THE NORTH WESTERN SAHARA AQUIFER

BASIN AWARNESS

HYDROGEOLOGY

(Synthesis)

October 2002

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I – THE AQUIFER FORMATIONS

1. Definition of the aquifer reservoirs

The North Western Sahara Aquifer System (NSAS – SASS) covers a wide zone whose limits are located in Algeria, Tunisia and Libya. This basin includes a series of aquifer layers that – in the course of the studies carried out since 1970 – have merged into two reservoirs called the Intercalary Continental Shelf (I.C.S.) and the Terminal Complex (T.C.).

The wording «**Intercalary Continental Shelf** » means, according to its Author (C. Kilian, 1932), a continental episode located between two marine sedimentation cycles:

- At the bottom, the Paleozoic cycle which completes the hercynian orogenesis,
- At the summit, the upper Cretaceous cycle.

The **Terminal Complex** is a very little homogeneous set including carbonated formations from the upper Cretaceous and some detitric episodes from the Tertiary and especially from the Miocene.

These definitions were adopted, at the beginning, in order to analyse and schematize the hydrodynamic functioning of the Algerian aquifers, then by extension, of the Tunisian aquifers.

With the NSAS programme, the Libyan Saharan basin was added to the study, which required a new analysis of the geological, geophysical and hydrological information, on the basis of the former studies as well as on the collection of new data.

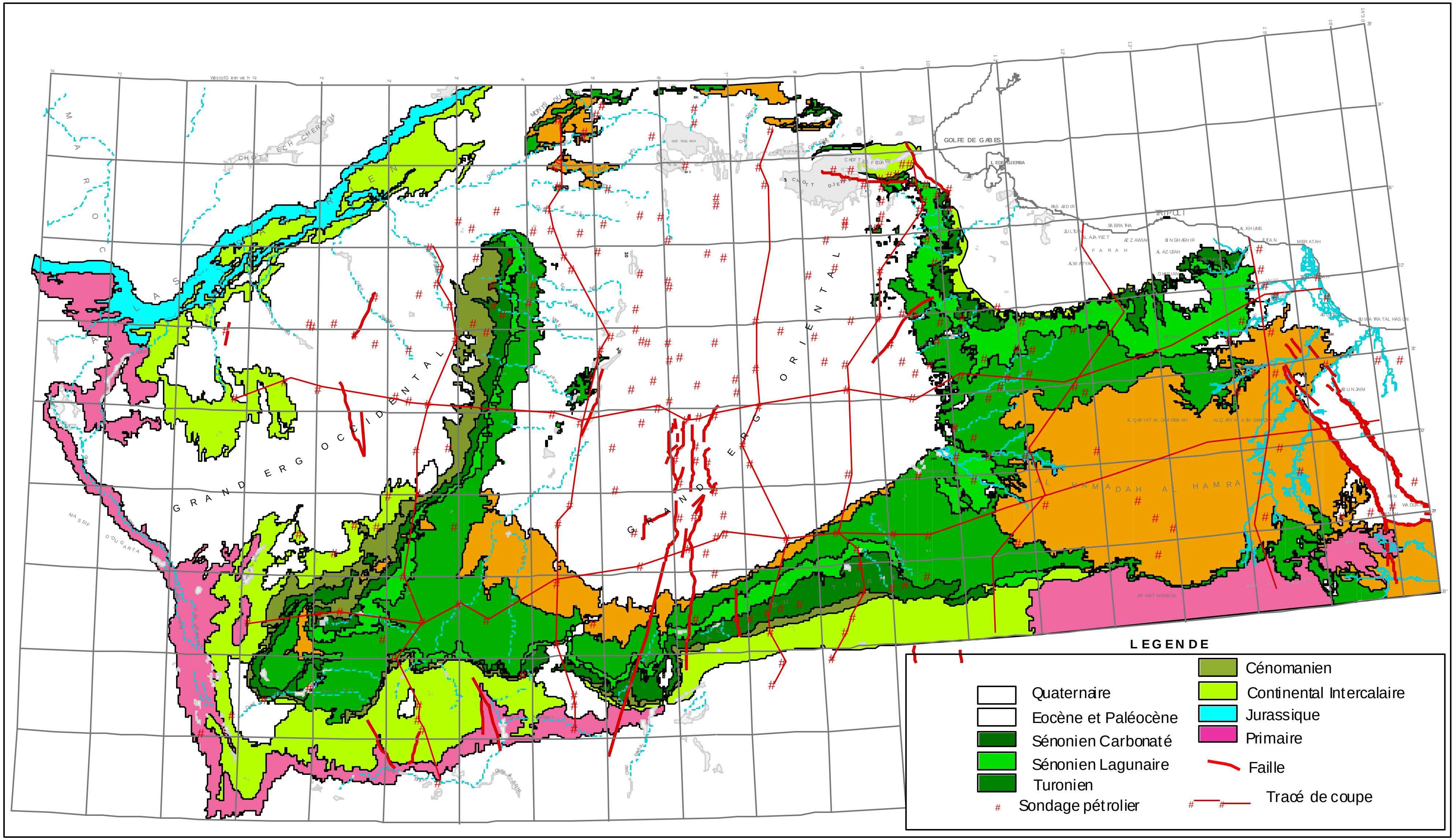
The outcrops of the whole Saharan basin explain the structure of this entity, composed of two basins, namely the basin of the Western Big Erg (in Algeria) and the basin of the Eastern Big Erg (in Algeria and in Tunisia), and of a shelf called "Hamada El Hamra" (in Libya). The outcrops of the older formations can be seen on the southern and western borderlines of the basin. The secondary and tertiary sedimentation series are subject to a thickening in the middle of the two basins and on the borderline of the South – Atlas flexure.

The sub-basin of the Western Big Erg is a geographic entity where the Intercalary Continental sheet is free, to a very large extent, and makes up, because of this fact, an underground water reservoir, easily accessible, through the execution of works (such as foggaras, wells and drillings) which are not very deep (a few dozens of meters).

The geology of this part of the basin shows that the passage from the Saharan Atlas in the North to the Valley of the Saoura in the south is accompanied by a burying of the Terminal Complex series under the Hamadian flagstone, which is, itself, covered in some parts, by the sand hills of the Western Erg. This flagstone is sometimes the direct continuation of the Intercalary Continental sands.

The emersion of the zone located at the north of the paleozoic mole of Gargaf (Jabal Fazzan, Jabal Hassawnah) continued throughout all the period from the Trias up to the end of the lower Cretaceous and it was characterized by a predominance of the detritic sedimentation of a continental origin. Further north, some marine or lagoon episodes, favoured by the subsidence of the basin, alternated with emerged periods that are characterized by a very little deep continental or marine sedimentation. The marine transgression had entirely invaded the Libyan Saharan basin only in the Cenomanian.

GEOLOGIC MAP OF NWSAS



2 - Schematization of the aquifers

The permeable layers, which seem to be hydraulically linked together, are grouped inside an aquifer reservoir whose thickness varies according to the local conditions of their sedimentation. The other layers treated in "aquitards", allow securing the horizontal continuity of the aquifers over the whole basin.

The setting up of a representation of all the aquifer layers of the Sahara basin within one single multi-layer system, allowed to discover the lateral and vertical links conditioning the hydraulic and chemical exchanges.

The litho-stratigraphic sequence which is common to the three countries and which allows schematizing the aquifer system of the North Western Sahara, according to the pattern, is drawn out, as follows, from the bottom, upwards.

II – HYDRODYNAMICS OF THE SYSTEM

ALGERIA	TUNISIA	LIBYA
Waterproof roof	Waterproof roof	Waterproof roof
Semi-permeable	Semi-permeable	Semi-permeable
Semi-permeable	Semi-permeable	Semi-permeable

Waterproof Substratum				
Paleozoic	Lower Jurassic - Trias	Lower Jurassic – Trias	Carboniferous	Cambro ordovician sheet

1 – Piezometry

1.1. Piezometric configuration

- ***Terminal Complex***

This Piezometry enhances:

- The division of the Sahara into two main hydrological sub-basins, namely the Eastern Big Erg and the Hamada El Hamra,
- The same main supply zones as those of the I.C.S/Kikla (Saharan Atlas, Dahar J., Nafusa and J. Hassawnah),
- The outlet zones mainly centred on the Algerian Tunisian Chotts and the Golf of Syrte between Misratah and Buwayrat Al Hasun.

The Piezometry «Upper Cretaceous » T.C./CS sheet shows, in the Eastern Big Erg sub-basin, the role of the Tunisian Algerian Lower-Sahara in the focusing of the underground flowing, making up an endoreic basin. The Marouan-Melrhir Chotts in Algeria and Gharsa-Djerid, in Tunisia, make up **the sheet outlet** and, at the same time, the region where the intakes for the springs and the drillings, are concentrated.

