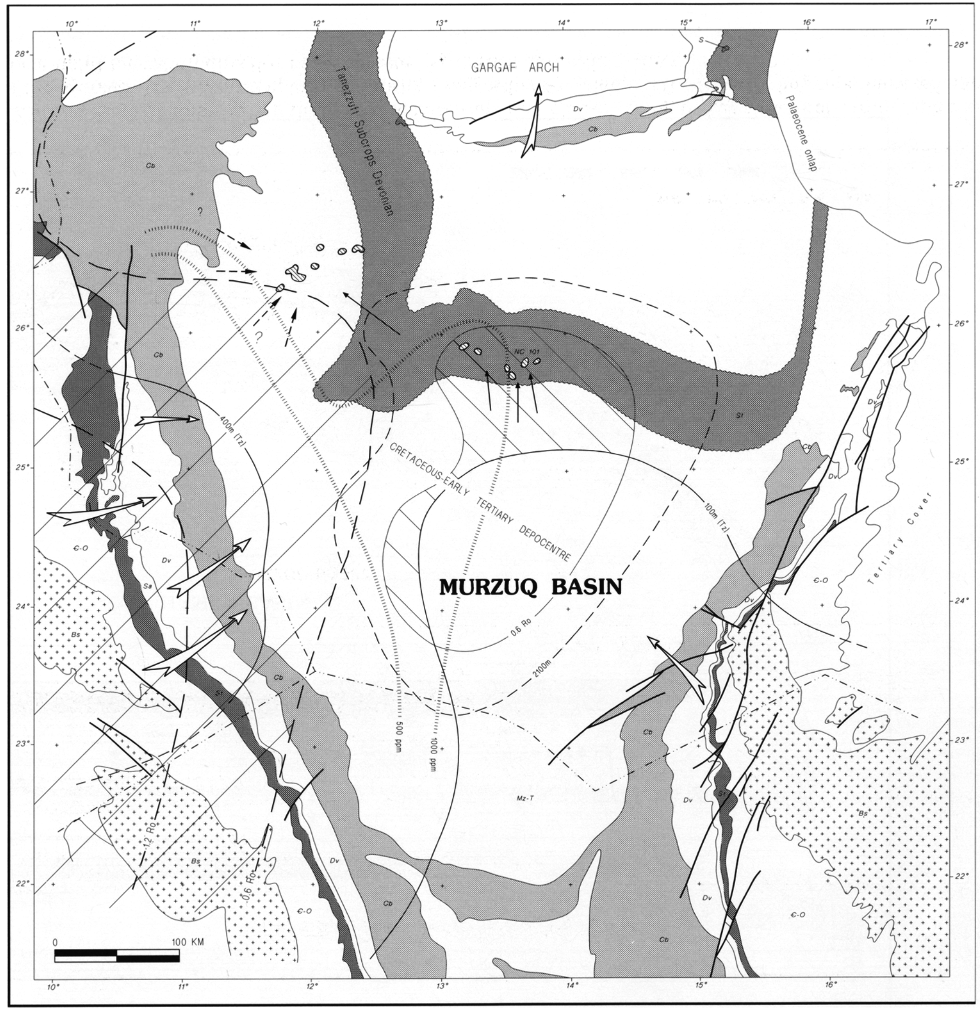


Fig. 18. (**a**) Murzuq Basin petroleum system summary map (see Fig. 2 for location). One Tanezzuft-sourced petroleum system is recognized in the Murzuq Basin, reservoired within Ordovician sandstones. The Silurian outcrop and Tanezzuft subcrop below the Devonian is highlighted. Decreased source quality to the southeast is suggested by the 100 m Tanezzuft isopach contour. An exhumed Palaeozoic depocentre is shown by diagonal lines. Cretaceous and early Tertiary migration directions are indicated by arrows. Possible remigration from pre-Austrian palaeo-accumulations is shown with dashed arrows. Late-stage meteoric invasion is suggested by isosalinity contours. (Refer to the legend for further detail.) Partly based on information from Bellini & Massa (1980), Dubuy (1980), Lorenz (1980), Pallas (1980), Clark-Lowes (1985), Clark-Lowes and Ward (1991), Meister *et al.* (1991), Pierobon (1991) and Thomas (1995), Gumati *et al.* (1996).

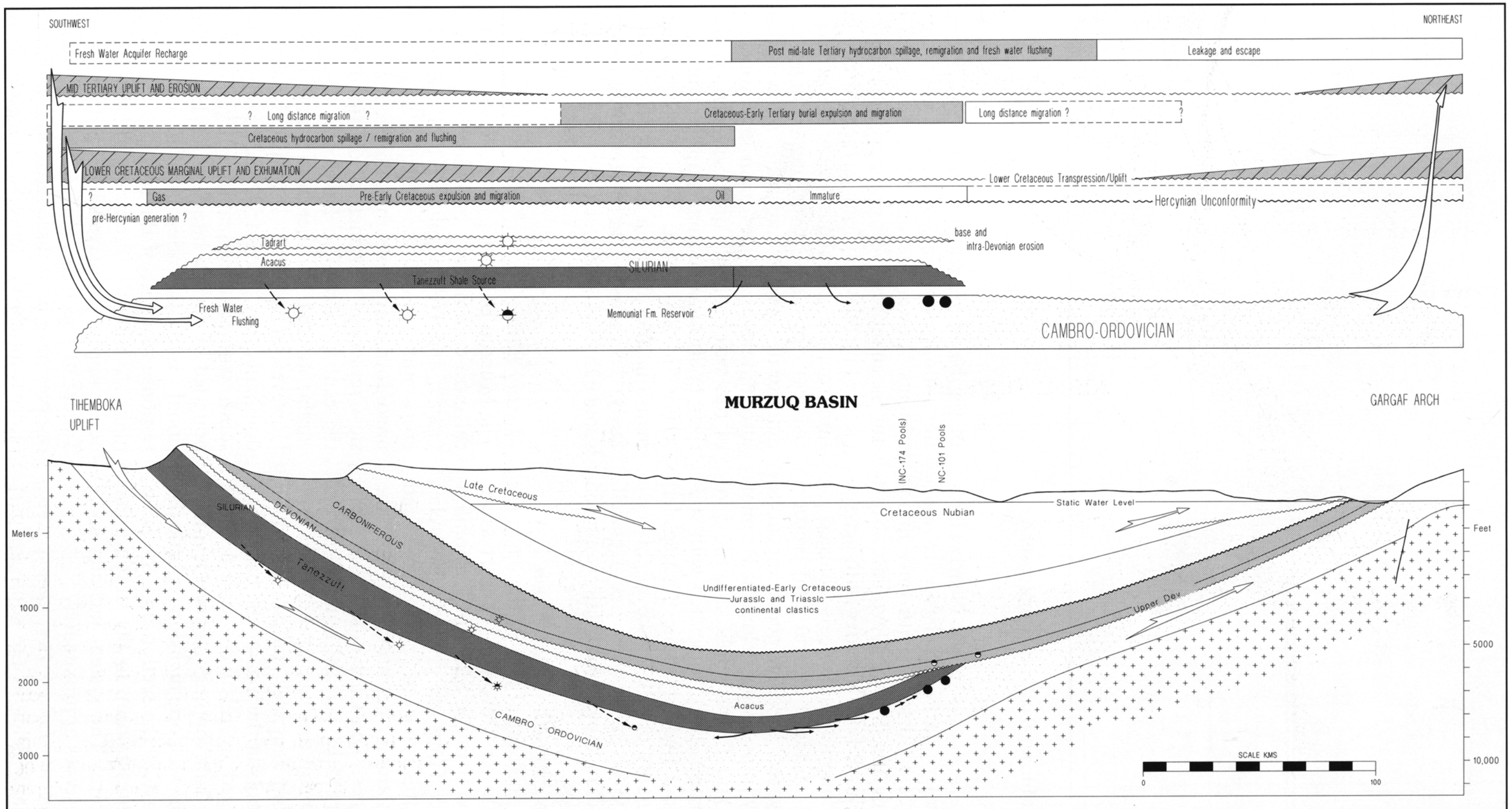


Fig. 18. **(b)** Critical elements analysis for Murzuq Basin petroleum system, illustrating the spatial relationship and relative timing of key structural, stratigraphic and thermal variables controlling hydrocarbon distribution in the Murzuq Basin. Stratigraphic relationships suggesting Austrian uplift and unroofing superimposed upon the Hercynian deformational event are illustrated. Pre- and post-uplift migration directions are suggested by dashed and solid arrows.

