A review of the East Algerian Sahara oil and gas province (Triassic, Ghadames and Illizi Basins)

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Introduction
Algeria has enjoyed renewed interest from international exploration and production companies in the last few years. This is the result of an active policy of encouraging foreign investment by the Algerian government. Many companies have taken, or are in the process of negotiating, licences in the well-known East Algerian oil province as well as in other areas. Several new discoveries have already been reported by Agip, BHP, Cepsa and Anadarko from the Ghadames basin in East Algeria, suggesting that areas with untapped potential still exist. A large amount of geological literature is relevant to these hydrocarbon-bearing basins. Most of this is in French and often in journals that are not easily accessible. The aim of this paper is to summarize the relevant literature into a short overview of the East Algerian oil province.

The oldest hydrocarbon discovery in the East Algerian Sahara dates from 1956 and since then over 14 billion barrels of oil and 100 tcf of gas have been found. Most of these reserves were found before 1965. Reserve additions after 1965 have been relatively insignificant, suggesting that the area has reached a mature exploration stage. Originally, French energy companies dominated the area, but after Algeria gained its independence the oil and gas industry was gradually nationalized. In recent years Algeria has strongly encouraged foreign investment in exploration and development, in an attempt to reverse the trend of rapid depletion of reserves. The result of the new policy is that tracts covering most of the eastern Saharan oil basins are now leased to a variety of foreign oil companies. In addition, Algerian authorities have invited private operators to take over operatorship of several fields in an advanced stage of depletion in order to implement EOR methods.

Geological setting
Several Palaeozoic basins exist on the northern edge of the African craton. From west to east the following basins or sub-basins may be recognized (Fig. 1): the Tindouf, Reggane, Sbaa, Timimoun, Ahnet, Mouydir, Illizi, Mourzouk and Kufra basins (the latter two are in Libya). These basins are the result of Hercynian (late Palaeozoic) tectonic movements. Before the Hercynian orogeny the North African craton was one large and flat depositional basin with little regional differentiation. Uplift, deformation and deep erosion during the Hercynian orogeny removed large parts of the Palaeozoic section in most areas. Subsequently a Jurassic–Cretaceous basin (the ‘Triassic basin’ and its eastern continuation the Ghadames basin; see Fig. 1) became established on the eroded remains of the Palaeozoic basin. Similarly a Late Cretaceous–Early Tertiary basin (the Sirte Basin; Fig. 1) is superimposed on deeply eroded Palaeozoic strata in the Libyan area. Mesozoic and Tertiary strata are over 4000 m thick in the centre of the Triassic basin (Fig. 2). The general structure of the Triassic basin and underlying Palaeozoic basins are shown in the cross-sections of Figs 3, 4, 5, and 6.

Several rich source-rock horizons are known in the Palaeozoic succession. Deep burial during the Mesozoic resulted in maturation of source rocks. Hydrocarbons accumulated in Palaeozoic clastics of the Illizi basin and in Lower Palaeozoic and Triassic clastics of the Triassic basin. Thick uppermost Triassic and Jurassic salt deposits form a ‘super’ seal in most of the Triassic basin. The large Triassic basin may be subdivided into three parts (Fig. 2):

- The NW part is also known as the Oued Mya Basin. Only Silurian and older rocks are preserved below the Mesozoic succession. Hassi R' mel and Ben Khala are important fields in this part of the basin.
- The Amguid El Biod–Hassi Messaoud Zone is a NNW-oriented zone of faults separating uplifted and down-faulted blocks. Many faults originated in the Palaeozoic, but were reactivated during the Hercynian orogeny and in the Cretaceous. This fault zone is a part of the system of major fault and rift zones subdividing Africa (Guiraud and Maurin 1992). Hassi Messaoud, Rhourde el Baguel and Rhourde Nous are important fields in this area.
- The Ghadames (or Rhadames) Basin shows a fairly complete Palaeozoic succession below the Mesozoic with Upper Carboniferous rocks preserved. Oil and gas fields are in Devonian and Triassic sandstones. Most of this area is covered by Pleistocene sand dunes.

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of the Great Eastern Sand Sea. The presence of these dunes has resulted in poor seismic data and difficult access in the past. New technologies and careful (re)processing have resulted in dramatically improved seismic data, leading to several new discoveries. The large El Borma field straddles the Tunisian-Algerian border; its oil is in Triassic sandstones.

Just south of the Ghadames Basin is the productive Illizi (or Fort Polignac) basin (Fig. 2). This area is near the depositional edge of the Lower Mesozoic. Here, many oil and gas fields are in Ordovician, Silurian and, most importantly, Devonian sandstones. Smaller accumulations have been reported from Carboniferous sandstones.

