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WATER SUPPLY FOR URANIUM MINES IN SOUTHERN ALGERIA

STAGE I REPORT

MAY 1977

SIR ALEXANDER GIBB & PARTNERS
READING and LONDON

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ACKNOWLEDGEMENTS

This Report has been prepared in association with the Institute of Hydrology.

The experts for the Institute of Hydrology who have made the principal contribution are:-

Mr. A.G.P. Debney - Hydro-geologist

Mr. B.S. Piper - Hydrologist

CHAPTER 1

INTRODUCTION

1.1 Terms of Reference

At the outset of the study it was understood that the Terms of Reference included estimates of demand, evaluation of sources of supply, and engineering of methods of transferring water from source to demand centre.

During the field visit it became apparent that estimates of demand and engineering aspects were being covered by Charter Consolidated Ltd. and Constructors John Brown Ltd. respectively. However, the scope of the evaluation of sources of supply proved to be more extensive than had been assumed previously.

This Report is therefore concerned with the hydro-geological aspects of sources of supply covering:

(i) an examination of the available documentation of the area,

(ii) a regional reconnaissance of resources and the general mechanism which control them,

(iii) the taking of water samples for analysis,

(iv) the establishment of the most favourable areas which may be the subject of study in Stage 2,

(v) the preparation of detailed plans for Stage 2.

1.2 Method of Study

Work in Stage 1 has involved the following personnel:

Project Engineer
Hydro-geological Adviser
Hydrologist
Water Resource Consultant

The Project Engineer, Hydro-geological Adviser and Hydrologist visited Algeria from 22nd March to 1st April 1977. Two field trips were carried out from the SONAREM base camp at Tamanrasset:

(i) to the principal potential water supply source, namely the extensive sandstone aquifer of the Tin-Seririne basin,

(ii) to the mines at Abankor and Timgaouine, returning to Tamanrasset via Silet and Abalessa.

Discussions were held with SONAREM in Algiers.

An itinerary of the visit to Algeria is included as Appendix A.

CHAPTER 2

CATCHMENT CHARACTERISTICS AND CLIMATE

2.1 Topography and Drainage Pattern

As shown on the location plan (Figure No. 1) the mining prospects are situated about 250 km southwest of the central mountain core of the Hoggar. These mountains, which rise to 2700 metres, form a major watershed around which a system of radial drainage has developed. Timgaouine-Abankor lies close to an important watershed separating basins draining westwards into the Tanezrouft from basins discharging southwards into the River Niger.

The broad drainage pattern of the Hoggar is also shown on Figure No. 1. The high mountainous area is of relatively limited extent and is centred upon the basalt massif of the Atakor. Tamanrasset, the principal town of the Hoggar, has a general elevation of about 1400 metres although isolated peaks nearby rise to over 1900 metres. The 1000 m contour marks the approximate limit of low level mountainous rocky terrain; below this elevation the drainage systems open out, the ground relief becomes more subdued and a fairly extensive alluvial cover is developed. The mine has an elevation of about 650 metres with the land falling gently away to the west and to the south.

The general pattern of drainage and the catchment configurations southwards from the Hoggar are controlled to a large extent by the geology. In the central area shown on Figure No. 1 major faulting and a strong north-south geological lineation has led to the development of long, narrow drainage basins with small headwater areas in the Hoggar. The Wadis Ighaghar, Zazir, Tin Amzi and in part the Wadi Tamanrasset fall into this category. Drainage westwards from the Hoggar to the Tanezrouft has developed through broader catchments with larger headwater areas in the higher mountains. The boundary between the westward and south-westward draining wadis and the southerly discharging catchments of the central zone coincides with a major structural contact in the crystalline Pre-Cambrian basement. The Abankor mine lies close to this major north-south contact where river capture has occurred diverting the Wadi Tamanrasset from the southerly draining system to the Tanezrouft.