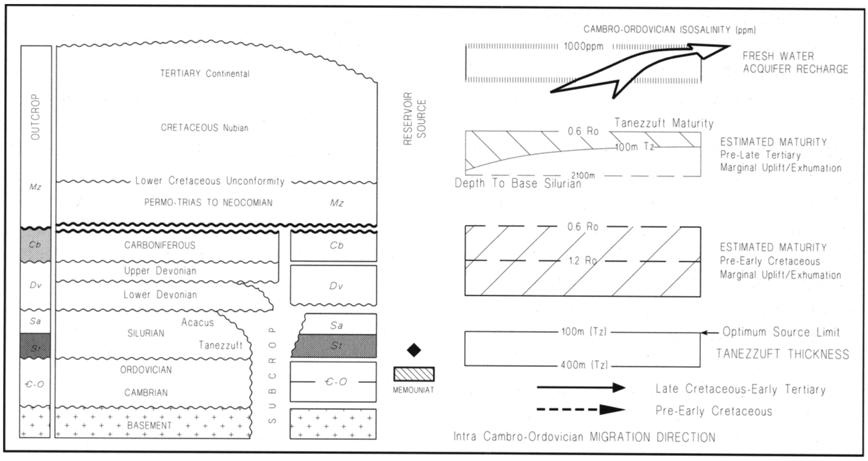


Fig. 18. Legend. Murzaq Basin petroleum system.

(North) Tanezzuft–Acacus system. Nearly all the fields in the northern part of the basin are reservoired in Acacus sandstones with only minor production from the Lower Devonian. Most are trapped by small fault closures with across-fault intra-formational shale seals charged by relatively short distance lateral and vertical migration. However, the Tigi pools appear to be unconformity traps, sealed below the Permian Bir Jaya Shale. Mid-Tertiary uplift and tilting of the Djeffara–Nefusa Arch, associated with spillage and pervasive hydrodynamic flushing, left only small remnants of what once might have been quite large accumulations (see Chiarelli 1978). The system now reservoirs some 65 MMBOE reserves.

(Central) Tanezzuft–Devonian system. Hydrocarbon pools in the central part of the basin are reservoired in Lower Devonian Tadrart sands with lesser amounts in the Silurian, Carboniferous and Triassic. Traps are generally low-relief structural closures charged by vertical and short distance lateral migration through the Acacus sandstones. The Carboniferous Tahara sands were charged by vertical migration from the Lower Devonian through stratigraphic gaps in the intervening Emgayet shales. Two small basal Triassic pools in the axis of the basin may have been charged by relatively long distance migration from subcropping Upper Devonian shales to the west. Meteoric invasion is particular severe in this part of the section and the fields may owe their preservation to the stratigraphic nature of the traps. The system includes some 250 MMBOE reserves approximately.

(South) Tanezzuft–Lower Devonian system. The small Hamada fields in the southern part of the basin are trapped in low relief culminations along northeast–southwest trending fault systems. Lower Devonian Tadrart sandstones are the main reservoir and appear to have been charged by relatively long distance lateral migration from the central part of the basin. The effectiveness of the overlying Emgayet seal deteriorates towards the south, allowing leakage into middle–upper Devonian sandstones. Much of this was probably dispersed during mid-Tertiary uplift but one small pool remains. As elsewhere in the basin, late Tertiary meteoric invasion and flushing appears to have been fairly destructive. The system now reservoirs some 635 MMBOE reserves.

Murzuq Basin.

The Murzuq Basin (Figs 2 and 18) is a symmetrical intra-cratonic sag bounded by the Hoggar, Gargaf and Tibesti uplifts. The Palaeozoic now crops out around the margins and is buried unconformably beneath undifferentiated Triassic–Cretaceous continental clastic deposits in the central part. The Palaeozoic succession is similar to that further north and northwest. However, it becomes increasingly sandy and dominated by terrestrial facies towards the south, with reduced seal integrity. This is compounded by several late Silurian–Devonian erosional unconformities, which developed in response to uplift of the surrounding structural highs. As a result, significant petroleum systems never appear to have developed in the post-Tanezzuft section. In contrast, significant reserves have been discovered within underlying Ordovician clastic deposits, charged and sealed by basal Tanezzuft Shale on the northern flank of the basin. The associated accumulations are clustered in two distinct areas, but appear sufficiently similar to be considered as part of one system (Fig.18).

Tanezzuft–Ordovician Petroleum system. The Tanezzuft Shale is organically rich in the northern part of the basin with TOC content of up to 8%. It thins to the south and southeast across a Lower Palaeozoic arch, with a corresponding deterioration in organic quality and thickens significantly northwestwards towards a now exhumed Palaeozoic depocentre, where maturities of greater than 1.2 *R*o were achieved before Hercynian and Austrian uplift and unroofing. During the later Cretaceous and early Cenozoic, the Tanezzuft was buried to sufficient depth only in the central part of the basin, where moderate maturities of *R*o 0.6–0.7% were reached. Hydrocarbons generated in this area migrated northwards through the Ordovician to charge the NC 101 fields. The NC 115 pools (including the Murzuq field) lie some distance to the northwest, and it is possible they were charged both by long distance migration from the late Mesozoic depocentre and by remigration from pre-Austrian palaeo-accumulations to the south and southwest.

Ordovician sandstone reservoir quality varies greatly. However porosity as high as 20% has been observed. Although largely secondary and often tectonically induced, it is at least partially controlled by depositional facies. Glacial and peri-glacial clastic deposits of the Memouiat Formation provide the best reservoirs, infilling incised north–south aligned palaeo-valleys in the NC 101 region. These may have acted as efficient migration conduits into traps formed by updip facies changes and differential compaction. The northwestern NC 115 pools appear to be trapped within low-relief fault structures of Austrian age. Mid to late Tertiary uplift of the basin margins terminated further expulsion and encouraged extensive meteoric invasion and flushing. The system reservoirs approximately 600 MMBOE reserves.

Palaeozoic charged systems with Palaeozoic shale seals

Gourara and Ahnet Basins.
The southern Gourara and Ahnet Basins (Figs 2 and 19) form part of a strongly deformed Palaeozoic depression, bounded by the Azzene High and Azel Matti Swell to the west and the Idjerane Horst to the east (Conrad & Lemosquet 1984; Aliev *et al.* 1971; Pelet & Tissot 1970; Rahmani *et al.* 1994). It was once part of a much larger depocentre subsequently uplifted, folded and erosionally truncated during the late Hercynian deformational episode. The Palaeozoic now crops out around the southern margins of the Ahnet Basin and unconformably subcrops a thin veneer of late Jurassic to Cretaceous sediment to the north.

Important reserves of gas have been discovered in large anticlinal traps mostly reservoired in Devonian sandstones but with lesser amounts in the Ordovician and Carboniferous. These accumulations are all considered part of a single petroleum system, charged by extremely mature Lower Silurian shales (Fig. 19).

Tanezzuft–Devonian (Carboniferous, Ordovician) system. Tanezzuft shales preserved within the depression have TOC content ranging up to 4%. They are extremely mature as a consequence of deep burial and a regionally elevated thermal event, generally linked to widespread Hercynian igneous activity (Cawley *et al.* 1995; Takherist *et al.* 1995). Logan & Duddy (this volume) have argued that this occurred somewhat later, towards the end of the Triassic or early Jurassic, based upon apatite fission track analysis. However, the complete absence of liquid hydrocarbons in the associated accumulations indicates that the shales had already reached high maturities by the time the anticlinal traps had formed in late Palaeozoic and supports an earlier event.