The Palaeozoic of the Illizi Basin
Palaeozoic strata in the Illizi Basin are 2000–3500 m thick. Traditionally the Cambro-Ordovician succession in the Sahara has been subdivided into four units (Fig. 7): Unit I consists of coarse sands and conglomerates at places preserved in pockets in the Precambrian basement. It is absent in the Illizi basin.

Unit II (Ajers Formation in outcrop) consists of non-fossiliferous sandstones and shales up to 250 m thick in places in the Illizi Basin, but absent in the eastern and northeastern part of the basin over the Tihemboka Arch (Fig. 2). Three formations have been recognized in the Illizi Basin: the Hassi Leila Sandstones, the In Kraf
Fig. 2. Sketch map of the Triassic basin showing depth to the Hercynian unconformity, major faults in the Amguid El Biod–Hassi Messaoud fault zone and some major oil and gas fields. The -1000 m isochore is also on Fig. 1 for ease of comparison. An arrow indicates the area with new discoveries in the Ghadames basin. 1 = Hassi R'Mel, 2 = Hassi Messaoud, 3 = El Borma, 4 = Houd Berkaoui, 5 = Ben Kala, 6 = El Agreb, 7 = Rhourde el Baguel, 8 = Messdar, 9 = Nezza, 10 = Gassi Touil, 11 = Hassi Touareg, 12 = Hassi Chergui, 13 = Brides, 14 = Rhourde Nous, 15 = Hamra, 16 = Tin Fougé, 17 = Ohanet, 18 = Merksene, 19 = Aïtar, 20 = Zarzaltine, 21 = Edjeleh.

Fig. 3. NE–SW cross-section A–A' in the Triassic basin. Line of section shown in Fig. 2. (Adapted from fig. 4 of Magloire 1970).
shales-sandstones with the ichnofossil Tigillites (= Scolites) and the Hamra Quartzites with Tigillites. The Hassi Leila and Hamra Formations contain gas and oil in places, but reservoir characteristics are poor. Unit III (In Tahouite Formation in outcrops) has a facies which is largely transitional between non-marine and marine. It is the Edjeleh Formation in the Illizi Basin and it consists of alternating sandstones and shales with intervals rich in marine fauna, including Tigillites and graptolites. It is unconformable and transgressive over older units and has a conglomeratic base. Eruptive volcanics are present in places.

A major unconformity surface is present below Unit IV: the infra-Ordovician Unconformity of Beuf et al. (1971). In most areas it is an erosional surface of glacial origin, in places it is an angular unconformity.
Unit IV (Tamadjert Formation in outcrop) is a heterogeneous clastic complex, consisting of micaceous shales (locally rich in quartz grains and clasts), sands and conglomeratic sands. This unit, the Gara Louki Formation, is of glacial origin (Beuf et al. 1971; De Charpal et al. 1971). It fills and covers the infra-Ordovician unconformity surface. Glacial valleys and heterogeneous valley fills have been recognized in outcrop and in the subsurface. Oil and gas are present in sandstones in some structures but reservoir characteristics are poor.

Silurian graptolitic shales overlie Unit IV with a flat contact surface and almost without transitional lithologies, suggesting a rapid transgression. The Silurian (‘Gotlandian’ in the older French literature) has been subdivided into a lower clay-rich unit (‘Argileux’, up to 400 m) and an upper sand-rich unit (‘Argileux-Greseux’ or ‘zone de passage’; 150 m). The base of the clay-rich unit is a transgressive shale, which is organic rich (up to 30% TOC; Tissot et al. 1973), radioactive, and an important source rock. Demaison (1984) mentions a thermal maturity between 0.6–1.0 Ro for the oil productive part of the Illizi Basin and 1.6–1.7 Ro for the southwestern part (Tissot et al. 1987). Towards the north, below the Mesozoic cover (Fig. 5), Ro values also increase.

Devonian rocks in the Illizi Basin consist of a succession of shales and possibly deltaic sands up to 1000 m thick. Marine influence increases towards the north or north-west. Productive sand units have been labelled F6, F5, F4, F3 and F2. An approximately NNW-oriented high, the Tihemboka Arch (Fig. 2) is located near the border with Libya. It was a positive feature in the Palaeozoic, and often tectonically active. Stratigraphic thinning towards the Tihemboka Arch and several periods of tectonic activity causing local uplift and erosion have complicated the stratigraphy in the area. Beuf et al. (1971) described three erosional unconformities in the Lower Devonian from outcrops south of the Illizi Basin. Boudjema (1987) and Claracq et al. (1963) show several Lower, Middle and Upper Devonian angular unconformities (Fig. 9). The Frasnian unconformity is followed by Upper Devonian marine transgressive shales which cover the Tihemboka Arch. The basal part of this Upper Devonian shale unit has high TOC values, is radioactive and an important source rock in the Illizi and Ghadames basins. F2 sands are followed by another unconformity.