Drainage in the eastern Hoggar is concentrated within the single large system of the Wadi Tin Tarabine which discharges south-eastwards eventually to flow into the River Niger in Mali. This wadi crosses a large basin of sedimentary rocks resting unconformably upon the Pre-Cambrian crystalline basement some 250 km east of Abankor. The western margin of this sedimentary basin of Tin Seririne is near to the catchment divide between the Wadi Tin Tarabine and the most easterly of the southerly draining narrow wadis.

On the assumption that it is the higher areas of the Hoggar which receive most rainfall and thus generate the runoff which promotes recharge to any aquifers, then the distribution of the headwater areas with altitude is a first indication of the water resources potential of the various wadis. Table No. 1 shows the sub-division into altitude ranges above 1000 metres for the catchments in the vicinity of the mine. There are significant differences between the various runoff potentials, with those wadis furthest from the mines (W. Abalessa and W. Ighaghar) having two to four times the headwater areas of the Wadi Tamanrasset. The Wadi Tin Amzi, the Wadi Zazir and the Wadi Tinef have virtually no contributing catchment areas above about 1500 metres.

TABLE NO. 1

AREAS OF HEADWATER BY ALTITUDE RANGE
(km^2)

	Altitude Range (m)			
	>1800	1800-1400	1400-1000	>1000
WADI ABALESSA	442	707	2430	3579
WADI TINEF	-	-	428	428
WADI TAMANRASSET	136	427	971	1534
WADI TIN AMZI	-	127	516	643
WADI ZAZIR	-	78	1341	1419
WADI IGHAGHAR	538	1306	1613	3457

Wadi Tin Tarabine is probably comparable to Wadi Ighaghar so far as altitude ranges is concerned, but lack of complete map coverage prevented a detailed assessment.

The above topographic information provides a first indication that the more distant catchments will generate more frequent and larger volumes of runoff than those close to the mine. Underground water supplies in the Wadi Ighaghar, Wadi Abalessa and Wadi Tin Tarabine are likely to be recharged more frequently and at greater distances from the Hoggar than those in the Wadi Tamanrasset. The distribution of the major rock types in the headwater areas of these three larger catchments, basalt on the highest ground giving way to crystalline basement at lower elevations, suggests that they have similar potentials for generating runoff from the rock slopes. By comparison the smaller catchments of Tin Amzi and Zazir have no basalt areas. During our field survey the appearance of the wadis in the vicinity of Silet suggested that the basalt areas generated more runoff than similar basement areas. If this is the case then the Wadis Tin Amzi and Zazir have an even lower potential for runoff than is indicated by elevational and areal considerations alone.

2.2 Rainfall

The extreme aridity of the area hardly needs emphasising. The Idrotecneco[1] and Burgeap reports make slightly different interpretations of the rainfall data. Annual rainfall on the highest ground of the Hoggar is given as 100 mm by Idrotecneco but is shown as only 60 mm in the Burgeap study. In both studies the annual rainfall at Timgaouine-Abankor is reported to be less than 10 mm. These varying views regarding the amounts of average annual rainfall on the highest ground are not too important to this study. It is the intensity, duration and distribution of individual rainstorms which is significant.

[1] The various Sonarem publications provided are listed in Appendix B. Throughout this study these reports are referred to in abbreviated form by reference to the cooperating agency.

Rain falls mainly during the summer in the southern Sahara. The pattern of wind circulation is such that the air masses reaching the area at this time have experienced reasonably long trajectories over the southern Atlantic Ocean. However the mere presence of moist air is in itself insufficient to produce precipitation, for some triggering mechanism such as topographic ascent, convection or frontal and convergence zone instabilities is needed to produce condensation and ultimately precipitation. The extremely high temperatures over the area in the summer accentuate the problem and the need for a triggering mechanism is very great before condensation takes place.

Rainfall in the Hoggar is therefore characterised by occasional, short, often very intense storms which can cover large areas. In general over 90% of the storms observed have durations of less than 2 hours. Although over 70% of the annual rainfall occurs between May and September the variability of the rainfall from year to year, and from month to month within a given year is very high. For example the Tamanrasset record from 1931 to 1974 shows variations in annual rainfall from 170 mm to 1 mm with an overall mean of 46 mm.