The Devonian reservoir sandstones are developed in a rather more distal marine facies than further east in the Illizi Basin, with lower porosities averaging 12% but locally as high as 24%. They are sealed by intra-formational Siegenian and Eifelian shales. Charge and migration are assumed to have occurred rapidly where vertical migration along faults filled growing anticlinal structures. It appears probable that significant amounts of gas generated and trapped at this time were dispersed during the final phase of Hercynian uplift and unroofing. Later Mesozoic and early Tertiary burial was followed by late-stage uplift and erosion with further dispersal of hydrocarbons. The reserves discovered to date for this system are 1250 MMBOE. The large volume of hydrocarbons still retained suggests the pre-Hercynian petroleum system was very prolific with robust shale seals (Table 3).

Sbaa Basin.
The Sbaa Basin (Fig. 19a) is a small Palaeozoic sag yoked between the Ougarta Arch and the Azzene High (Aliev *et al.* 1971; Baghdadli 1988). The present basin formed as a result of Hercynian uplift and erosional truncation, and was subsequently buried unconformably beneath

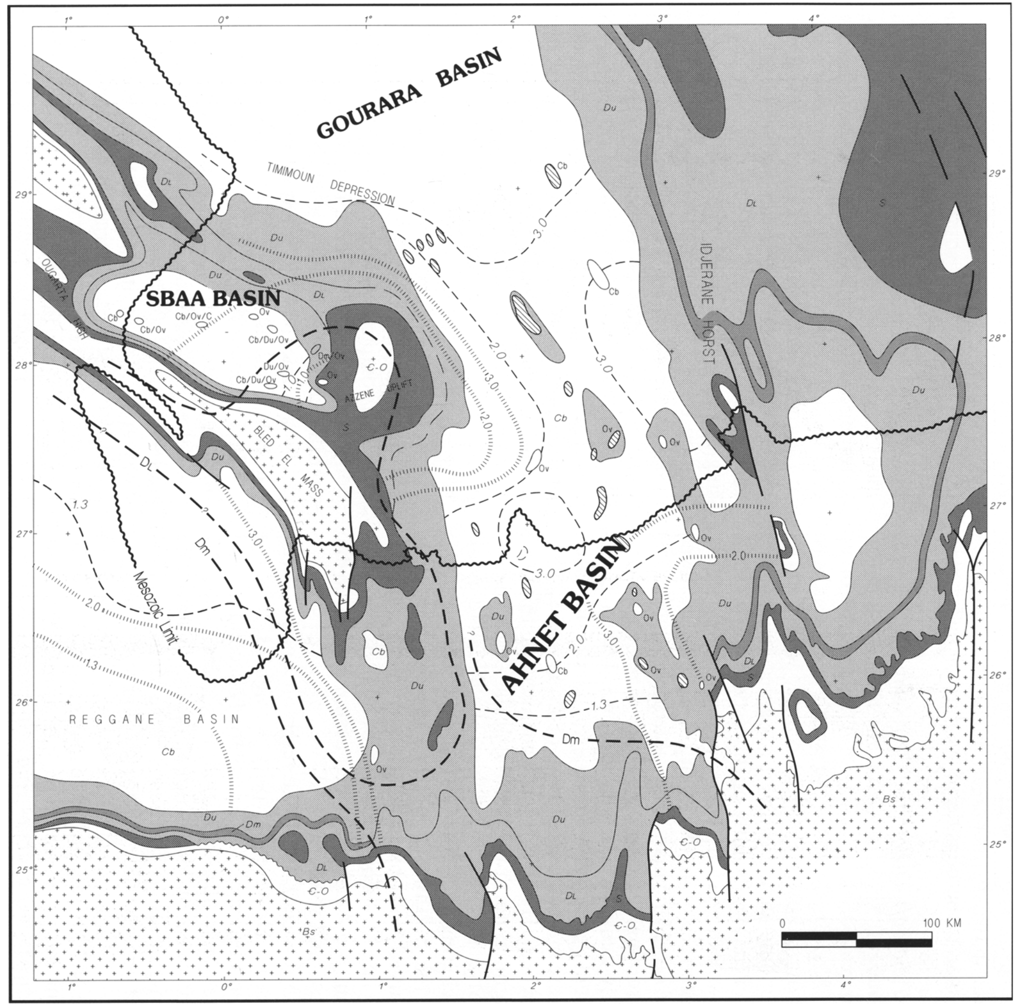


Fig. 19. (**a**) Gourara–Ahnet and Sbaa Basins petroleum systems summary map (see Fig. 2 for location). One Tanezzuft-sourced petroleum system is recognized in the Gourara–Ahnet depression reservoired in Devonian sandstones with subsidiary oil and gas in the Cambro-Ordovician and Carboniferous (from a possible Devonian source). Two systems are distinguished in the Sbaa Basin, an Upper Devonian-sourced system reservoired in Carboniferous sandstones and a Lower Tanezzuft system with Cambro-Ordovician reservoirs. Lower Devonian reservoired accumulations are hachured, and Palaeozoic outcrop and subcrop below the Mesozoic is highlighted. Tanezzuft and Frasnian source rocks achieved very high maturities during the late Hercynian. Reflectance equivalent contours are indicated, adapted from Logan & Duddy (1997). Partly based on information from Pelet & Tissot (1970), Aliev *et al.* (1971), Conrad & Lemosquat (1984), Conrad *et al.* (1986), Baghdadli (1988), Cawley *et al.* (1995) and Takherist *et al.* (1995).