The Carboniferous is characterized by rapid facies changes which render lithological correlations difficult. The succession is up to 1200 m thick and consists of shales with some minor sandstones and carbonates. A few hydrocarbon accumulations of limited size are present in Carboniferous sandstones.

Tissot et al. (1973) investigated relations between hydrocarbons and source rocks in the Illizi Basin. Three types of oil could be chemically differentiated and correlated with three different sources: an Upper Devonian, a Lower Silurian and an Upper Silurian-Lower Devonian source. The first two sources are well known from the literature (Fig. 7); however, no other references have been found regarding the Upper Silurian-Lower Devonian source.
Palaeozoic strata below the Triassic basin

A thick unit of Cambrian fluviatile sandstones is present over an extensive area in North Africa. These sandstones are exposed in the ranges of the south (Fig. 1) and produce oil in the Hassi Messaoud, Rhourde el Baguel and El Aget fields. In the area of the Hassi Massaoud field these sandstones have been subdivided, based on lithology, into three units – R3, R2 and Ra – which together are about 500 m thick (Fig. 8). R3 is a poorly bedded shaley sandstone with some cross-bedding. R2 consists of well-bedded sandstones and siltstones, Ra consists of sandstones and may be subdivided into three zones as the lower and upper zones show cross-bedding, and the middle zone shows predominantly horizontal bedding and the ichnofossil Scolites. An angular unconformity is present on Ra which is overlain by the sandstones/siltstone and shale succession of Ri (L’Homer 1967). Tigliitites (= Scolites) is abundant in Ri. The presence of this ichnofossil probably suggests shallow-marine conditions. Ra is the main reservoir zone in Hassi Messaoud (Malenfer and Tillous 1963; Balducchi and Pommier 1970; Bacheller and Peterson 1991). Diagenesis and clay minerals control the reservoir quality of the sandstones. Similar sandstone reservoirs produce oil in the El Ager, El Gassi fields (Ali 1975) and the Rhourde el Baguel field (Allouani et al. 1992).

The Ordovician consists of a succession of marine shales and quartzites several hundreds of metres thick. Towards the north an increase in marine characteristics has been noted. Locally the Azzel Shales have a high TOC and are radioactive (e.g. in the Ghadames basin). Bacheller and Peterson (1991) suggest that the El Gassi Shales may have contributed to the hydrocarbons of the Hassi Massaoud field. The Hamra Quartzites may be over 300 m thick and are a gas reservoir in the Rourde Nouss and Nezla fields. Unit IV is a heterogenous clastic unit of glacial origin. In the south, glacial sediments overlying a glacial unconformity similar to those of the Illizi Basin have been described. In northern areas, marine environments persisted during the glaciations, resulting in deposition of shales. Clasts originating from drifting ice-rafts (dropstones) resulted in ‘microconglomeratic clays’.

Marine Silurian shales overlie the glacial sediments with a sharp contact. In northern areas where the upper Ordovician is in marine facies, the contact is less clear. Basal Silurian shales are black, laminated, organic-rich and radioactive. They are the main source for hydrocarbons in the area.

A phase of erosion following uplift and deformation (the Hercynian Orogeny) removed much of the Palaeozoic section. The effects of Hercynian erosion vary in different areas. A subcrop map of Palaeozoic
units below the Hercynian Unconformity is shown in Fig. 10.

**The Mesozoic and Cenozoic of the Triassic basin**

Figure 11 shows the stratigraphic column of the Mesozoic (for a comprehensive description see Boudjema 1987). Mesozoic and Cenozoic deposits reach a thickness of over 4000 m in the centre of the basin (Fig. 2). Clastics of Late Triassic age directly overlie the Hercynian Unconformity and are overlain, in turn, by a thick salt and evaporitic succession of early Jurassic age. Upper Triassic clastics are a major reservoir unit in the Triassic basin. Oil and gas reservoirs are not known higher in the section; therefore, only Upper Triassic strata will be briefly described below.