In Libya, the supply from the South seems to be prevailing over the supply from J Nafusa. The El Hamada zone is a flat-shouldered area where the piezometric gradient is relatively small, but where the flowing directions seem to indicate that the Hamada is a supply zone. It is most probably a large underground reservoir which is not presently fed and whose slow draining maintains an outward flowing of the zone. In the north-eastern part of the Libyan basin, the tertiary and quaternary sedimentation layers seem to be playing an important role in the loading of the T.C./CS sheet and its losses, through a vertical draining, in the outlet zones.

The piezometry of the Terminal Complex sheet for the year 2000, witnesses a generalized draw down of the piezometric surface, which is more acute at the levels of the strong exploitation zones.

- The lower-Sahara between Touggourt in the South and Biskra in the North, where the main oases and built up population centres, using this sheet, are concentrated,
- The chotts' region in Tunisia (Nefzaoua and Djerid) where the main Tunisian oases are located,
- The eastern side of the Hamada El Hamra in Libya (Wadi Zemzem – Ain Tawargha) where the main collecting fields, for the agricultural development based on the water resources, coming from the aquifers of the upper Cretaceous and the Tertiary, were created between 1972 and 1985.

The Algerian chotts (Marouen and Melghir chotts) and the Tunisian chotts (Djerid and Gharsa chotts) are still working as outlets for this sheet.

*** *Intercalary Continental Shelf and its connection to the Paleozoic***

The piezometry of the I.C.S. sheet shows, in the sub-basin of the Western Big Erg, an almost total independence from the remaining part of the sheet, with a flowing out from the Saharan Atlas towards the South and then the South-West, a dividing line in the underground waters separates the flowing towards the west from that which concerns the eastern part of the basin.

the piezometric dome centred on the Dahar-Jabal Nafusa makes up a local supply area in a zone where the sheet is not gusher type. This real re-loading is reflected in the chemical composition of the water and its isotopic characteristics.
The piezometric anomaly on the Amguid backbone can only be explained by a vertical draining towards the Terminal Complex, through the faults in this zone.

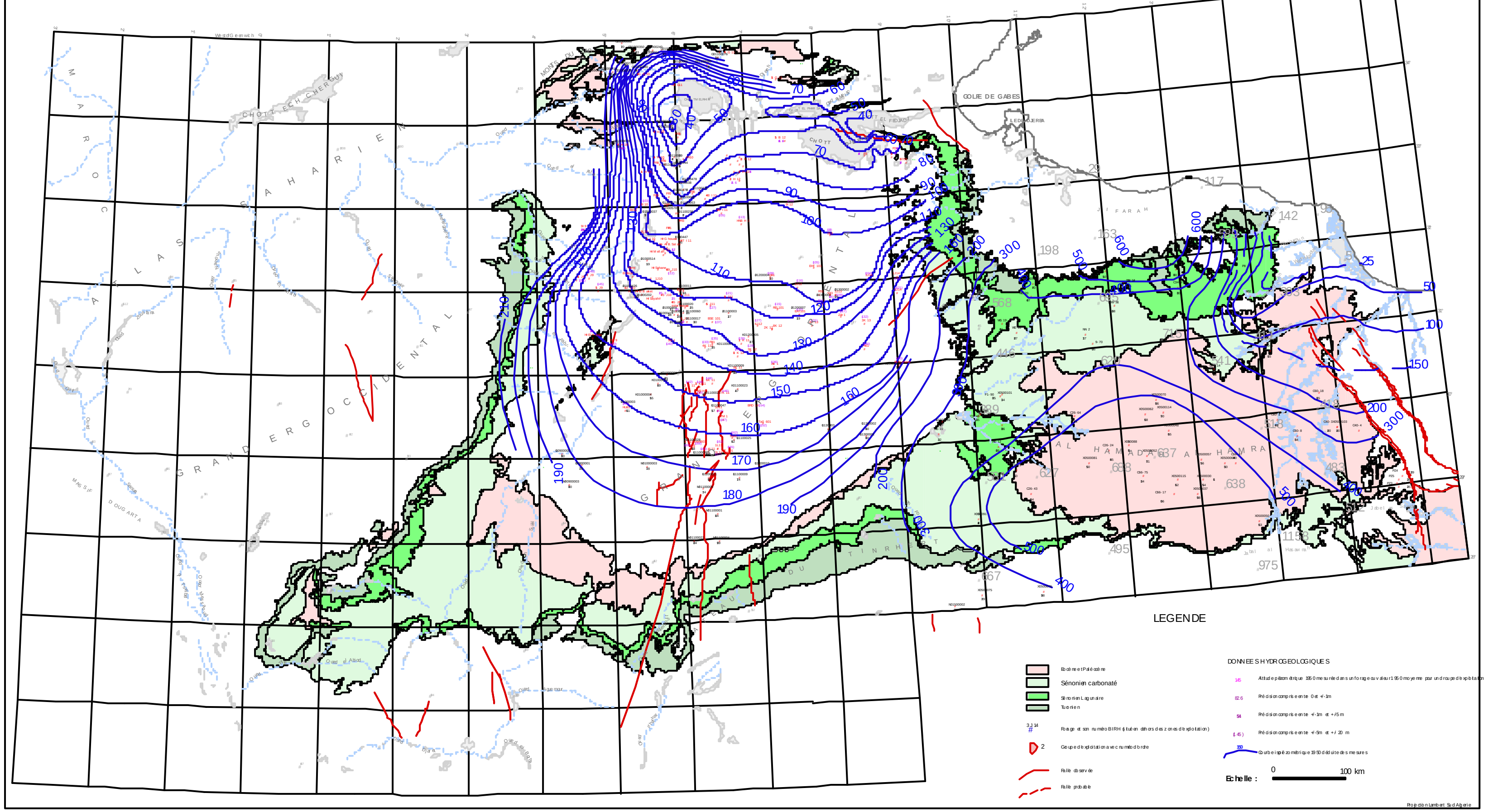
The I.C.S. piezometric chart for the year 2000 shows, in the sub-basin of the Western Big Erg, some flow directions heading to the outlet of the sheet made up by the foggaras outcrops area (In Salah-Reggane).
In the central part of the sheet (sub-basin of the Eastern Big Erg) the flowing, starting from the Tinrhert shelf in the south, towards the Eastern Big Erg, is maintained and it shows the same aspect as in 1950, it heads from the south towards the north, throughout the far Tunisian south. The chotts region, where the outlet of the sheet towards Djeffara is located, is the zone towards which this flowing as well as the one coming from the Saharan Atlas, converge.

In the eastern part of the Libyan Saharan sub-basin, the feeding zone, located in the south (Jabal Hawasnah) is at the origin of the flowing towards the eastern side of the Hamada whose outlet is made up by Ain Tawurgha and the sea. The flowing of the sheet towards Ghedames and the Tunisian south dominates over the flowing coming from Jabal Nafusah towards the south.