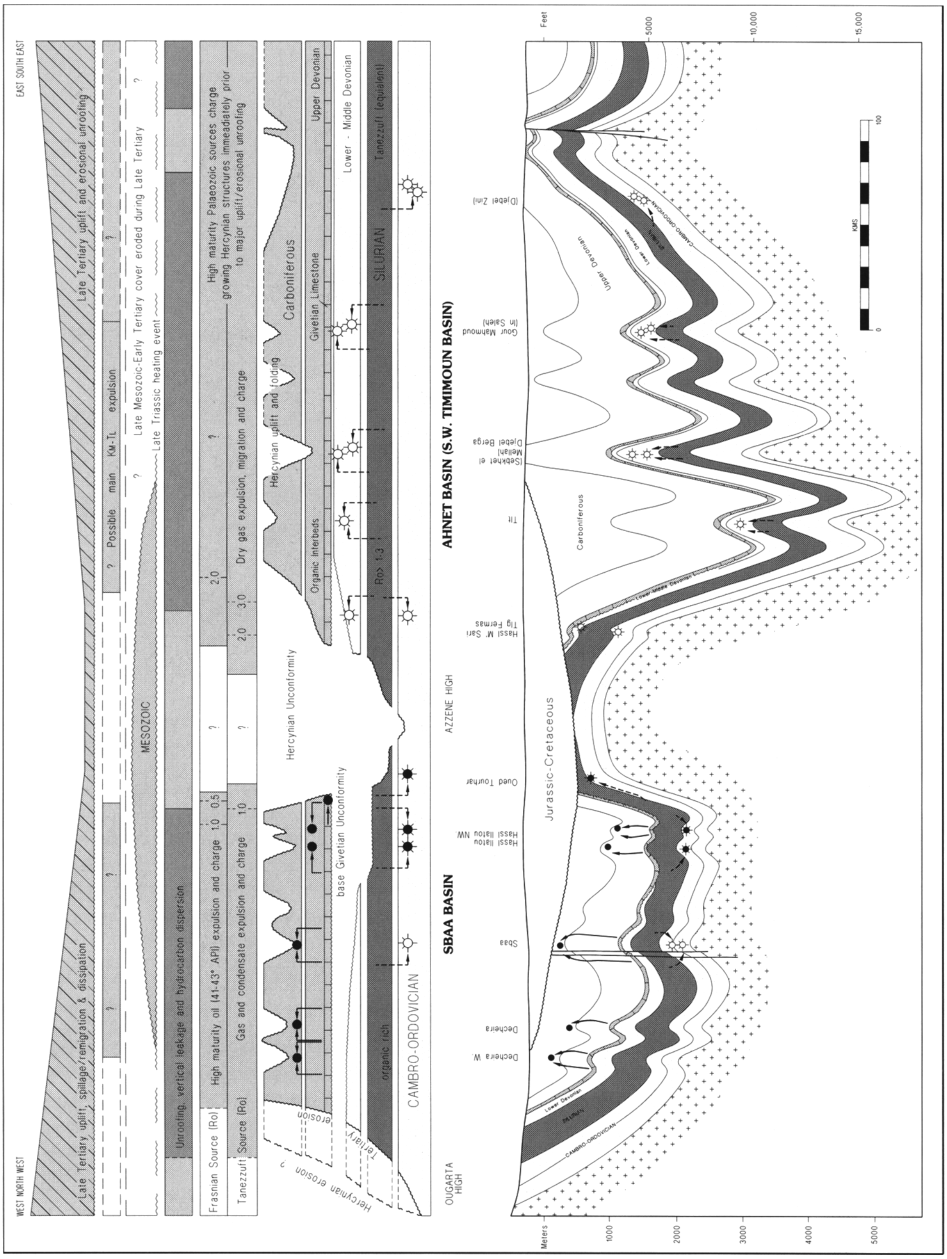


Fig. 19. (**b**) Critical elements analysis for Gourara–Ahnet and Sbaa petroleum systems, illustrating the spatial relationship and relative timing of key structural, stratigraphic and thermal factors controlling hydrocarbon distribution. Migration and charging in both Sbaa and Gourara–Ahnet Basins occurred during late Hercynian deformation before the final phase of uplift and unroofing. Vertical migration was dominant, and is illustrated by arrows with dashed lines (Tanezzuft) and with continuous lines (Upper Devonian). A possible late Triassic heating event (after Logan & Duddy, this volume) is acknowledged, but further discussion is given in the text.

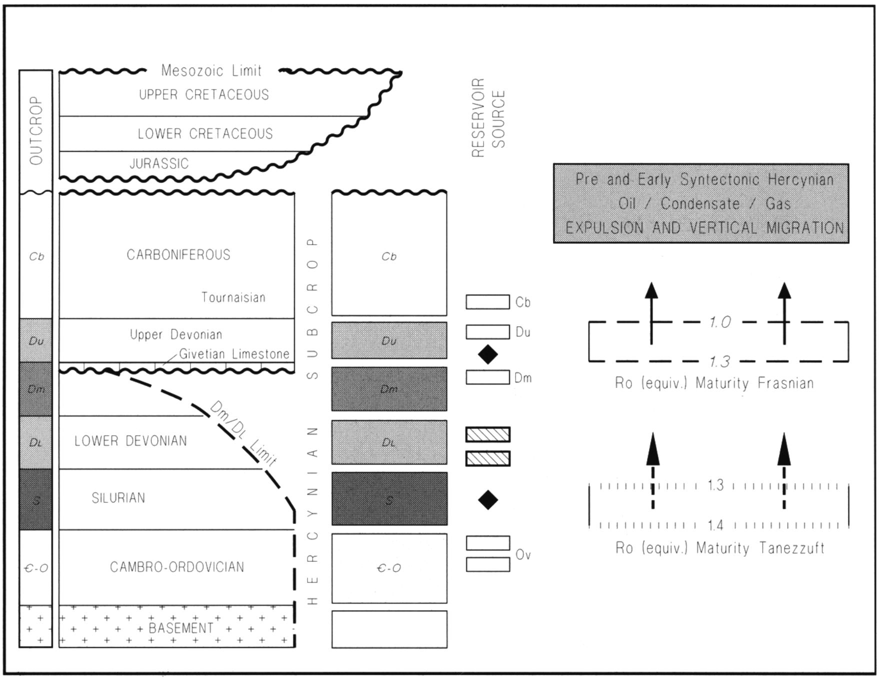


Fig. 19. Legend. Gourara–Ahnet and Sbaa Basins petroleum systems.

a thin blanket of late Jurassic and Cretaceous sediment. Partial unroofing in the mid to late Tertiary exposed the Palaeozoic in outcrop over the western part of the basin.

Only moderate amounts of oil and gas have so far been discovered, in highly faulted anticlinal traps, draped over basement blocks (Baghdadli 1988). Two petroleum systems have been distinguished, one charged by Upper Devonian shales with Strunian and Tournaisian sandstone reservoirs and a second Lower Silurian sourced system, reservoired in Cambro-Ordovician sandstone (Fig. 19).

Sbaa Basin petroleum systems. The Sbaa Basin initially developed as part of the larger Ahnet–Gourara Palaeozoic depression, but was never buried as deeply. As a result, the Lower Silurian and Upper Devonian source rocks preserved within it are significantly less mature. Both systems were active immediately before and during the late Hercynian deformational event, charging growing structures by vertical migration through syntectonic bounding faults. The Upper Devonian sourced system has estimated reserves of 50 MMBOE. The more mature Lower Silurian source has charged underlying Cambro-Ordovician sands with some 100 MMBOE. of gas and condensate reserves (Table 3).

Tindouf Basin.
The Tindouf Basin (Figs 2 and 20) is the westernmost of the North African Palaeozoic basins, bounded by the Anti-Atlas Mountains and Ougarta Arch to the north and the Reguibate Massif in the south (Aliev *et al.* 1971). Although once covered unconformably by a blanket of Mesozoic to early Tertiary sediments, the Palaeozoic now crops out over much of the region, preserved in an asymmetric depression with a broad gentle southern flank and steeply dipping more structurally complex northern margin.

A number of well-placed exploratory tests have been drilled in the basin without success. The black bituminous basal member of the Tanezzuft shale extends over a wide area of the basin, buried beneath a thick sequence of Devonian and Carboniferous rocks. It is now highly mature, but could once have generated a considerable amount of oil and gas. Hydrocarbon shows are fairly widespread and it is likely that these represent the remnants of one or more pre-Hercynian petroleum systems, destroyed during late Hercynian or Tertiary unroofing. A speculative reconstruction of the region suggests that two or three may once have been active in the basin. The most significant of these was prob-

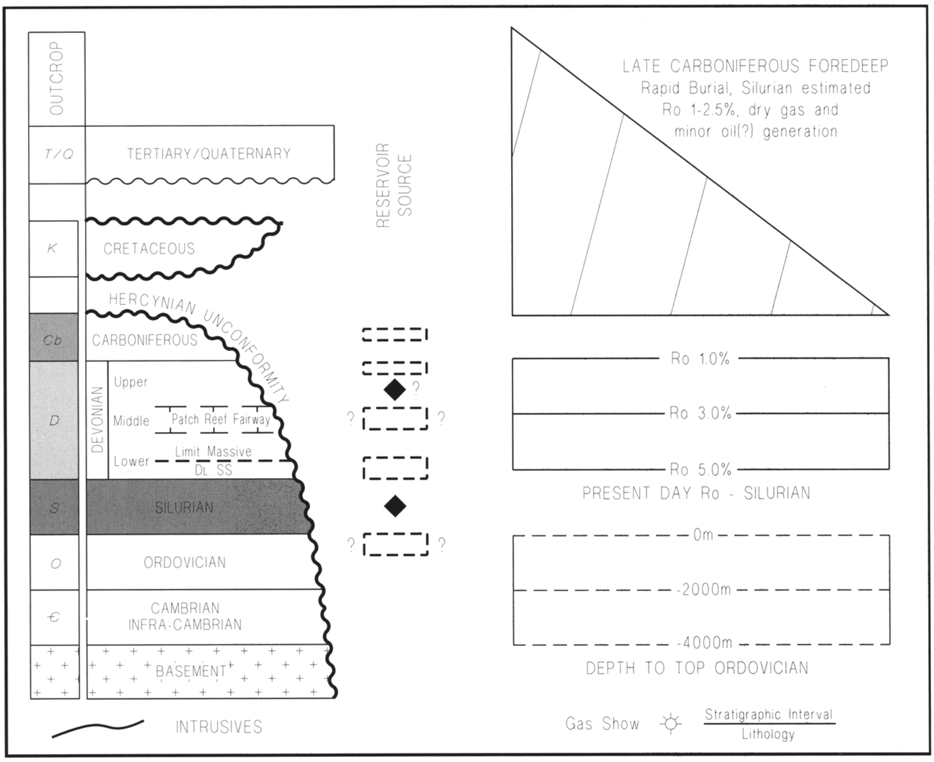


Fig. 20. Legend. Tindouf Basin extinct petroleum systems.

ably the Tanezzuft–Devonian (Carboniferous) system (Fig. 20).