**The Upper Triassic clastic units**

The basal units directly on top of the Hercynian Unconformity are probably Upper Triassic (Boudjema 1987) and consist of non-marine sands and shales, marginal marine shales, carbonates and volcanics. The lack of diagnostic fossils precludes detailed age assignments and subdivisions. Triassic clastics are followed by thick evaporitic deposits of latest Triassic and Jurassic age. Older literature suggests a Permo-Triassic age for the pre-salt clastics and a Triassic age for the salt deposits. The Triassic sands are important reservoir units, hosting the giant Hassi R'Mel gas field (Delclaud 1960; Magloire 1970) and many oil fields, including Haoud Berkaoui, Ben Khala and El Borma.

Near Hassi R'Mel pre-salt Triassic clastics are about 160 m thick (Magloire, 1970) and may be subdivided into four lithological units. The lower unit contains an andesite. Ali (1973) suggested that lithological correlations could be carried over a distance of some 200 km as a result of dense well control. A study by Hamouda (1980) in the area near the Haoud Berkaoui and Ben Khala fields (Fig. 2) suggested that sands in the Triassic could be correlated over some distance using a 'sequential analysis'.

In the area of the Rhourde Nouss field Upper Triassic clastics are about 400 m thick and have been subdivided into three units (Claret and Tempère, 1967) (Fig. 12):

- the lower sand-clay succession or Nezla Formation ('Argilo-gréseux Inferieur'),
- the clay-carbonate succession or Oulad Nsir Formation ('Argilo-carbonaté'); and
- the upper sand-clay succession or Gassi Touil Formation ('Argilo-gréseux supérieur').

The lower unit thins rapidly towards the north. Sands in the upper unit shale out towards the north (Fig. 12). Both the upper and the lower sands are productive, although the number of hydrocarbon accumulations is larger in the upper sands (Claret and Tempère 1967). Volcanics of spilitic character towards the north exist at the level of the clay-carbonate succession, suggesting deeper marine environments (Claret and Tempère 1967).

Near the El Borma field the Upper Triassic clastic succession is also about 400 m thick, but its stratigraphy
is different (Boudjema 1987). The lower part consists of some 100 m of laterally variable sands and shales with volcanics in places. This is overlain by a clay-carbonate unit, followed by salt and an upper clay unit. The lower 100 m contains four main fluvial aggradation cycles. The lower two cycles contain channels with a braided character, while the upper two contain channels with meandering characteristics (Rossini et al. 1991). Oils in Triassic and Devonian sandstones in El Borma and in the new discoveries from the Ghadames basin originated from the Upper Devonian source.

Extensive volcanic flows with a thickness up to 120 m exist in a broad E–W oriented belt from Ben Khala field to El Borma. Maps showing the distribution and thickness of the volcanics are found in Boudjema (1987).

Thick deposits of halite and other evaporites are now included in the Lower Jurassic. These form the seal for Triassic reservoirs. Halokinesis is not known from the Triassic basin.

**Trap formation**

North African Palaeozoic basins are of Hercynian origin. Palaeozoic strata show little regional lithological differentiation (Beuf et al. 1971), and are uniform over large distances. However, the main arches were already in existence during the Lower Palaeozoic and can be demonstrated by isopach maps. Some tectonic activity on and along these arches is evident as early as the Cambrian (e.g. the unconformity on Ra strata—Fig. 13; L'Homer 1967). Devonian and Early Carboniferous tectonic movements and structuration have been demonstrated near the Tihemboka Arch in the Illizi Basin (Fig. 9), suggesting that some structural traps may have their origin in the Palaeozoic. The larger fields are all located on broad Palaeozoic arches: Hassi R'Mel on the Tilrhemt Arch ( = Talempzane = M'Zab arch), Hassi Messaoud on the El Gassi–Hassi Messaoud Arch and Illizi Basin fields are related to the Tihemboka Arch (Fig. 2). The main phase of tectonic deformation is near the end of the Palaeozoic with uplift, deformation and deep erosion on a large scale (the Hercynian orogeny). Many structural traps in Palaeozoic rocks originate from this period, or were modified by it.

The main structural feature in the Triassic basin is the broad NNE-oriented El Biod Amguid–Hassi Messaoud fault zone (Fig. 2), the tectonic history of which has been described in detail by Boudjema (1987). Several phases of tectonic activity have been recognized in this zone:

- Hercynian tectonic movements with differential uplift and erosion. Isopachs of Triassic strata show the presence of a long and narrow uplift over the El Agreb–Messaoud area, suggesting transpressional movements;
- A Lower Jurassic extensional regime has been observed in the same area with active normal faults having a general NE–SW orientation;
• Transpressional tectonics in the Early Cretaceous affected N–S oriented faults resulting in reactivation and reversal of fault movements (the ‘Austrian orogeny’) (Fig. 13);
• A third major compressional phase is pre-Oligocene (the ‘Pyrenean orogeny’) and affects NE–SW oriented faults, which were strongly extensional in the Early Jurassic. This resulted in faults with a ‘Sunda type’ inversion geometry.