The annual rainfall data for stations within the Hoggar show evidence for the existence of a relationship between rainfall and elevation, but the non-availability of recent data and the nature of the temporal distribution of rainfall make the form of this relationship difficult to define. There appears to be a tendancy for higher rainfall in the northern and western areas of the Hoggar and for somewhat lower rainfalls at similar elevations in the headwaters of the wadis draining southwards toward the mine.

It has not been possible to adopt a quantitative approach and develop assessments of rainfall volumes for the catchments of major interest. Isohyetal maps are available only for two storms in 1964 (Idrotecneco) and unfortunately only one of these had a distribution which might have resulted in runoff within the principal area of this study. However, in order to emphasise the relative importance of the various catchments we have estimated the approximate rainfall volumes for the October 1964 storm (Table No. 2). This storm probably had a fairly uniform rainfall distribution relative to the headwater elevations, producing 35 mm above 1800 metres and 20 mm between 1400 and 1800 metres. Examination of the Tamanrasset monthly rainfall data suggests that many years produce a storm of similar proportions. The period between November 1969 and September 1974 is the longest interval without such an event since records began in 1931.

TABLE No. 2

RAINFALL VOLUMES 16-18 OCTOBER 1964
(million m^3)

	Altitude Range (m)		Total Volume
	1800	1800-1400	
WADI ABALESSA	15.4	14.1	29.5
WADI TINEF	O	O	O
WADI TAMANRASSET	4.8	8.5	13.3
WADI TIN AMZI	O	2.5	2.5
WADI ZAZIR	O	1.6	1.6
WADI IGHAGHAR	18.8	26.0	44.8

As in Table No. 1, Wadi Tin Tarabine is probably comparable to Wadi Ighaghar.

2.3 Runoff

Lack of information concerning runoff distribution and volume is the most obvious gap in the data record compiled during the past seven years. Discussion of surface flow must therefore be largely qualitative although we have used our detailed knowledge of another mountainous arid area to gauge the possible dimensions of runoff volumes.

A summary of runoff conditions is given by Burgéap. They suggest that in most years surface flow occurs in the upper 30-40 km of the drainage network reaching for example as far as Tamanrasset. More widespread runoff normally follows exceptionally heavy rains and Burgéap suggest than on average about one storm every 25 years might be capable of producing runoff in the Wadi Tamanrasset at Abankor. It is difficult to comment objectively upon these interpretations as supporting evidence is not provided and the analysis may well be based upon local information. In our experience, local information of this nature often proves to be unreliable.

Bearing in mind the catchment area and elevation observations, it is perhaps surprising to find that the Wadi Tamanrasset is shown by Burgéap to be as responsive to runoff as the Wadi Abalessa and the Wadi Ighaghar. We would have expected more frequent and more extensive runoff in these larger catchments. Nevertheless, we would agree that runoff and hence recharge of any aquifers in the vicinity of Abankor is a rare event. Development of local groundwater supplies must therefore depend on large underground storages and natural replenishment cannot be relied on within the planned lifespan of the mine.

From studies we have made into runoff volumes and streamflow distribution in Northern Oman[1], we estimate that runoff from the Hoggar is likely to be about 15-25 percent of the rainfall volume. Unfortunately, we are unable to apply our Oman model further to the Hoggar due to important geomorphological differences between the two areas and lack of rainfall data.

The problem is largely concerned with assessing runoff distribution relative to the size of the storm and in this respect our field survey provided conflicting evidence. For example, channel conditions suggested fairly active runoff in the minor wadis draining the low level basalt area between Tamanrasset and Silet but gave little evidence of large flows in the middle reaches of the Wadi Igharghar. Channel geometry could give rise to short violent runoff from the basalts and to longer periods of low flow conditions in the larger major wadis. Alternatively rainfall distribution may not be simply related to elevation with the basalt area around Silet having unusually high rainfall.