Extinct Tanezzuft–Devonian (Carboniferous) petroleum system. Early Hercynian orogenesis commenced in late Devonian to earliest Carboniferous with the uplift of the Anti-Atlas and Ougarta Ranges and active subsidence of the Tindouf Basin. During the Carboniferous, the Tanezzuft within this foredeep was buried beneath a thick wedge of detritus shed from the rising orogen. By late Carboniferous, it achieved maturities of 1.0–2.5% R_0 along the northern flank with significant generation of oil and gas. There are few porous conduits in the overlying Silurian and Lower Devonian but fractures and faults associated with growing syn-orogenic structures may have encouraged vertical migration into Upper Devonian and Lower Carboniferous reservoirs above. Residual hydrocarbon shows now present in these structures are thought to represent palaeo-accumulations formed during this time.

As in the northern margin of the basin, the Tanezzuft on the southern flank must have generated considerable volumes of oil and gas. However, in contrast to the north, a Lower Devonian sandstone sequence is well developed in this part of the basin and could have provided an efficient lateral hydrocarbon conduit to charge low-relief fault closures further south.

As intensity of deformation increased during the late Hercynian, the Tanezzuft Shale in the foredeep reached an extremely high level of maturity ($>3.0\%$ R_0). It appears too high to be explained by overburden alone and is probably related to regionally elevated heat flow associated with widespread igneous intrusive activity. At these elevated temperatures, reservoired hydrocarbons in the deeper northern part of the basin would have been thermally destroyed, and with continuing deformation, uplift and unroofing, structural traps must surely have been breached. Maturities of the Tanezzuft Shale along the southern flanks of the basin are also believed to have increased at this time (0.6–3.0% R_0) in response to the regionally elevated heat flow. Expulsion and lateral migration may have continued to charge fault traps to the south with increasingly higher maturity oil and gas. Residual gas shows found in the Devonian and Ordovician may be the remnants of such accumulations.

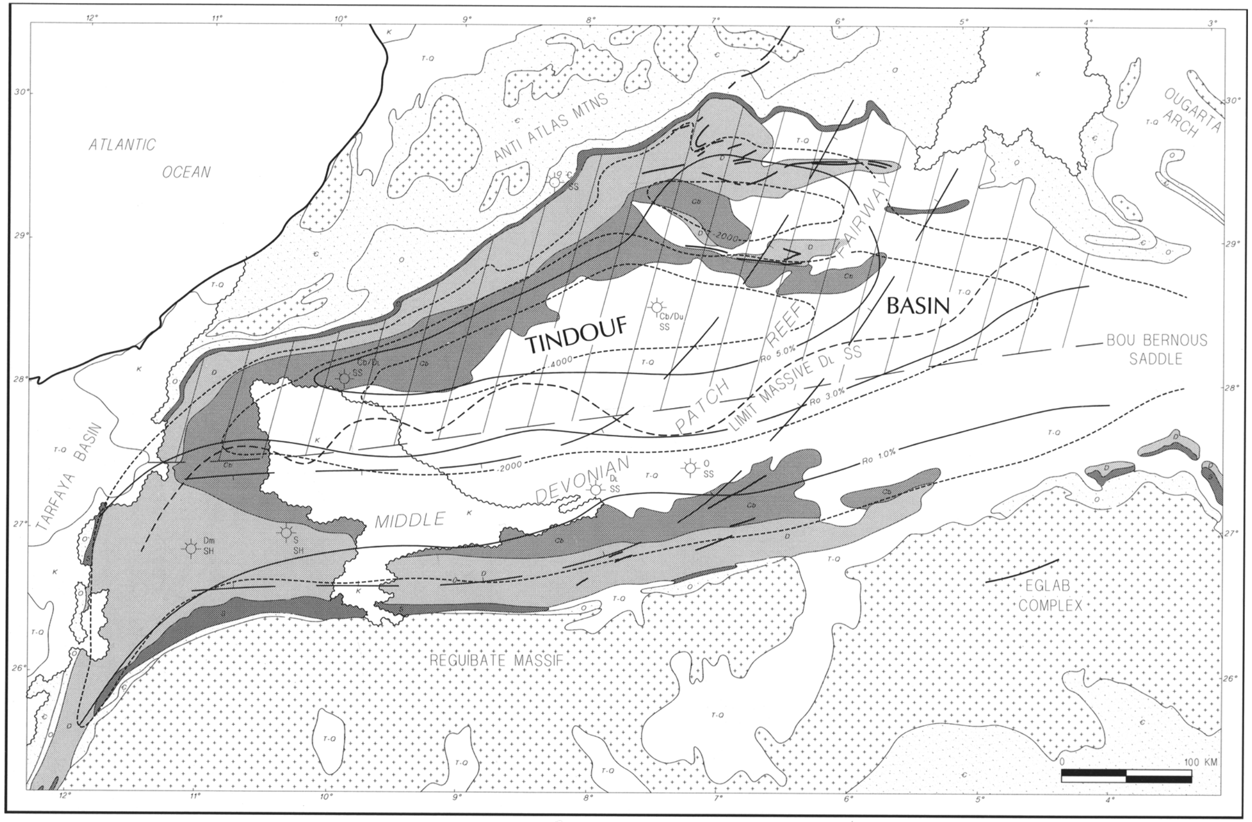


Fig. 20. (**a**) Tindouf Basin, extinct Palaeozoic petroleum system summary map (see Fig. 2 for location). Residual hydrocarbon shows suggest one or more petroleum systems were active in the Tindouf Basin before Hercynian uplift and unroofing. These palaeo-accumulations are presumed to have been sourced from Tanezzuft Shale (with perhaps a minor contribution from the Upper Devonian), now very mature throughout the basin as a result of Late Devonian–Carboniferous burial and regionally elevated heat flow. The distribution of the postulated Tanezzuft source rock is defined by the mapped outcrop. Hydrocarbons generated on the northern side of the basin probably migrated vertically via syntectonic faults into Upper Devonian–Lower Carboniferous sandstones, whereas a more widespread Lower Devonian sandstone may have provided a conduit for hydrocarbons migrating laterally to the south. A Devonian patch reef trend projected across the basin from outcrops on either side may have been associated with a second system.