Thus at least four periods during which structural traps were formed and modified can be demonstrated: (i) Devonian (Illizi Basin), (ii) Hercynian, (iii) Early Cretaceous ‘Austrian Orogeny’ (El Biod Amguid–Hassi Messaoud Zone) and pre-Oligocene (Pyrenean Orogeny) (El Biod Amguid–Hassi Messaoud Zone).

The generation of hydrocarbons from Lower Palaeozoic sources was relatively late. Tissot and Welte (1978) state that the main phase of generation and entrapment of oil in Hassai Messaoud and Rhourde el Baguel was during the Cretaceous. The presence of traps of different ages, Hercynian uplift, several levels of source rocks, and differences in timing of the onset of maturation, resulted in a complex distribution of gas-charged and oil-charged reservoirs in the El Biod Amguid–Hassi Messaoud Zone. A pioneer study by Poulet and Roucache (1969) reported on these matters.

### Hydrocarbon reservoirs and reserves

Table 1 shows reserves figures for the larger fields of Algeria. Discovered reserves are about 14 billion barrels oil. Production is around 800 000 b/d of oil, 400 000 b/d of condensate and 12 bcf/d of gas of which about 50% is reinjected. Cumulative production has been estimated at 8.6 billion barrels of oil (1-1-92, *Oil and Gas Journal*, 1992).

Cambero-Ordovician sandstones and quartzites produce oil in El Agreb, El Gassi (Ali 1975), Hassi Messaoud (Mafenier and Tillous 1963; Balduchi and Pommier 1970) and Rhourde el Baguel. The reservoir characteristics are relatively good in Hassi Messaoud but they are poor in some other fields. Natural fracturing strongly enhances producibility. Early studies comparing outcrops and reservoir rocks of these units are by Massa et al. (1972). The Hassi Messaoud field has 26 billion barrels in place. Primary recoveries have been estimated to be in the 6–9 billion barrel range.

Ordovician Hamra Quartzites (or their equivalents) contain gas in several fields in the Illizi Basin and in fields on the south-east side of the El Biod Amguid–Hassi Messaoud Zone, e.g. in Rhourde Nour field (Freyss and Bouteille 1965) and Nezla South field (Claret and Tempères 1967). Upper Ordovician (Unit IV) clastics of glacial origin contain hydrocarbons in several pools in the Tin Fouyé field. De Charpal et al. (1972) report 1.1 billion barrels oil and over 2 tcf gas in place in this unit, but recovery factors are low.

The main reservoir units in the Illizi Basin are a succession of Middle and Upper Devonian sands, labelled F2 to F6. Millouet et al. (1963) described the Ohanet field (Fig. 2), which is a fault-bounded anticlinal structure. Claraq et al. (1963) described the Zarzaitine field. Chiarelli (1978) studied the hydrodynamics of the Illizi Basin, demonstrating formation water flow from outcrops in the south (the Tassili des Aijers) towards the

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**Table 1.** Estimates of recoverable oil and gas from the Triassic and Illizi Basin. Reserves of several major fields have also been given. Figures have been compiled from trade journals and are probably fairly accurate within a range of ±10%.

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(Algerian side)
Fig. 12. Stratigraphic section in upper Triassic clastics. Sands shale out in the area between Hassi Touareg and Rhourde el Baguel fields (see Fig. 2). (Modified from Claret and Tempère 1967, figs 6 and 8.)

Fig. 13. Cross-section through Gassi Touil and Hassi Touareg fields (modified from fig. 5 of Claret and Tempère 1967).
north. This results in a tilted water contact in pools in the Tin Fouyé field of 10 m km\(^{-1}\). Several other fields have tilted water contacts (Aliev et al. 1971). Hydrodynamic flow plays an important role in the trapping of oil in subtle structures. This is especially significant as structural closure in some Tin Fouyé pools has been reported as minimal.

Upper Triassic sands are productive in the giant Hassi R'Mel gas field (Delcaud 1960; Magloire 1970). Other large Triassic fields are El Borma, straddling the Tunisian–Algerian border, and Hassi Touareg and surrounding fields. Triassic reservoirs are overlain by Triassic–Jurassic salt deposits forming a 'super seal' and resulting in undercompacted Triassic shales and high reservoir pressures (Chiarelli 1978).

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References