OBSERVATOIRE DU SAHARA ET DU SAHEL / SAHARA AND SAHEL OBSERVATORY

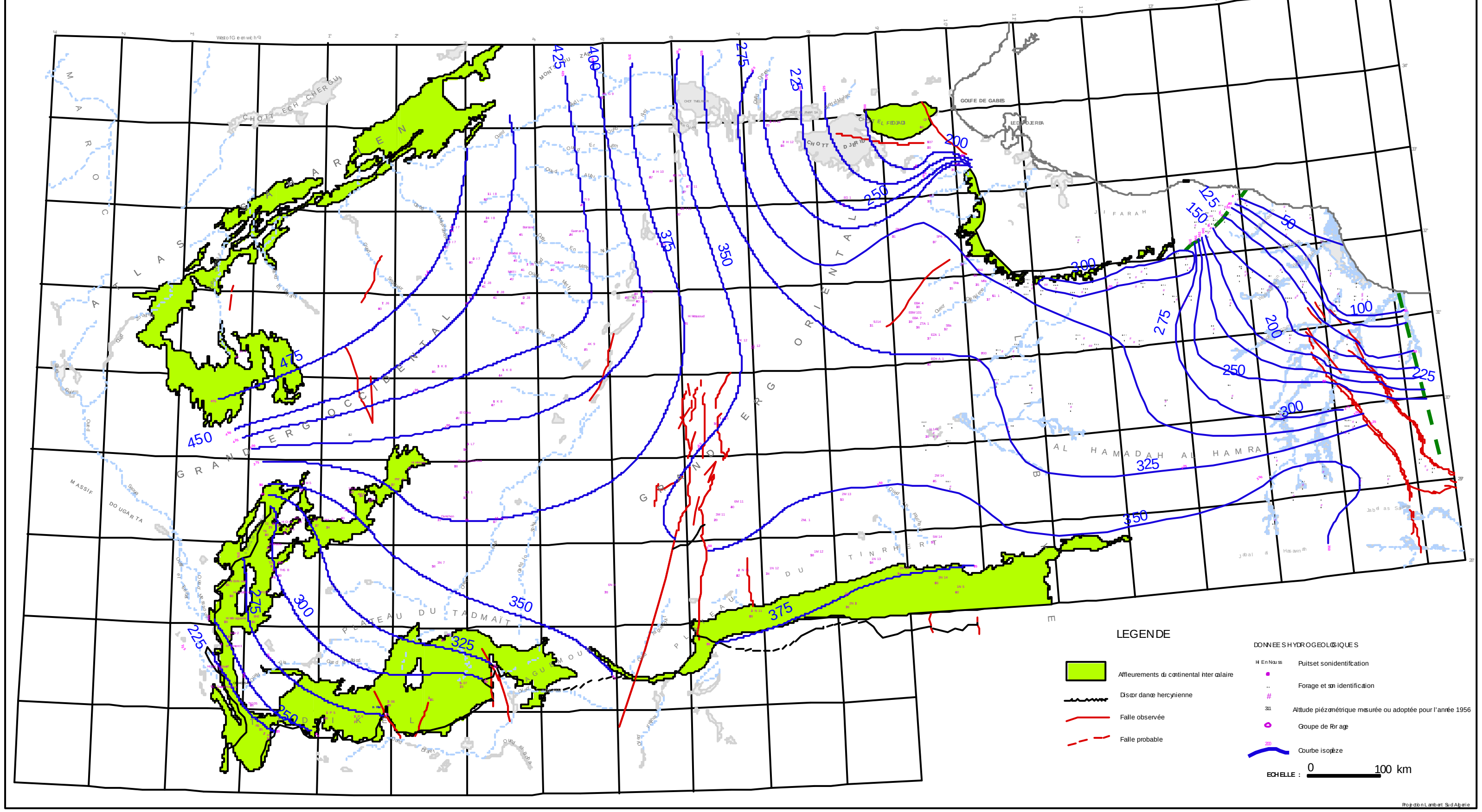
SYSTEME AQUIFERE DU SAHARA SEPTENTRIONAL / NORTH WESTERN SAHARA AQUIFER SYSTEM

CARTE DE LA PIEZOMETRIE INITIALE DU COMPLEXE TERMINAL



OBSERVATOIRE DU SAHARA ET DU SAHEL / SAHARA AND SAHEL OBSERVATORY
SYSTEME AQUIFERE DU SAHARA SEPTENTRIONAL / NORTHWESTERN AQUIFER SYSTEM

CARTE DE LA PIEZOMETRIE INITIALE DU CONTINENTAL INTERCALAIRE / KIKLA



1.2 – Piezometric History

- **Terminal Complex**

In Algeria, over the whole Algerian lower-Sahara, the piezometric fall of the Terminal Complex, goes from 32m **in 43 years** in the north **Wadi Rhir**, to about **50m in 30 years** in Ouargla. It is mitigated towards the nearby zones where the density of the drillings exploiting this sheet, is low.

In Tunisia, the development of the piezometry of the Terminal Complex between 1950 and the year 2000, showed a continuous decrease, whose curve became more pronounced starting from the 90's. This decrease is more perceptible in the **Kébili Peninsula** (**23 to 30 m in 25 years**). It is of **25-30 m in 50 years**, in the remaining part of the Nefzaoua and reaches 15 to 25 m over years. The artesianism has almost disappeared in the Djerid. It has dwindled more and more in the Nefzaoua area where the highest pressures vary from **20 to 35 m**.

In Libya, the piezometric decrease became perceptible in the middle of the 70's with the creation of agricultural projects, developing fields with several drillings. The piezometric decreases recorded in this country ranges between **35 and 40 m over 20 years**.

- **Intercalary Continental Shelf**

In Algeria, the piezometry of the I.C.S. sheet witnessed a perceptible decrease as early as of the beginning of the 80's, following the creation of many new drillings in Wadi Rhir, Ouargla, El Wadi et Hassi Messaoud. In these zones, the piezometric decrease often exceeds **2m/year**.

In the Adrar where the I.C.S. sheet is free over a large surface, the witnessed piezometric decrease is as follows : **5 to 20 m in 20 years, in the Gourara, 3 to 28 m in 30-35 years, in the Touat and of 5 to 10 m in 30-35 years in the Tidikelt**.

In Tunisia, the piezometric decrease of the Intercalary Continental Sheet, which was regular and somewhat weak from the 50's up to the 70's, became more perceptible in the course of the last twenty years. Over 50 years, it is of approximately **50 m in the Chott Fedjej region**, **30 to 40 m in the Nefzaoua area and 25 to 35 m in the far Tunisian south**.

In Libya, the decrease of the piezometric level varies in the Wadi Sufajjin basin, from **30 to 45 m in 30 years**. **Near the Tawurgha spring**, this decrease corresponds to **24m** in the course of the period between1985 and 2000. In **the western part of the Hamada El Hamra**, this decrease **is less acute.**

2 - The present feeding : data and assumptions

At present, the feeding of the sheets appears on the northern borderlines of the Sahara basin where the three following conditions are met :

- Sufficient rainfalls and a relatively mountainous area in order to produce the streaming of water into the Wadies,
- the outcropping of permeable formations belonging to one of the aquifer systems or being in direct relation with the Saharan aquifers.

Notwithstanding the foregoing, the feeding of these sheets is, at present, weak with respect to the present and future intakes, and no matter the result of more precise hydrological

studies, the latter shall not have any impact on the non-renewable nature of the water resources in the Sahara.

In Algeria, these conditions are met all along the Northwest borderline, at the foot of the Saharan Atlas. The flowing, coming from the Atlas, infiltrate into the sand hills of the Western Big Erg, before reaching, as a final step, the Intercalary Continental Shelf. The Mzab backbone, although suffering from a shortage of rainfalls, is however the junction point for flowing, which run down into the Wadies, which flow towards the East and participate in the feeding of the limestone layer of the upper Cretaceous and of the Eocene belonging to the Terminal Complex.

In Tunisia, the feeding of the sheets making up the terminal Complex and indirectly the Intercalary Continental Shelf depends essentially on the rainfalls and the streamings on the Dahar massif. Hydrological studies on the Wadies of the Dahar Western side allowed working out an evaluation of the streaming coefficient and of the specific outflow. This feeding, which is also evaluated on the basis of the underground circulation speed, deducted from the activities in Carbon 14, gives a reloading flow of about **190 l/s** (10% of the rainfall). This figure is in keeping with the piezometric development of the sheet, which shows, in the far Tunisian South, a downward tendency (**from 1 to 2.5 m/year**).

In Libya, the feeding of the carbonated aquifers of the upper Cretaceous concerns all the western and eastern sides of the Jabal Nafusa. Two big slope basins drain the stream waters towards the Mediterranean Sea, namely through wadi Sufajjin and Wadi Kaam. An evaluation of the Wadi Sufajjin basin streamings (GEFLI, 1976, 1978) shows that the Wadies beds embody the preferential reloading zones. This was confirmed by the isotopic analyses. The endoreic western basin, including the wadi flowing towards the South West, also participates in the feeding of the upper Cretaceous sheets (a surface covering 12 000 km^2) and **the infiltration coming from the streamings into the Wadies** is estimated therein at about 20 Mm^3/year.

3 - The natural outlets

3.1 – The Springs

In the Tunisian South, the springs coming from the Intercalary Continental Shelf and the Terminal Complex sheets have always been subject to a more or less regular chronological follow up. Those linked to the Terminal Complex are, by far, the most important.

- **The Intercalary Continental Springs** of the Tunisian south are located in the chott Fedjej zone and concern, more particularly, the two levels of upper sandstone and of forest sandstone. Their flow is most of the times of only a few liters per second and does not exceed, in its totality **50 l/s**. It has been continuously decreasing since 1950 and reached in **the year 2000**, approximately **15 l/s**. This situation reflects the drainage, which the upper sandstone aquifer undergoes within the multi-layer system of Chott Fedjej (**70% decrease of the initial flow**).

- **The terminals Complex springs in Tunisia are** located in the two regions of the Djerid and the Nefzaoua. They correspond to emersions functioning under the effect of the pressure generated by the gusher sheet. Their flow dwindles along with the increasing exploitation of the sheet and the decompression, which grows more and more, under the effect of the multiplicity of the drillings.

  The evolution of the flow of the Djerid springs which was of about **1600 l/s in 1950**, showed a net decreasing tendency, which accelerated as early as the beginning of the

70's (**1100 l /s**). This decrease, which became more acute since **1982** (**350 l/s**), translates a clear cut dry up regime. These springs dried up entirely in 1988. With a global flow of approximately 450 l/s in 1950, the Nefzaoua springs suffered from a dry up regime, which got worse at the beginning of the 70's and reached less than **100 l/s** at the beginning of the **80's**. At present, **most of these springs have dried up** and the flow of those, which have not, yet dried up, does not exceed a few liters per second.

In Libya, the two main springs of the Sahara basin are those of Tawargha and Wadi Kaam. They represent a visible manifestation on the surface, of different aquifer levels.