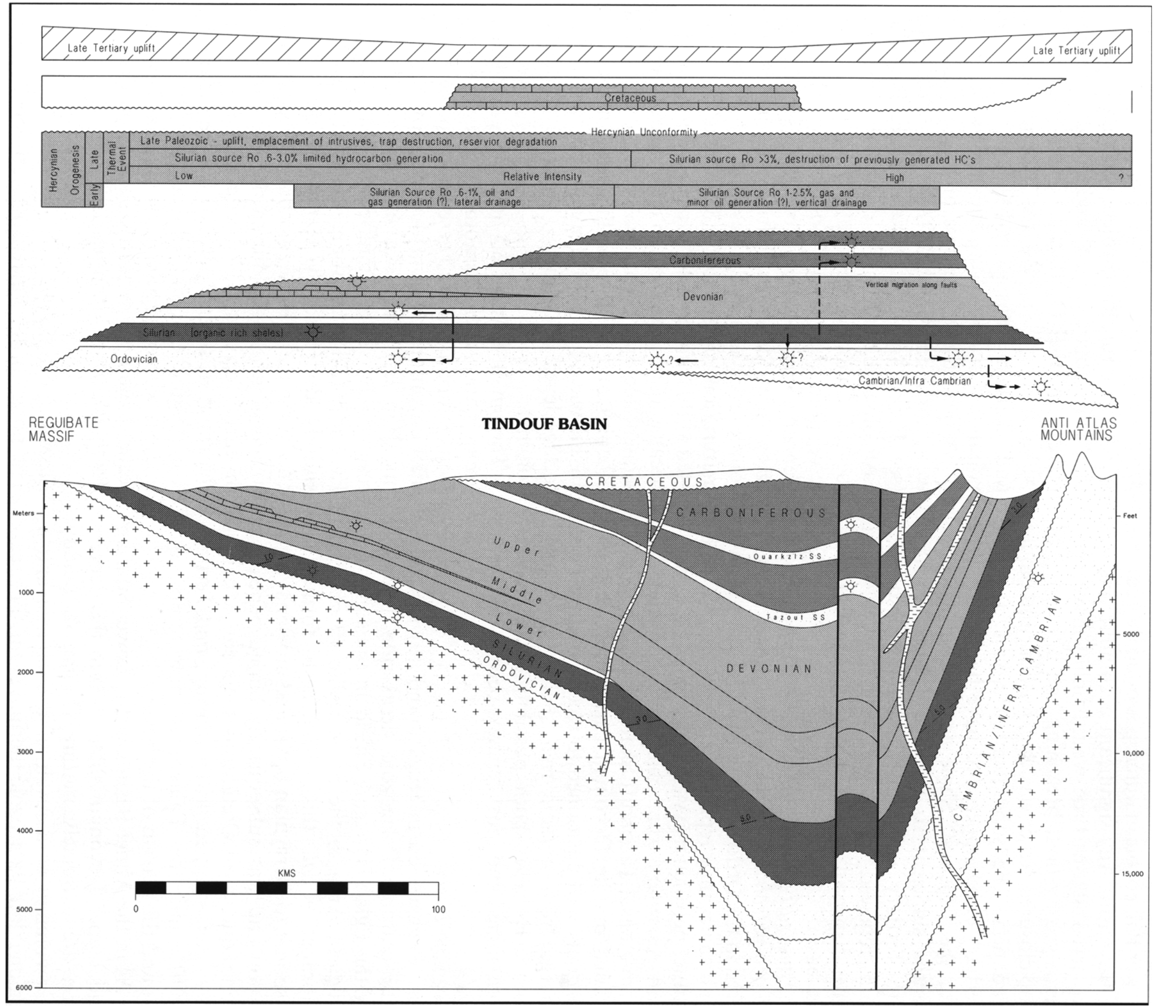


Fig. 20 (**b**) Critical elements analysis for extinct Tindouf Basin petroleum system(s), illustrating the spatial relationship and relative timing of critical stratigraphic, structural and thermal factors which may have been responsible for hydrocarbon entrapment and subsequent dispersal in the Tindouf Basin. Maximum Tanezzuft Shale maturities are highlighted and postulated preferred vertical and lateral migrations directions are suggested.

Late Hercynian deformation culminated with uplift and erosional unroofing, exposing the Lower Palaeozoic in outcrop around the margins of the basin. Any significant accumulations still preserved at this time would finally have been destroyed by fault breaching and late tilting of trap closures, water washing, flushing and biodegradation. The subsequent Mesozoic to early Tertiary cover appears to have been fairly thin and the Tanezzuft Shale never again achieved depths sufficient to renew expulsion. Further late Tertiary uplift and unroofing associated with renewed freshwater aquifer flow, must have dispersed any remaining hydrocarbons in the basin.

Tanezzuft–Ordovician and Intra-Devonian palaeo-petroleum systems. Gas shows encountered in the Ordovician and middle to late Devonian shales may represent the remnants of other extinct petroleum systems. It is possible Ordovician reservoirs were charged by downloading from a basal Tanezzuft Shale source, and a postulated middle Devonian carbonate trend was certainly well positioned to receive hydrocarbon charge from organic rich shales immediately above. However both possibilities are weakly constrained and must remain speculative.

Reggane Basin.
The Reggane Basin (Figs 2 and 19) is a large intra-cratonic Palaeozoic depression bounded by the Eglab (Hoggar) Shield in the south and Ougarta Arch to the north (Aliev *et al.* 1971; Morabet *et al.* this volume). It formed in response to Hercynian uplift and erosional truncation and was subsequently buried beneath a thin sequence of Cretaceous sediment. Much of this was stripped away during mid-Tertiary uplift, and the Palaeozoic now crops out around the margin of the basin.

As in the Ahnet Basin nearby, Lower Silurian and Upper Devonian shales within the depression are extremely mature (Logan & Duddy this volume) as a result of deep burial and a regional late Palaeozoic thermal event. The scattered oil shows and a small gas accumulation encountered in the northern part of the basin (Boudjema *et al.* 1990) may be the remnants of a pre-Hercynian petroleum system(s) later dispersed during Hercynian and mid-Tertiary uplift and unroofing. The relative frequency of hydrocarbon shows within Lower Devonian sandstones of the basin suggests these may once have provided the reservoir for a Lower Silurian sourced system. However, other porous sands are developed in the Cambro-Ordovician and Carboniferous and could also have been important.

Marginal to non-productive basins

Moroccan Basins.
A Silurian-sourced petroleum system is present in the Essaouira Basin, and could once have existed in the Doukkala, Tadla (Jabour & Nakayama 1988), Rharb, Boudenib–Bechar and Tarfaya Basins (Morabet *et al.* this volume). Located along the northwest margin of Africa, these intra-cratonic sag basins lie west, north and northeast of the Tindouf Basin (see Fig. 2 for location; the Tadla Basin lies east of Doukkala). All except the southerly located Boudenib–Bechar and Tarfaya Basins have been extensively modified by Mesozoic/Cenozoic compressional tectonics (see Fig. 12). Deep pre-Hercynian burial of the Silurian source rock generally resulted in Palaeozoic maturation and expulsion. Hydrocarbons generated at this time had a low preservation potential because of the strength and complexity of subsequent tectonic events (see Fig. 3), and effects of uplift and freshwater flushing. In the south an intrusive-related thermal event contributed to high levels of maturity (Logan & Duddy this volume).

The small Triassic oil and wet gas Meskala accumulation of the Essaouira Basin was sourced from Silurian shales. These subcrop the Hercynian unconformity immediately below the accumulation and charged a silty fluvial sandstone reservoir by vertical fault-controlled migration. Evidently Silurian source capacity was not entirely destroyed by Hercynian deformation and subsequent Mesozoic burial was sufficient to renew generation during the late Cretaceous or early Tertiary. The accumulation is clearly the result of several perhaps unique factors but it is possible that similar fields may be present in areas where the Silurian source has been protected from over-maturity, such as on the more gently deformed offshore shelf.

Eastern Libya–Egypt.
The potential for Palaeozoic petroleum systems in eastern Libya and Egypt has been identified on the southern platform of Egypt, in the Kufrah Basin and in Cyrenaica (Figs 2, 6 and 7).

The Kufrah Basin is a large intra-cratonic depression bounded by the Tibesti Massif to the west and the Jebel Awaynat High in the east (Bellini & Massa 1980; Pallas 1980; Turner 1980; Bellini *et al.* 1991; Gumati *et al.* 1996). The Palaeozoic succession was once part of the regionally extensive Gondwana platform sequence with very similar facies to the Murzuq. The basin first developed as an intra-cratonic sag during the late Hercynian phase of deformation and was subsequently buried unconformably beneath poorly dated Jurassic(?) and Cretaceous continental Nubian clastic deposits. Later mid-Tertiary uplift and erosional unroofing of the surrounding highs exposed the Palaeozoic in outcrop around the basin margins.

Although very lightly explored, with only four deep exploration tests, the basin is considered unprospective. The Tanezzuft Shale equivalent sequence appears significantly more silty than elsewhere, and is difficult to distinguish from the Acacus Sandstone Formation. A full geochemical analysis of its source capacity is not available but published lithological descriptions suggest it is probably fairly lean (Bellini *et al.* 1991). Furthermore, it was never deeply buried and probably only reached maturity locally in the deepest part of the basin (Keeley & Massoud this volume). Any early crudes generated before mid-Tertiary uplift and unroofing were probably dispersed by the very extensive meteoric invasion and flushing which followed.