[1] Water Resources of Northern Oman, June 1976. Sir Alexander Gibb and Partners in association with the Institute of Hydrology.

With regard to recharge we would consider this as a process confined to the wadi channels during periods of runoff. From Table No. 2 some general idea of the relative recharge potentials can be gained, with about 15-25 percent of these rainfall volumes appearing as runoff; however, no information exists to show what proportion of the runoff goes to recharge or where such recharge occurs.

CHAPTER 3

GROUNDWATER

3.1 Hydrogeology

The geology of the central Sahara is dominated by a large inlier of igneous and metamorphic rocks of Pre-Cambrian age. These are surrounded by a plateau of Palaeozoic sedimentary rocks and intruded by recent volcanics. The products of erosion of the Pre-Cambrian basement are found throughout the area. Gravels and boulder beds floor the drainage channels in the central Hoggar, these alluvial deposits becoming progressively finer grained throughout the length of the wadi systems occurring as fine sands and silts in the lower reaches of the basins.

Groundwater has been shown to occur in all the major geological units. However, there are only two main hydrogeological environments containing exploitable resources:

(i) A zone of weathering in the upper layers of the Pre-Cambrian basement. This is a complex system of water bearing strata in hydraulic connection with fault zones and the alluvial deposits of the wadi beds.

(ii) A more conventional aquifer comprising Cambro-Ordovician sandstones of the Palaeozoic era. These occur preserved either in gentle depressions in the basement or in down-faulted blocks.

The distribution of the major hard-rock elements of the geology is shown on Figure No. 1. Pre-Cambrian rocks form the central part of the area of investigation around the mine. Palaeozoic sediments are preserved in the basin of Tin Seririne and at Tin Missaou, 200 km east and 150 km west of Abankor respectively. They also occur 150 km to the south of the mine along the southern border between Algeria and Mali. Volcanism of Tertiary and Quaternary age has produced large basalt areas which form the highest ground in the Hoggar, i.e. the Atakor and the Ta-Settefet to the north and west of Tamanresset which form the head-water areas of the drainage system.

3.2 Groundwater in the Fissured Basement

The crystalline Pre-Cambrian basement is divided into two groups: the old metamorphosed crystalline schists of the Suggarian and the less strongly metamorphosed conglomerates and quartzites of the Pharusian. Rocks of Suggarian age occupy the central area where a strong geological fabric produced by extensive north-south fracture systems has given rise to persistent rocky ridges forming parallel watersheds between wadis. A major fracture system running north-south passing close to Abankor separates rocks of Suggarian age from Pharusian rocks which underlie the western wadis. At Abankor river capture has occurred diverting the Wadi Tamanrasset to the westerly draining system from the area of Suggarian rocks.

The 1973 catalogue of water sources in the Hoggar describes 30 deep boreholes into fissured basement. About 50 percent produced a supply although only 6 yielded more than 1.0 l/sec. It is difficult to make an objective assessment of this part of the exploration programme; the boreholes are widely scattered and cover a wide geological range. Geophysics was used to locate some of these trial boreholes while others are in the areas of detailed mineral prospecting and probably include groundwater discovered incidentally during other exploration. Generally the results are more favourable than would be expected from groundwater exploration of faulted basement rocks.

There is one production borehole at Abankor in faulted gabbro of Pharusian age (Borehole 15). When tested it yielded 1.4 l/sec and supplied the mine for several years. It is no longer used as the source of supply, the water is not potable and the initial yield was reported to have declined. The borehole is located close to the point of river capture of the Wadi Tamanrasset where either recharge from occasional flooding or any wadi groundwater could be intercepted. A sample of water from this borehole has been analysed to determine deuterium (D) and oxygen-18 (^{18}O) and concentrations compared with groundwater from the wadi at Tamanrasset (Appendix C). The isotopic concentrations are significantly different and there is little if any modern wadi water in the Abankor borehole.