- **The Tawurgha spring,** located in the middle of a marshy zone, continue to offer an important flow which has relatively slightly changed in the course of the last fifty years, in spite of the increasing intakes. In **1977**, this **flow** was of **1.966 m3/s**. **In February 2001, it was of 55.9 Mm3/year**. Based on the chemical and isotopic analyses (Pallas P. & Bufila T., 1978), the measured up flow is likely to come – within the proportion of 35% - from the upper Cretaceous sheet of the Wadi Sufajjin, and of 65% from the deep sheets of Kikla and the Paleozoic.

- **The Wadi Kaam spring** emerges in the bed of a Wadi, which has given its name to it. It originates in the Limestone and the dolomitic limestone of the upper Cretaceous. Its flow was of **450 l/s at the beginning of the 70's** but it rapidly began to decrease with the creation of the drillings supplying with water the agricultural projects of Wadi Kaam.

3.2 – The chotts and sabkhas

In Algeria and in Tunisia, the water coming from the saharan sheets and which flows into the superficial sheet of the Chotts, through vertical draining, is subject to evaporation throughout all the surface of the Chott. A similar situation is observed in Libya, in the eastern part of the Hamada El Hamra. The evaporation flow, thus lost, is doomed to decease with the draw down of the piezometric surface of the sheet.

4 - Intakes

4.1 – intakes per aquifer and per country

Since1950, the exploitation of the two I.C.S. and T.C. sheets has never stopped increasing. The corresponding intakes which were of about **14 m^3/s in 1950**, reached **20 m^3/s in 1970**, **29 m3/s in 1980 and 82.5 m^3/s in the year 2000**. This situation expresses a tendency, in the three countries, towards an intensification of the mobilization of the water resources coming from these aquifers, through an increase of the exploitation works (particularly the drillings), as well as the more and more clear cut recourse to the pumping in the zones where artesianism has weakened (in Tunisia and Algeria). The **flow of the natural emergences** (Foggaras and springs) which was of approximately **11.5 m^3/s**, at the beginning of the **20th Century,** has continuously decreased and reached in **the year 2000**, the equivalent of **4.5 m^3/s**.

- ***Exploitation of the terminal Complex per country***

The sheet of the terminal Complex is largely exploited in Tunisia and in Algeria (Lower Sahara or the Chotts region) and in Libya (north eastern part of the basin). The **global exploitation** of this sheet reached about 41.4 **m^3/s**. **in the year 2000**.

In Algeria, this exploitation was of about 22.3 **m^3/s** in the year 2000. It has thus recorded a net evolution since 1950 when this exploitation was of **5.77 m^3/s,** only. This evolution has clearly increased at the beginning of the 80's, as a result of the creation of new drillings.

In Tunisia, this exploitation started in the Djerid and in Nefzaoua, by tackling the springs. It recorded, at the beginning of the 20th Century, the creation of gusher drillings, which contributed, to a large extent, to the increase of the volume of exploited waters and to the creation of new irrigated zones. The multiplicity of the drillings has rapidly affected the artesian activity and the spring's flow, and starting from the 60's; the recourse to water pumping has prevailed. In the year 2000, the most important part of this exploitation came from the flow of the drillings that are pumped out because of the drying up of the springs of Kebili and Tozeur. It went from **3.4 m^3/s in 1950**, to **14.4 m^3/s in the year 2000**.

In Libya, the exploitation of the terminal complex is mainly carried out in the eastern coastal area and in the zone of Al Jufrah. It went from approximately 2.0 **m^3/s in 1950**, to **4.7 m^3/s in the year 2000**.

- ***Exploitation of the intercalary Continental shelf per country***

The intercalary continental sheet is mainly exploited in Algeria where the intakes taken from its resources reached, in the year 2000, **29.9 m^3/s,** which represents 84 % of the total volume of its exploitation in the Saharan basin. In Libya, the exploitation of this sheet reaches 3,4 **m^3/s**, which corresponds to 9 % of its global exploitation and in Tunisia, it is of **2.4 m^3/s**, i.e. 7% of the total exploitation.

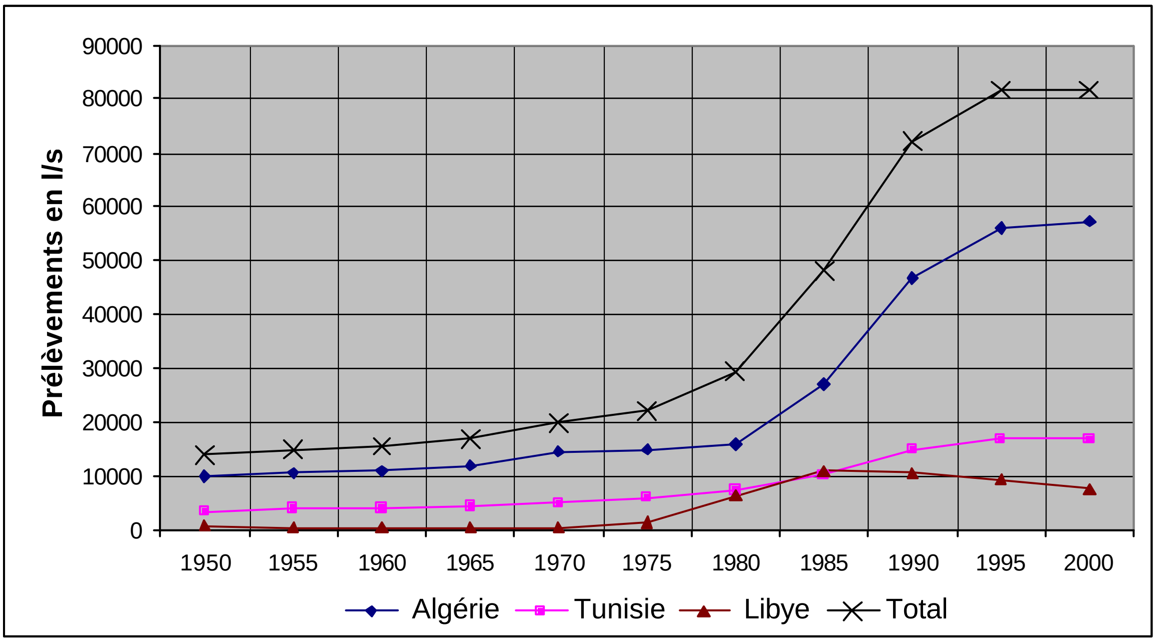
In Algeria, the gauging made in the foggaras[1] of Gourara, Touat and Tidikelt, in 1932, 1950 and 1960, showed that while the unit flows of each foggara changed, the global flows per palm grove remained more or less constant. The global flow taken from the sheet by the foggaras is estimated at 3.6m3**/s** in 1980. Gauged in 1999, this flow is of **2.7 m^3/s**. The exploitation of the whole I.C.S. went in Algeria from approximately **4.0 m^3/s** in 1950, to **29.8 m^3/s in the year 2000**.

In Tunisia, the exploitation of the Intercalary Continental Sheet was carried out until the beginning of the 80's, in Chott Fedjaj and in the far south. The creation of deep drillings in the Djerid and Nefzaoua contributed to extend the exploitation of the sheet to these regions. The exploitation through the drillings, which was of 52 l/s in 1950, went up to 865 l/s in 1970 and then it substantially increased to reach 2.54 m^3/s in the year 2000.

In Libya, the Intercalary Continental sheet is exploited in the zone of Tawurgha, in the wadi Sufajjin valleys, in the valleys located on the eastern side of the Hamada al Hamra and at Al Jufrah. This exploitation which was limited, in 1950, to the springs flow (1.35 m^3/s), became intense through the creation of drillings in order to reach, by the year 2000, approximately 4.6 m^3/s, among which 1.2 m^3/s come from springs.

At present, a new exploitation programme of this sheet is under study between Derj and Ghadamis. This programme aims at supplying drinking water to the towns of the western part of the Jifarah, which are not part of the objectives of Phase II of the Big River coming from Jabal Hassawnah. The flow, which shall be secured by this new drilling field, is not yet definitely fixed but it shall probably range between 50 and 90 million m^3/year.

[1] *The foggaras are man drilled draining galleries in order to exploit the sheet whose piezometric surface is shallow.*



In parallel, an important exploitation programme of the Cambro-Ordovician sheet was set up in the south east of the Libyan Saharan basin, in Jabal Hassawnah. This programme consists in a group of more than 500 drillings whose forecast total flow amounts to 912 Mm^3/year (29 m^3/s). The pumped out water is destined to feed the Big Artificial River transporting water into the plain of Jeffarah.