In coastal Cyrenaica, northeast Libya, a Palaeozoic petroleum system has been suggested by the drilling of well B1–2 (Sola & Ozcicek 1990). Non-commercial gas in Late Carboniferous reservoir sands was generated from Carboniferous gas-prone shales buried deeply off-structure to the north (Keeley & Massoud this volume). Intraformational shales provide the seal for this trap which was charged from the Late Jurassic onwards. The system is believed to extend eastwards into offshore Egypt.

Discussion

Petroleum system characteristics

Despite the relative geological simplicity of the Saharan Platform, the Palaeozoic-sourced petroleum systems it harbours vary widely in character and productivity (Tables 1–4). This reflects differences in source charging efficiency, migration drainage style, critical period and degree of impedance or dispersal (Demaison & Huizinga 1994) as described below.

Charge factor. The Tanezzuft and Frasnian source rocks responsible for these petroleum systems are regional in extent, and local variations of thickness and quality appear too small to have much direct effect on their charge factor. However, charge is strongly influenced by drainage area. Extremely efficient charging was facilitated by proximity of large volumes of mature source rock with regionally continuous intra-Palaeozoic and basal Triassic migration conduits. Efficient charge was further enhanced locally by fracturing and faulting offsetting source rock intervals against primary carrier beds.

Migration drainage style. The exceptional stratigraphic continuity of the Palaeozoic and basal Triassic succession provided multiple regionally continuous migration conduits. In less structurally deformed parts of the Saharan Platform this allowed lateral migration to occur over very long distances. Vertical migration was significant only in faulted and deformed areas such as the Ahnet–Gourara depression, the Amguid–Hassi Touareg axis and perhaps formerly in the Tindouf and Reggane Basins before their uplift and unroofing.

Critical period. The relative timing of trap charge varies widely. Although speculative, it seems likely that most of the pre-Hercynian accumulations in the Tindouf and Ahnet–Gourara Basin, and elsewhere, were predominantly gas and gas condensate. A tentative reconstruction of their history suggests that the Tanezzuft source rock had reached relatively high maturities by the time associated traps had begun to form. Consequently, a significant part of their charge was probably late stage.

The relative timing of charge and formation of post-Hercynian traps is not always well constrained. Nevertheless, the Hassi Messaoud closure is clearly Hercynian, although later enhanced by differential subsidence of the flanking basins. Certainly, it was well timed to receive an oil charge. In contrast Hassi R'Mel achieved closure only during the later Cretaceous, some time after its primary generative pod in the Benoud Trough had reached gas-generating maturities.

Further to the south, the Hassi Touareg and Rhourde Chouff area accumulations developed in Austrian aged traps after the Tanezzuft source in the adjacent basin had passed through the oil generating phase. At least some structures in the Illizi Basin developed early during the Hercynian, either forming closures at that time or later, after Austrian uplift and regional tilting. Certainly they existed throughout the main period of expulsion from the Tanezzuft and Frasnian source rocks in late Jurassic to Cretaceous and were available to receive both oil and later gas. Based upon limited information, the recently discovered Ghadames Basin accumulations appear to be trapped in very low relief Austrian (and perhaps Jurassic) aged closures, and were charged in the late Cretaceous.

Entrapment style. In this region of high-continuity sand conduits and robust shale and evaporite seals, entrapment style, or impedance, was largely dependent upon basin geometry and degree of structural deformation. In the less deformed parts of the platform, broad regional arches such as the Tilrhemt and Hassi Messaoud Domes focused migration very efficiently and the associated petroleum systems are of very high impedance. In contrast, the gentle synclinal form of adjacent depressions encouraged dispersal and only local focusing along intra-basin structural axes. With very subtle low-relief closures, both the Oued Mya and Ghadames petroleum systems were probably of moderate impedance, with large volumes of hydrocarbons escaping to the south beyond the evaporite seal. Structural traps are more common in the Illizi Basin, where the petroleum systems may have been of rather higher overall impedance as a result. Although sealed by shales rather than evaporites, they were only very mildly deformed and so largely retained their trapping integrity. Even where faults or local erosional windows in intraformational seals allowed hydrocarbons to move up into overlying conduits, still higher shales were present to act as new seals.

In structurally more deformed areas with greater frequency of high-amplitude traps, associated petroleum systems were of relatively high impedance locally, and seal integrity has sometimes been maintained to the present. This appears to have been the case in the Ahnet–Gourara depression. Elsewhere, large displacement faulting, such as at the southern end of the Hassi Touareg horst, rendered the Triassic–Liassic evaporite seal locally ineffective by offsetting reservoir against Cretaceous sandstones. As a result, the associated petroleum system is less productive than in the structurally similar but less faulted Rhourde Chouff area further south.

Post-charge destruction processes. Pre-Hercynian petroleum systems in the Tindouf and Reggane Basins, and elsewhere, were all largely destroyed by Hercynian or later Austrian unroofing. However, significant gas accumulations still remain in the Ahnet–Gourara depression. At least some of the hydrocarbons originally reservoired in this basin must have been dispersed by spillage or vertical leakage through faults and hydrodynamic flushing along the basin margin while anticlinal traps in the central part have preserved their sealing integrity.

Austrian deformation and uplift almost certainly had a very significant impact upon petroleum systems initiated earlier in the Mesozoic and Late Cretaceous gas flushing appears to have been significant in deeper reservoirs of the northern Illizi area. However, these earlier destructive processes were overshadowed by mid-Tertiary uplift and unroofing, which had a profound influence upon the entire region. Its effect was fairly mild in the central and northern part of the Triassic Basin. The large regional culminations of Hassi R' Mel and Hassi Messaoud were entirely unaffected, with only minor spillage and remigration from low-relief accumulations in adjacent depressions. However, the eastern flank of the Ghadames Basin was strongly tilted in response to uplift along the Djeffara–Nefusa Arch and although the broad El Borma structure retained its closure, smaller low-relief pools nearby were partially or completely dispersed by spillage and hydrodynamic flushing. The region to the south and west beyond the Triassic–Liassic evaporites was even more strongly affected. Hydrodynamic flushing was especially severe in the Hamra Basin as a result of uplift and unroofing to both north and south, and accumulations in the Illizi Basin are in various phases of dispersal as a result of regional tilting and flushing. However, large volumes of oil and gas are still retained in this basin suggesting the process of dispersal is only in a very early phase.

Hydrocarbon productivity; controlling factors

With broadly equivalent charge factors and multiple reservoirs, seals and traps, differences in productivity between Palaeozoic-sourced petroleum systems of the North African Platform appear to be directly related to migration and entrapment style and post-charge destructive processes. These can be considered in three broad categories.

Mesozoic to early Tertiary charged systems with Triassic–Liassic evaporite seals (Tables 1 and 4). The Hassi R'Mel and Hassi Messaoud fields contain *c*. 56% of the reserves in the entire province. They owe their enormous size to their position on large regional structural arches, with extremely high impedance trapping style. In contrast, the Northeast Oued Mya and Frasnian sourced Ghadames Basin systems rely upon very local migration focusing along gentle intra-basinal structural axes immediately above or just updip of the subcropping source. The Triassic sands form excellent conduits in both basins, largely unaffected by faulting. These systems appear to be of rather lower impedance, allowing large volumes of hydrocarbons to dis-