A chemical analysis has also been obtained (Table No. 3). Magnesium, chloride and sulphate exceed the World Health Organisation recommended maximum permissible levels, the concentrations being about ten times that of recent groundwater in the wadi. Although not determined in the routine chemical analysis, we have also recorded the presence of an unusually high concentration of strontium in the borehole sample. The significance of this is not understood, strontium salts are relatively insoluble and are not normally found in groundwater.

Groundwater exploration has also taken place at Amselka about 40 km to the north of Abankor. No records of this recent exploration are available; however, the site was visited during the field reconnaissance and the boreholes appear to be dry. Drilling was in the fracture system of the Suggarian/Pharusian fault contact in the bed of the Wadi Tamanrasset. Earlier reports suggested Amselka as a potential site for a supply to Abankor and the location was an obvious choice for exploration. Failure to find groundwater at such a favourable site emphasises the difficulty of providing supplies of any magnitude from these fracture systems. In our view further general exploration is not justified, as possibly only one major exploration site in five can be expected to yield a maximum of 1 l/sec.

However, small groundwater supplies might be available in the Timgaouine-Abankor area. Fifteen mineral exploration boreholes have encountered groundwater. They have not been test pumped, the quality is unknown, and we were unable to determine the source of the water. Details of the sites are given in Table No. 4 which also shows the depths at which groundwater was encountered. The Hichem and Daira Nord data are sufficiently consistent to warrant test pumping to obtain samples for water quality and to give an indication of yield.

TABLE NO. 3

CHEMICAL ANALYSIS OF WATER SAMPLE FROM BOREHOLE 15 - ABANKOR

This sample shows faint opalescence with a slight deposit but is free from colour after filtration. The reaction is on the alkaline side of neutrality and the water is excessively hard in character. The amount of mineral and saline constituents in solution is above World Health Organization International Standards for drinking water maximum permissible level of 1500 mg/l. The water also contains an excessive amount of nitrate. Apart from minute traces of iron and manganese and a very small trace of zinc metals were not detected.

TABLE NO. 3 Continued

CHEMICAL ANALYSIS OF WATER SAMPLE FROM BOREHOLE 15 - ABANKOR

RESULTS IN MILLIGRAMMES PER LITRE

Appearance . Faint opalescence giving a slight deposit on standing. ....

.... Turbidity (Formazin, A.P.H.A.units) ... 5 ..

Colour (Hazen) ... Filtered ...... NIL . Odour .... NIL ..

pH .... 8.1 . Free Carbon Dioxide .... 1 .

Electrical Conductivity .... 2230 . Dissolved Solids dried at 180°C ... 1700 ..
Reciprocal Megohms (Micro-Siemens) per cm. at 20°C.

Chlorine in Chloride .... 400 . Alkalinity as Ca CO_3 .... 92 .

Hardness as Ca CO_3:Total .... 860 . Carbonate ... 92 ..... Non-carbonate .. 768 .

Nitrogen in Nitrate .... 52 . Total Organic Carbon ....

Nitrogen in Nitrite ... approx. 0.01 . Permanganate Value ....
4 hrs. at 27°C

Ammoniacal Nitrogen less than 0.05 . Residual Chlorine ....

Albuminoid Nitrogen ....

Iron .. 0.07 .. Zinc .. 0.23 .. Copper Absent . Lead .. Absent Manganese .. 0.03 ..

Cadmium . Not detected, <0.001 ...... Fluorine in Fluoride .. 0.3 .. Silica .. 35 ...
("absent" refers to a detection limit of 0.03 of each metal unless otherwise stated)

MINERAL ANALYSIS (after filtration if necessary) (milligrammes per litre and millequivalents per litre)

	Cations mg/l	Cations me/l		Anions mg/l	Anions me/l		mg/l	me/l
Ca	155	7.75	* CO_3	55	1.83	Calcium Carbonate	92	1.83
Mg	115	9.45	SO_4	480	10.00	Calcium Sulphate	403	5.92
Na	215	9.35	Cl	400	11.28	Magnesium Sulphate	246	4.08
K	11	0.28	NO_3	229	3.72	Magnesium Chloride	256	5.37
						Sodium Chloride	345	5.92
						Sodium Nitrate	292	3.44
						Potassium Nitrate	28	0.28
						Silica	35	
Total		26.8			26.8		1697	26.8