4.2 - Conclusions

The exploitation of the Saharan basin sheets has gone, during the last thirty years, through a phase of intensive mobilization of resources, which has resulted in the increase of the intakes from the drillings, which have negatively affected the gusher feature of the springs, and the artesian flows. The increase of the intakes with respect to the situation at the beginning of the 20^{th} Century, reached 71 m^3/s. This situation is the cause for the decrease in the flow of the foggaras in Algeria (23%), of the springs in Chott Fedjej in Tunisia (70%) and in Ain Tawargha in Libya (11%). At another level, it was also at the origin of the drying up of the Tunisian springs exploiting the sheet of the Terminal Complex in the Djerid and in Kebili.

The increase in the pumped out volumes and the development of the Saharan agriculture at the level of these Saharan sheets resulted in the drying up of the springs and the weakening of artesianism. This increasing exploitation is likely to entail, in the long run, in the vulnerable zones, changes in the quality of the water.

III – WATER CHEMICAL QUALITY

1 - Evolution of the salinity

1.1 – Terminal Complex sheet

The differentiation in the evolution of the total mineralization of the T.C. waters is possible between the sand sheet and the limestone sheet. This is explained by the fact that the senonian and the eocean limestone formations are more accessible, for re-loading, on the borderlines of the basin than the moi-pliocen sands located in the Tunisian-Algerian Lower

Sahara. Particular phenomena, such as the intensive exploitation and the return of the irrigation waters, are at the origin of certain localized chemical anomalies.

The sand sheet is in relation with the quantities coming from the surface water. The limestone sheet shows an increase of its salinity in the eastern Lower-Sahara zones of the Hamada El Hamra, which are outlet areas. These zones also the deepening place of the aquifer formation.

Generally speaking, the relations between this sheet and its props affect the salinity of the terminal Complex water, to a great extent. With the increase of the exploitation, this salinity witnessed a certain evolution. The two main potential sources at the origin of the increase of this salinity are the water from the chotts and the return to the sheet of the draining waters in the zones where its roof is not very thick. The eventual contamination by the waters of the Turonian, which are saltier, depends on the differences of loads in the piezometry of the two sheets.

1.2 – The Intercalary Continental sheet

In Algeria, the salinity of the waters from the Western Big Erg basin is often inferior to 1 g/l. This is not the case in the Eastern Big Erg basin where the sheet is confined several hundreds of meters beneath.

In Tunisia, the salinity of the waters from the Intercalary Continental Shelf is somewhat high (RS> 2g/l), which limits their use in the drinking water supply. This situation is explained by the fact that these waters are often located in the confined part of the sheet where they remained for a long time (very weak underground circulation), in contact with accumulating formations containing argillaceous and gypseous impurities.

In Libya, the waters from the Kikla formation in El Hamada El Hamra include some dry residues, which are often inferior to 2.0 g/l. This is explained by the fact that the aquifer formation is clean and does not accept any argillaceous inclusions.

2 – Vertical variation of the mineralization

The vertical evolution of the mineralization does not seem to be progressing within the aquifer, but it appears with the lithological changes. The horizons of different mineralization are separated by layers, more or less argillaceous, which are, in general, a few dozens of meters thick.

With the increase of the exploitation, the piezometric unbalance, induced by the intakes operated in the most permeable layers, has led to vertical exchanges, through draining, between the different superposed levels. It results there from a certain homogenisation of the water salinity, with an upward tendency. Generally speaking, the high mineralization levels observed in certain horizons are due to the fact that the aquifer levels sheltering them are relatively isolated from the main aquifer. The reloading contributes to make the contact time, between the water and the rocky matrix, longer.

In the Algerian Sahara, the lower layers of the intercalary continental shelf are the saltiest and it is only in the upper part that the aquifer levels of good quality are located (Barrémien & Ablien).

In Tunisia, the situation is inversed in the Chotts region where the intercalary continental shelf is decomposed into several aquifers levels. The lower part, attached to the Neocomian (Series of Kébeur el Hadj) makes up the main aquifer whose water has the best chemical

quality in the region. The other levels on top of this series (Barrémien & Aptien) contain water with a worse quality.

In Libya, the salinity of the water of the Intercalary Continental Shelf is largely affected by the underground supply contribution from the Cambro-Ordovician with less than 1 g/l. This good quality is locally spoiled in the eastern part of the Hamada as a result of the burying of the I.C.S. layers under a thick cover.

3– Hydrochemical evolution according to the exploitation

The variations of the total mineralization of the I.C.S. waters in the drillings, for which a series of chemical analyses were conducted, show, very often, some fluctuations, which remain within the limit of the analysis error, allowance. Certain drillings catching the I.C.S. however show a slight increasing tendency as the time goes by. This is particularly the case in Algeria (Wadi Rhir and Ouargla) and in Tunisia (Nefzaoua and Djerid).

This phenomenon must however be interpreted with a lot of care and one should not deduce there from a clear cut tendency for the increase of the salinity along with the increase of the exploitation. In the case of the I.C.S., the draining from the upper levels seems to be the cause to this salty water.

4 – Hydrochemical evolution according to the remoteness of the supply and feeding zones

The role of the tunisian-libyan Dahar, as the present re-loading zone, is well enhanced by the evolution of the total mineralization of the I.C.S. water. The increase of the salinity as well as the concentration of the chemical composition, mainly in Na^{+} and Cl^{-} and accessorily in Ca^{++} and SO_4^{--} (A. Mamou, 1990) are made during the flowing from the free part of the sheet towards its confined part. The pressure and temperature increase, which go along with the reloading of the sheet, is also causing a certain salt clearance during the long underground journey of the water.

In Libya, the chemical evolution of the Kikla waters shows – from the south-east where it is in continuous contact with the Paleozoic up to the level of Tawurgha and towards the sea, at the level of Zliten- the passage from a chemical aspect somewhat homogeneous, in the south, to a sulphated-calcic nature at the level of Tawurgha, then to a chlorinated-sodium aspect near the sea, in Zliten.

IV – ISOTOPIC CHARACTERISTICS

1 –Intercalary Continental Sheet

1.1 – The Eastern Big Erg Basin

In the Eastern Big Erg Basin, the average contents in stable isotopes are as follows: **$d^{18}O=-8.4\pm0.4$**‰ and **$d^{2}H=61\pm3$**‰. These low values are characteristic of the water coming from the fossil sheets, protected from any recent deposits (Gonfiantini & al., 1974 & Gandouz A., 1985).
As we draw closer to the bordering areas (Tinrhert and Dahar shelves), these contents grow higher. These waters have, generally, a low activity in ^{14}C. It is only in the reloading areas or close to them that the contents in ^{14}C become somewhat high (54.7% of ^{14}C in Laghouat on the south side of the Saharan Atlas, from 44.9 to 53.3% on the Dahar, of 22.8% in Fort Flatters and of 17.3% in Tabankort in the Tinrhert). These contents decrease starting from

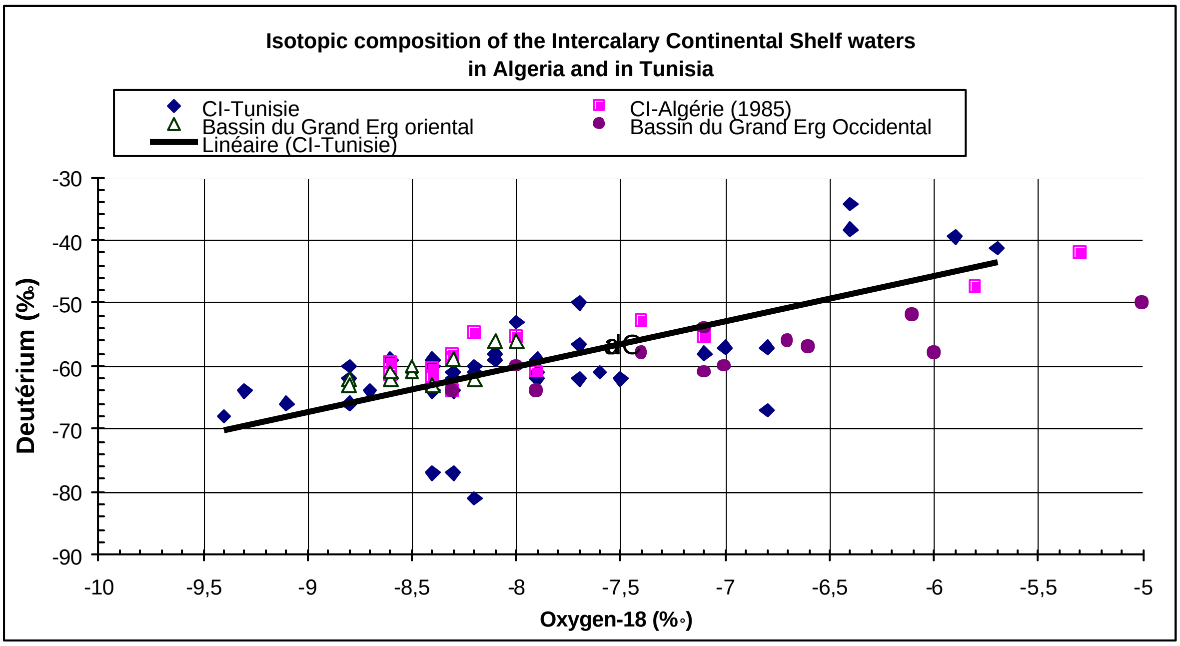
the reloading areas under the Hamada of Tinrhert and the sand hills of the Eastern Big Erg and accounts for the time spent to cover the underground distance.