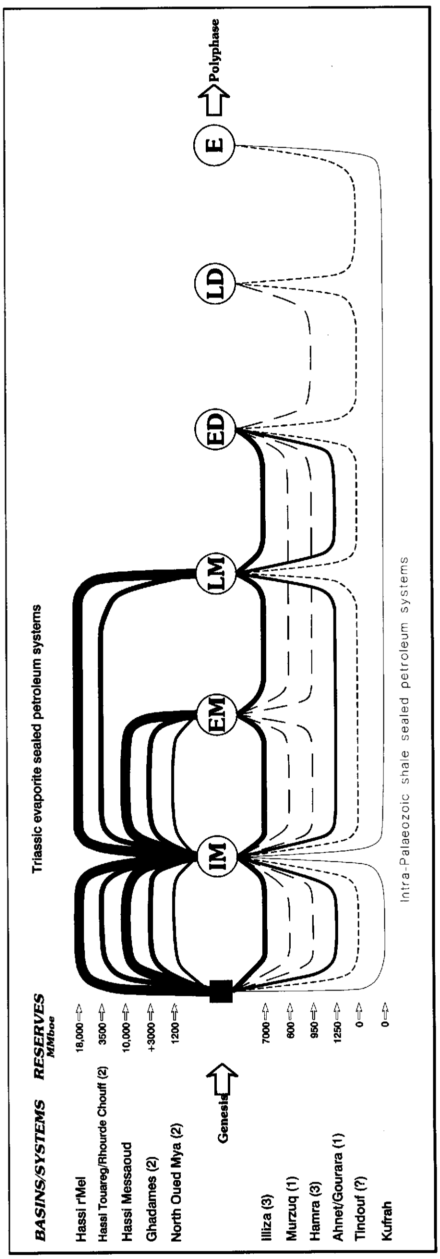


Fig. 21. Evolution of North African Palaeozoic petroleum systems; a working model illustrating the evolution of the main Palaeozoic-sourced petroleum systems of Algeria and western Libya from initial genesis through immaturity (IM), early maturity (EM), late maturity (LM), early destruction (ED) and late destruction (LD) to extinction (E). The thickness of the lines provides a relative measure of the productivity of the systems.

perse and escape by long-distance lateral migration, except where captured by regional arches.

The small reserves associated with the Northwest Oued Mya system are probably a reflection of limited trap volume as well as inefficient migration focusing. The area is entirely overshadowed by the Tilhremt Dome and may have experienced significant late tilting. The Tanezzuft-sourced system of the eastern Ghadames Basin is dominated by El Borma. This was preserved by a very robust closure on the culmination of a regional arch but other fields in the area are now very small, presumably as a result of post-charge tilting and spillage from once larger accumulations.

Differences in productivity between the three petroleum systems along the Amguid–Hassi Touareg Ridge are thought to be related to the distribution of adequate traps. Despite the frequency of high-amplitude structures along the trend, their trapping effectiveness is often limited by across-fault seals. The southern Tanezzuft–Triassic system is very productive because of relatively lower amplitude structures and more effective fault seals. In contrast, the central Hassi Touareg system is significantly less productive because of higher-amplitude structures and greater fault displacements with more frequent across-fault juxtaposition of reservoir against younger sands. The northern system is also relatively less productive because of poorer reservoir quality and fewer structural traps.

Mesozoic to early Tertiary charged systems with intra-Palaeozoic shale seals (Tables 2 and 4). Petroleum systems in the Illizi Basin, reservoir very large volumes of hydrocarbons. The reason for this high productivity is not entirely clear. However it may reflect the frequency of optimally positioned traps with multiple reservoir–seal pairs, and the effects of efficient migration focusing along low-relief intra-basinal structural axes, immediately updip of the generative area. Although these systems are now undergoing post-charge regional tilting and hydrodynamic flushing, this has been fairly limited so far and most of the hydrocarbons originally trapped are probably still retained.

The Hamra Basin is stratigraphically similar to the Illizi, with similar reservoir and source rocks. However, it is very much less productive. Any estimate of hydrocarbon volume originally reservoired in the basin must remain entirely speculative but it could have been significant. Late-stage basin tilting and hydrodynamic flushing is now very severe, and the small scattered pools which remain may represent the remnants of once much larger accumulations.

The Murzuq Basin to the south is also relatively unproductive. Hercynian and Austrian uplift and unroofing would have dispersed most early generated hydrocarbons from the western palaeo-depocentre, whereas later Cretaceous to early Tertiary burial was limited and only a very small area in the central part of the modern basin reached maturity. Consequently, the Tanezzuft–Cambro-Ordovician system was relatively undercharged. Furthermore, because of the gentle structural relief, significant volumes of hydrocarbons generated in the central part of the basin may have been dispersed by long distance migration to the north or by hydrodynamic flushing in the west.

Palaeozoic-charged systems with intra-Palaeozoic shale seals (Tables 3 and 4). Once fairly prolific petroleum systems probably existed in the south-western and western intra-cratonic basins of Algeria and Morocco, to be destroyed by later uplift and unroofing. The Ahnet-Gourara depression was strongly folded with many large anticlinal traps, and probably always reservoired far larger volumes of hydrocarbons than the less deformed Reggane and Tindouf Basins. Significant reserves still remain, although these may represent the remnants of an originally more prolific system(s). The relative frequency and size of traps, combined with the still very robust shale seals, point to a relatively high impedance system(s). Furthermore, their high amplitudes, would have tended to reduce the effects of later Mesozoic and Tertiary tilting and hydrodynamic flushing.

Accumulations in the neighbouring Sbaa Basin are very small and as in the Ahnet–Gourara depression, may represent once larger accumulations now partially destroyed by later tilting and flushing.

Conclusion

Large volumes of hydrocarbons have been generated, trapped and sometimes dispersed on the North African Platform since the Late Palaeozoic. Petroleum systems charged by Lower Silurian Tanezzuft and Upper Devonian source rocks developed around discrete sedimentary depocentres, first in the Palaeozoic and later during the Mesozoic and early Tertiary. Most of the hydrocarbons generated during the Palaeozoic were dispersed by later uplift and unroofing, whereas all the Mesozoic charged petroleum systems now lie directly beneath or around the Mesozoic sag basin of eastern Algeria, southern Tunisia and western Libya.

In this structurally simple region with highly continuous reservoirs and seals, intimately associated with excellent source rocks, productivity of active petroleum systems varies according to migration style and effectiveness of migration focusing, degree of impedance and stage of maturity. The petroleum systems range from those of the enormous Hassi Messaoud and Hassi R'Mel accumulations (56% of the total reserves in the region), characterized by broad regional culminations with very efficient migration focusing and high-impedance entrapment style, to the Hamra Basin systems (2% of total reserves) with small scattered pools now largely dispersed by hydrodynamic flushing.

Each of these systems is ephemeral in various stages of an evolutionary cycle from initial genesis, to maturity, destruction and final extinction (Fig. 21). The Triassic–Liassic evaporite sealed systems of the northern 'Triassic Basin' are all now in a mature phase of evolution. Hassi Messaoud and the Ghadames and Oued Mya systems are in early (oil-dominant) maturity, whereas Hassi R'Mel and the Hassi Touareg and Rhourde Chouff systems bypassed this phase and are now in late (gas-dominant) maturity because of later trap development. The southern intra-Palaeozoic shale sealed systems are in a more advanced stage in their evolutionary cycle, because of their position on the flanks of the Mesozoic depocentre away from the evaporite seal. Petroleum systems in the Illizi Basin appear to have passed through maturity and are now just starting to disperse, whereas those in the Hamra and Murzuq Basins moved directly from early maturity to a more advanced phase of destruction. The majority of the pre-Hercynian petroleum systems once active in the Tindouf, Reggane and Moroccan Basins are now extinct. Only the Ahnet–Gourara gas dominated system has been preserved into late maturity–early destruction, since its charge in the Late Palaeozoic.

From an initially very simple concept this paper expanded almost uncontrollably into its present size. A number of people helped to make it possible. J. Kidd, J. Means, W. Stewart and S. Elcano as well as others in the Occidental draughting department converted very obscure scribblings into legible illustrations. Without their creativity and persistence these very complicated diagrams would not have been practical. K. Alvarez typed the manuscript (and retyped it many times) and D. Monckton improved the English. Their support, patience and encouragement over what seemed like an interminable length of time is very much appreciated. S. Mills and D. Macgregor reviewed the text and suggested significant improvements. The management of Occidental International Exploration and Production Company is thanked for approving its publication. Imperial College Geology Department is thanked for its assistance in providing one of the authors with a research fellowship on North Africa. Assistance is also gratefully acknowledged from Anglo Siberian Oil Company with the preparation of some of the numerous drafts of this text and for some of the figures.

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