In general, and outside the reloading areas, the Intercalary Continental water is free from ^{3}H (less than 30 years of age). There were thus essentially ancient waters, which remained inside the sheet for a long period. The loading of the sheet made it that the most ancient waters were those, which were found in the confined part of the sheet. Those, which got mixed up with more recent waters, are located close to the reloading areas where the sheet is free upward.

The youngest and less homogeneous ages of these waters can be observed all around the reloading areas such as the Dahar (1000 to 24 000 years). Compared to those of the Kikla waters in Libya, these ages proved to be of the same epoch and translate the same dispersion (Salem O., & al, 1980, SRDOC D., & al, 1980), which means that there is a similar reloading effect.

The underground circulation speed of the sheet was evaluated in the confined zone of the sheet, it was estimated between **3 and 6 m/year**. Certain estimates of the age of the water (Gonfiantini & al., 1974), made after correction and with reference to the percentage in $d^{13}C$ and of the pH, gave values ranging between **46 000** (Wadi Nekhla - Tunisia) and **18 000** years (Ech Chouech-Tunisia) . The highest values, in matters of age, (> **35 000ans**) are close to the limit of the ^{14}C method.

In general, the oldest ages of the Saharan waters range between **50 000** and **20 000** years with the highest values in the part where the sheet is confined and spurting. The evaluation of the paleotemperatures by means of rare gases (Rudolph J., & al 1984) showed that, at that epoch, temperatures were lower than the present temperatures by **2°C at least**. The value of 18**°C** was evaluated for the el Golea waters on the Western Erg in Algeria as well as for those of Ksar Ghilane in the Tunisian South (Fontes J.Ch., & al, 1984).



Bassin du Grand Erg Oriental: Easter Big Erg Basin
Linéaire (CI-Tunisie) : Linear (ICS – Tunisia)
CI-Algérie : ICS-Algeria
Bassin du Grand Erg Occidental

1.2 – The Western Big Erg Basin

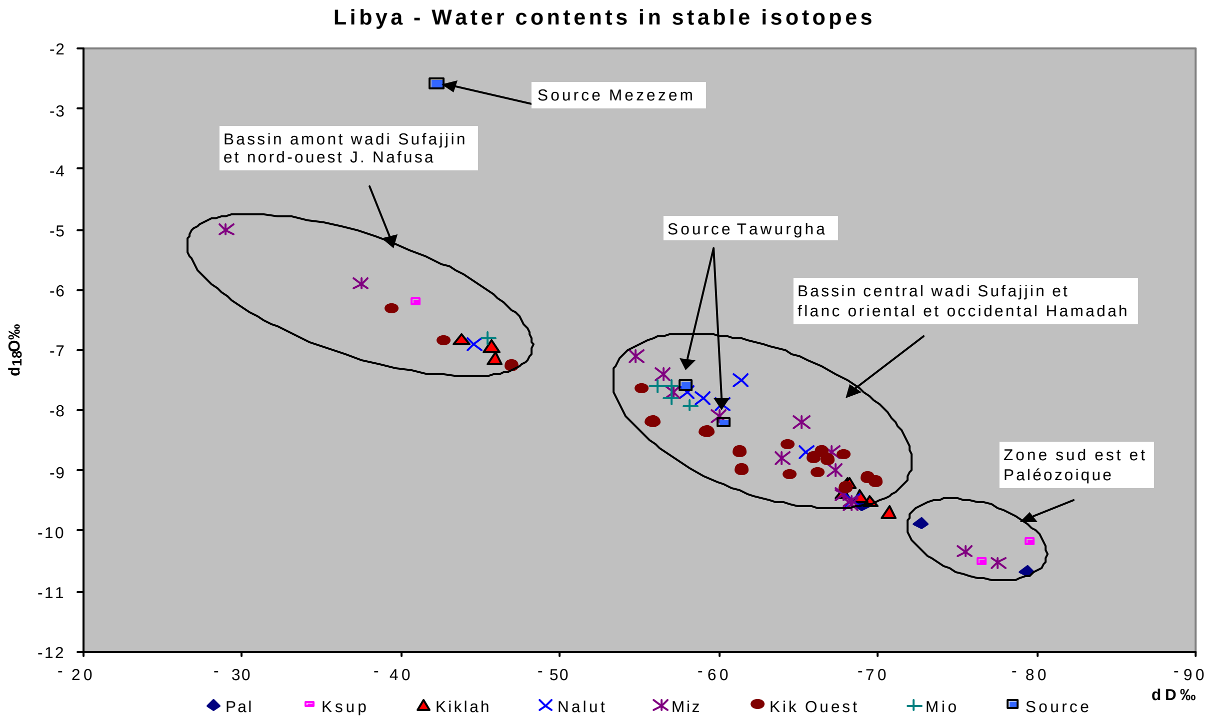
The I.C.S. sheet is either free or covered with the sand hills of the Western Big Erg. The outcrops zones of the lower Cretaceous make up natural outlets for the sheet. The contents in stable isotopes therein are very variable ($d^{18}O$= - 9.6‰ to – 4.1‰). The Tikidelt zone shows values very close to those of the Eastern Big Erg Basin, but with a more important activity in ^{14}C (4 to 40%), which confirms the existence of a local contribution to the feeding of the sheet.

These local contributions are at the origin of the waters mixings, inside the aquifer, which give out apparent ages, covering several thousand years. In the Touat and the Gourara where the I.C.S. waters show high level of activities in ^{14}C (up to 60%), the contents in stable isotopes are variable but higher than those found in the Tidikelt. In the east and in the south of the Western Big Erg, the I.C.S. waters show isotopic compositions, which are identical to those of the waters in the Erg sheet. This region corresponds to a large zone for the discharge of the Big Erg waters into the I.C.S. sheet.

1.3 - Hamada El Hamra

The contents in stable isotopes are very much scattered all over the Hamada area. These values are among the smallest in the region and correspond, hence, to those found for the water of the Intercalary Continental shelf, which is located in the confined part of the sheet (O. Salem & al., 1996). In the zones where the Kikla formation makes up a continuation of the Cambro - Ordovician, these contents are the smallest (^{18}O = -10.9‰ and ^2H= -80.7‰). The contents in ^3H are very low (<2 UT) and the activities in ^{14}C are often weak (from 1 to 5 %) giving thus ages to the water ranging between 16 800 and 31500 years for collecting depths of 600 to 1200 m.

Waters with a very low contents in stable isotopes are those found in the Paleozoic aquifers of the south of the Saharan basin and in the upper Cretaceous (Mizdah) and which are in direct contact with the Cambro-ordovician aquifer. Carbon 14 gives to these waters ages superior to 25000 years.

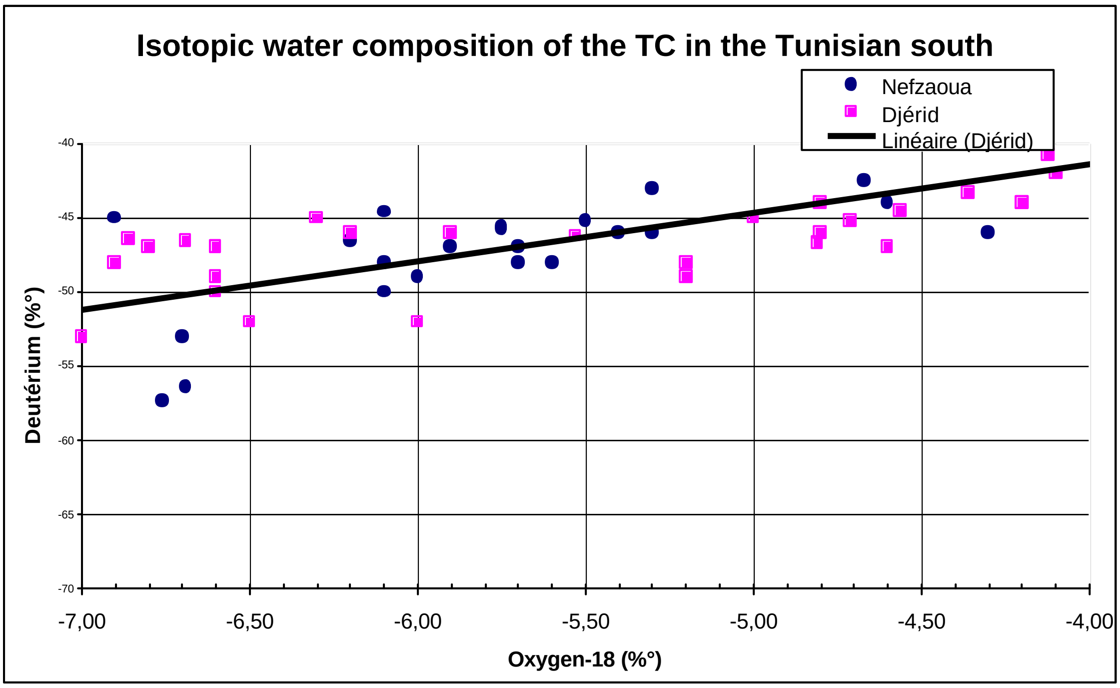


2 – The terminal Complex sheet

2.1 – Lower Sahara Sheet

The isotopic composition of the Terminal Complex waters reflects the heterogeneous nature of the aquifer reservoir as well as a greater accessibility of its different aquifer levels to the present reloading. The range of variation of the contents in stable isotopes is wider in the case of the T.C., than for the intercalary continental shelf, with values ranging between –9.3 and – 3.9%◦. The localized zones under the sand hills of the two Big Ergs are characterized by an enrichment in heavy isotopes, which reflects the effect of the present arid climate.

These waters bear the seal of water marked by evaporation through an enrichment in heavy isotopes, which reflects the effect of the aridity of the climate. The reloading of the T.C. sheet seems to have changed in time, along with the evolution of the climate during the last millenniums. The enrichment in heavy isotopes, which can be noticed even in the most confined waters of this sheet (El Wadi in Algeria), is explained by a paleoclimatic reloading which went through modifications in the isotopic composition of the waters during the evolution of the aridity.



The composition in heavy isotopes of the limestone sheet shows, in Algeria, somewhat uneven contents with an average of $d^{18}O$ = - 7.42 to ± 0.47%◦ and $d^{2}H$ = - 49.3 ± 3.6%◦ (an average surplus of +10).

In the Nefzaoua area in Tunisia, the contents in heavy isotopes are higher than those of the sand waters; they however undergo a dispersion resulting from their proximity to the Dahar reloading area.

The contents in ^{14}C of the water sources located near the outcropping area of the aquifer show relatively significant activities relating to a certain contribution to a modern feeding of the sheet. A decreasing gradient of concentration in ^{14}C exists in the Nefzaoua area, between Douz and Kebili, according to the sheet's flowing direction. This gradient allows evaluating the underground flowing speed from **1 to 2m/year** (A.Mamou, 1990). The T.C. waters rough ages range, in this zone, between **3500** (Douz) and **27 000** years (Aïn Tawurgha). The lowest values (< 10 000 years) are closer to those of the reloading zones

and the highest values (**18000 to 27 000 years**) correspond to the waters, which are more confined and closer to the outlet.

2.2 - Big Ergs sheets

The western Big Erg sheet circulates in the dolomitic limestone flagstone of the Hamada, which supports the Erg sand hills. This sheet is accessible at a very small depth. Its resources come essentially from the present feeding, out of rainwater's (after streaming in). The contents in heavy isotopes of these waters indicate an enrichment caused by the evaporation with:

- A group of non-evaporated waters, which fall into one line, along the straight line of the present rainwater's. The intersection of this curb with the straight line of the meteoric waters is located at the point ^{18}O= - 8‰ and ^{2}H= - 60‰.
- A group of evaporated waters, which fall into one line, along an inclination, less important than that of the meteoric waters.

These two groups embody the recent feeding mechanism of sheet with rainwater's. The first group corresponds to the waters, which infiltrate directly under the sand hills without streaming and the second group to the waters coming from the overflows which stream out into the Wadies.

2.3 - The Turonian Sheet

The Turonian sheet stretches over the far Tunisian south on the western piedmont of the Dahar and between Jabal Nafusa and Ghadames. The isotopic nature of the waters of this sheet is close to that of the Intercalary Continental waters. These waters are characterized by low contents in stable isotopes. The age of the waters lodged at that aquifer level is often superior to **20 000 years**.

3 - Conclusion

The North Western Sahara Aquifer System results from a long process of setting up the reserves, over several dozens of thousands of years. The essential part of the geological reserves, located in the confined part of the sheet, was formed at a time when the climate of the region was more rainy (quaternary rain of – 150 000 to – 20 000). This phase reached its peak with the transformation of the depressions in the tunisian-algerian chotts into big lagoons (Cardium lakes) whose extension corresponded to two or three times their present surface. This phase corresponds also to the reloading of the confined levels of the system and to the appearance of the main springs in the region both at the level of the I.C.S. and the T.C.

With the progressive aridity of the climate, the slow and continuous draining of the aquifer system started. The spouting of springs was the manifestation of the overflowing of these sheets, but the reloading of the aquifer levels kept on dwindling taking into account the reduction of the water feeding on the borderlines. Since then, the aquifer system knew a more and more important decompression, which got accelerated with the creation of the first drillings. This phenomenon got much intensified with the generalization of the pumping out.

The outcropping zones of the aquifer formations continued to play the role of reloading areas, but with small contributions to the sheets, considering the relatively low, irregular and not frequent rainwater quantities. The waters, which reach likewise the sheet, make up "mixtures" of the water, which infiltrates directly and the hydric reserves of the soil, which are subject to evaporation before reaching the saturated part of the sheet on the occasion of big

rainy events. This situation is also explained by the presence of water, under an evaporated aspect and under the form of "a mixture" near the system's reloading areas.

In the confined part of the system, water is older and has more homogeneous isotopic characteristics. Its reloading makes its underground circulation slower and allows it to have a longer time of contact with the rocky matrix. Hence, under the effect of high pressure and temperature, this water undergoes chemical exchanges with the accumulating formations. A part of the chemical nature of the water is also confirmed in certain zones, on the occasion of lateral and vertical communications between different aquifer levels. This is particularly the case during major tectonic accidents (Amguid Dorsal, Hun Faults, Kebili Fault, etc…) and the lateral passages of faces (passage from the lime stones to the sands).

V - CONCLUSIONS AND RECOMMENDATIONS

1 – Hydrodynamic functioning of the system

The North Western Sahara Aquifer System whose extension goes beyond the national borders of the three countries which shelter it, is at the **almost exclusive origin of the available water resources in this territory.** These resources which play a prevailing role in the economic and social development of the region, have also a strategic dimension because they are, in their most important parts, non renewable, and because they have already entered into **an intensive exploitation phase which has already provoked noteworthy modifications in the behaviour of the aquifers.** The controlled and concerted management of these resources becomes now a necessity in order to extend, in the best possible way, the longevity of the economic system depending thereon.

2 – Hydraulic functioning of the aquifer system

After a phase in the course of which the exploitation of this system was essentially based on artesianism (before 1970), **these aquifers are now more and more solicited by pumping** Along with this situation, the exploitation which was made before within groups of oases relatively limited in the space, has become now, more intensive and better distributed over several new poles of development.

This new arrangement resulted in a more acute piezometric draw down at the level of the groups of ancient oases, and also in a general draw down, much stronger than the one previously observed. **There resulted there from the almost total drying up of the main springs (Nefzaoua, Djerid and Kaam) and a very sensitive reduction of the artesianism in the basins of the oriental Big Erg and in the Libyan Saharan basin.**

The more and more frequent and intensive recourse to the pumping out leads, at the level of the whole aquifer system, to more important intakes from the geological reserves as well as to interactions between the different inter-connected levels, either directly or through draining across semi-permeable horizons. This hydrodynamic situation is reflected at the hydro chemical level, by exchanges of salt between:

- The aquifer levels attached to the same sheet, which leads to **a homogeneity of the salinity of its water around an average value**,

- The potential salination springs (Chotts, Turonien, Aptien, etc…) and the sheets adjacent to them, bringing out into the open more and more localized **chemical anomalies zones.**

3 - Recommendations on the follow up and the improvement of certain data

The follow up of the NASS aquifer system is, at the same time, a supplement of information to be obtained and new measures to be collected.

The present follow up of the exploitation of the water reserves of the system in the three concerned countries is not carried out sufficiently well enough to secure the periodic updating of the management patterns of the sheets and to have a clear cut idea on the choices to be made within the framework of the optimised management of these resources. This follow up suffers from important deficiencies in the evaluation of the intakes and in the evolution of the chemical quality of the water. Certain areas (under the ergs, in particular) which are not yet covered by the surveys or by the evaluation of certain

hydro geological parameters need the collection of additional information in order to improve the adjustment of the patterns.

3.1 – Improving the knowledge of certain data

- ***Geometry of the reservoirs***

The information on the geometry of the aquifer reservoirs and their communications still need to be better specified and analysed through **new geophysical data and through other data on the deep drillings conducted within the framework of the hydraulic and oil exploration.** This is particularly the case in the **western Big Erg basin in Algeria** where the exploitation was essentially made, until these last years, through the foggaras. The need to extend the exploitation to new zones and the piezometric decrease in this basin mean that the generalization of the drillings in the whole of the basin is only a question of time, which should lead **to the necessity to have a better idea on the thickness and depth of the I.C.S. all over this basin.**

The existing relations between **the pre-cenomanian formations of the Saharan basin and the Triassic formations of the Libyan Jifarah deserve** also a more elaborate study based on the drillings and the geophysical studies.

The multi-layer nature of the terminal Complex sheet makes that the geometry of its aquifer reservoir (sands and limestone) is still not well known in several zones and particularly at the level of Biskra (Tolga sheet) and more generally outside the exploitation zones. **The refining of the geometry of this aquifer reservoir allows designing in a better way the management patterns and the exchanges of water and solutions between the different aquifer levels.**

The role of the **turonian dolomy** in the flowing of the T.C. waters is partially well known only on the borders of the basin (Kebili peninsula and tunisian-libyan Dahar). Its role **as an aquifer level with a high degree of salinity under the oriental Big Erg (Hassi Messaoud and Tunisian far south), has to be carefully analysed, considering the potential danger of salination, which is associated with this aquifer.**

- ***Present feeding of the system***

The present sporadic feeding is essentially localized in the zones of the basin borderline. It mainly comes from the **direct infiltration of exceptional rains and more generally from the infiltration of streaming waters.** The evaluation of this infiltration should be based on **hydrologic measures allowing to define the surface flowing regime and to precise the occurrence of hydrologic phenomena and their amplitude.**

The geo chemical approach referring to the **speed of infiltration and to the dating of the waters** may, in certain cases, allow a better evaluation of the global infiltration. It seems however that, because of the remote location and the difficulty of access of the potential aquifer reloading zones, reliable measures, that is to say executed over several years, are very difficult to imagine.

It is highly recommended, before considering such measures, to carry out sensibility tests on the pattern, in order to determine whether errors of appreciation of the present reloading could entail very different behaviours of the sheet in the present and future exploitation zones.

- ***Flow of the natural outlets and losses by evaporation***

The losses by evaporation are also estimated and often evaluated as a quantity allowing finalizing the balance. The decrease of the piezometric level, resulting from the effect of the exploitation in the neighbouring zones, diminishes the raising of water up to the superficial layers which are subject to evaporation or to evapo-transpiration, but the vertical flow has always been calculated by applying theoretical formulae (Darcy Law) and by using values of vertical permeability which cannot be checked. **Here also university researches could be encouraged in order to try and determine the evaporatory flows through an analysis of the energy balance at the level of the soil.**

- ***Hydrochemistry***

The chemical analyses conducted at the acceptance of the drillings are relatively numerous in Libya and in Tunisia, however, they are rather scarce in Algeria. A first recommendation in this field would be **to increase the number of complete chemical analyses in Algeria.** However, in Libya, an exhaustive interpretation of the numerous existing studies is highly recommended in order to explain the space evolution of the contents in different ions in relation to the geology on one hand, and the characteristics of the flowing, on the other.

- ***Data relating to the use and cost of water***

Data relating to the **use of water** (irrigation, drinking water sully, industry, etc…), to the puming out means (artesianism, pumping, foggaras, etc…) and **to the costs associated with the exploitation** of the underground waters allow to better evaluate the socio-economic aspects of the water and to direct the management towards optimised usages.

Since the time when pumping became prevailing in the exploitation mode of the saharan basin waters (in the 80's), the exploitation costs underwent a growing importance which, unfortunately, is not evidenced by precise data. **The follow up of the economic aspect is felt on each occasion for the updating of the NASS pattern as a deficiency which should be made up for through the collection of certain socio-economic data** in order to better evaluate the stakes and to set up the scenarii for the future development of the water resources of this aquifer system, not only on hydrodynamic and hydro chemical bases but also on socio-economic criteria.

3.2 – Improvement of the follow up

- ***Follow up of the intakes***

All over the Saharan basin, **the periodical follow up of the intakes** is a necessity in order to allow the appreciation of the reliability of the patterns. The difficulties linked to a direct approach of the estimation of the intakes through enquiries and investigations are enormous and limit the chances of an earnest and viable follow up, all over the whole basin.

The adoption of statistical methods (sampling and representative zones) **cross-checked by other evaluation means** (irrigated areas by interpreting satellite images, power consumption, etc…) would enable to secure a better follow up of the exploitation and to dispose of more or less regular information on the intakes without however requiring considerable means.

The setting up of the methodology allowing to go from the reading of the electrical meters or the irrigated areas based on satellite images to the volumes of water which is extracted from the underground could be the subject matter of research works per zone, which may go as high as the doctor's degree thesis. This approach could facilitate the

task of the technicians in the administration who would be in possession of a rapid means for determinating the intakes per zone.

The periodical publication of the results of the measurements under the form of directories accompanied by critical analyses, would allow securing, in an efficient way, an updated knowledge of these information. For the time being, this approach is effective only in Tunisia. It could make up an option to be implemented within the framework of the concerted management of the Saharan basin.

- ***Piezometric follow up***

The piezometric follow up must be conducted in the three countries on a more regular basis in order to avoid having recourse to extrapolations concerning measures, which do not correspond, in their totality, to the same date. **A minimum network must be set up in each country** for the follow up of the Intercalary Continental Shelf and the Terminal Complex. This network must comply with e main following criteria:

- **A good representativity of the piezometry variations** in the different parts of the basin particularly on the borders of the zones offering high exploitation and a high density of water sources.

- **A regularity in the collection of information** in time which allows to deduct there from the answer of the sheet to the phenomena disturbing its hydro dynamism such as its exploitation or exceptional feeding.

- **A time pace adapted** to the piezometric variations of each sheet.

It is highly recommended to the three countries to try and obtain **a series of observations, which are as long as possible (liaisons with the replacement drillings). The acquisition of the altitude of the measuring points is complementary to the piezometric information** and allows the extrapolation between the points located in the same zone of influence.

- ***Follow up of the salinity and the chemical composition***

The quality of the water and its future evolution makes up the most preoccupying aspect in the mastering of the management of the NASS water resources, unfortunately, the chemical follow up **of the NASS aquifers is far from being well secured everywhere and when it is more or less conducted, it only relates to the salinity of the water.**

With the increase of the exploitation and the decrease of the piezometric levels under the natural ground, **the risks of inversion of the flowing within the aquifer formations have become greater**. This is particularly the case of the sheet of the **Terminal Complex** in the zones where its semi-waterproof roof is very thin. **The contamination risks of this sheet by the irrigation waters and those of the Chotts are important. This phenomenon observed in the oases of El Wadi and of Nefzaoua-Djerid needs to be better observed and analysed accordingly.** The risks of marine invasion in the **aquifers close to the sea in Libya also requires some watching out which is still missing.**

The management of the water resources of this system is not exclusively a management of the exploitable volumes but also of the quality of the water which is to be taken out and whose deterioration could seriously compromise its use in certain sectors such as the drinking water supply and the industry which require a good chemical quality. **This chemical follow up has to be gradually oriented towards the chemical**

composition of the water in addition to its global salinity. It is through the analysis of this composition that the origins of the contamination and to the measures to be made to remedy thereto shall be pinpointed in the best possible way.

3.3 - Acquisition of new data and data base updating

The data on the new drillings, contributing to the improvement of the knowledge of the geometry of the aquifer reservoirs (geological log) and to the updating of the hydro geological information (piezometry, exploitation flow, transmissivity, dry residue, chemistry, isotopic analysis, etc…) **should systematically be filed in the data base**, in conformity with the formats defined within the framework of the NASS project. The acquisition of this piece of information in the base shall furthermore allow its interpretation and its integration in the patterns.

4 - Recommendations for the setting up of a follow up network

The periodical measurements of the flows, the piezometric level, the water salinity and the chemical composition must be acquired within the framework of well structured national follow up networks which satisfy the different national surveillance and management objectives. The structuring of these networks is part of the policy of each country, aiming at securing the management of these water resources.

However, the setting up of **a minimum network for the surveillance of the levels and the follow up of the intakes and of the quality of the waters** allowing to collect the necessary information at the level of the whole basin **is a guideline which responds to the objective of the setting up of "a follow up and consultation mechanism"** allowing to coordinate the management of these resources.

The definition of this minimum network shall result from the pattern simulation in the different development scenarii allowing locating the sensitive zones, which require a special surveillance and which are essential for the adjustment of the patterns.

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Furthermore, in the course of the period between 1970 and 2000, the Algerian- Tunisian Sahara was the subject matter of several university studies on hydrogeology (Ben Dhia, 1985 & Mamou.A, 1990) and on isotopic hydrochemistry (Gonfiantini & al., 1974 and 1976 ; Yousfi, 1984 ; Gendouz, 1985 and Zouari, 1988). Several other studies, with a local nature, have also been used. The whole of these works listed in the bibliographical references allowed making clarifications on the climatic regime of the region, the geology of the Saharan underground and the functioning of the sheets.