* (Usually present as bicarbonate)

TABLE NO. 4

GROUNDWATER IN MINERAL BOREHOLES AT TIMG'AOUINE-ABANKOR

Location and Borehole Reference	Depth of intercepted* water (m)	Subsequent depth* to water (m)
Hichem		
B22	64.5	67.5
C14	70.3	51.4
C13	52.7	52.3
B14	70	52.9
W8	68	53.0
Daira Nord		
X25	-	95
X19	81	60.5
A19	83	60.5
A13	60.8	-
A7	87	-
Abankor Nord		
F38	80	-
F34	51	-
F18	94	-
F14	40-50	-
F10	49	-

* Depths relate to boreholes inclined at 70°.

3.3 Groundwater in Alluvial Deposits and the Weathered Basement

An important aquifer system has been identified in the alluvial deposits of the wadi channels and in an underlying zone of weathered Pre-Cambrian rocks. The maximum thickness of the system is about 40 m, the depth to water table increases away from the Hoggar while the saturated thickness decreases.

This aquifer system is the traditional source of water supply for the villages and towns of the Hoggar. Foggera are found where groundwater is available from the alluvial deposits, and supplies have been developed largely through this means as far downstream as Tamanrasset and Abalessa, groups of up to eight foggera providing supplies for a village with individual foggera providing up to a maximum of about 30 l/sec in the Wadi Abalessa. Wells become a more important source of supply further from the mountains, where the alluvial groundwater is less reliable, developing deeper storages in the weathered basement.

This is a system of great complexity. Extensive tracts of water bearing alluvial deposits do not occur in the area. The aquifer system is contained largely within the low ground of the major wadi channels and in small basins of weathered basement in minor wadis, and there is strong evidence to show that hydraulic continuity does not exist throughout a basin. For example the wadis Abalessa and Tamanrasset contain reaches of narrow rocky gorges with little alluvium and probably little depth of weathered basement which separate the headwater and foothill areas from the more distant parts of the catchments below an elevation of about 1000 m. The gorges mark the limit of the downstream development of the main villages with the resources of the aquifer system upstream of the constrictions being reserved for village development.

Exploration for groundwater downstream of the villages has occurred in the past seven years. About 40 boreholes have been constructed, mainly in wadi channels at six main sites, following extensive geophysical exploration. Unfortunately most of this detailed work has been at sites about 150 km from Abankor.

However, Burgéap have made an extensive analysis of the test pumping results to develop a semi-quantitative model of the general aquifer potential which has a broad applicability to all the wadis draining southwards from the Hoggar. They conclude that groundwater flow across the 900 m contour is a few 10's of l/sec per kilometre of aquifer width. They also consider the extent of the exploitable resources for two major aquifer configurations:

(i) a broad wadi valley, 200 m wide with 10 m of aquifer

(ii) a shallow basin of weathered basement extending over several hundred km^2.

and conclude that abstraction of 1 m^3/hour from shallow wells at 1 or 2 km spacing would exhaust the groundwater resources within a period of five years unless recharge occurred from a major runoff event.

The Burgéap analysis is probably optimistic in its approach. The aquifer properties are realistic estimates but the extent of the aquifer bodies used in their analysis are in our opinion unlikely to occur except at a few particularly favourable sites. Even so Burgéap dismiss the aqifer as a potential source of supply in the general vicinity of Abankor, as in broad terms it would require 200 wells over an area of several hundred km^2 to provide 5,000 m^3/day for the mine. We support this conclusion; large-scale exploitation of the aquifer system must depend upon a knowledge of the amount, distribution and frequency of recharge, and none of these factors are presently known, or could be made known in the short term.

3.4 Groundwater in the Cambro-Ordovician Sandstones

Several areas of Lower Palaeozoic rocks of the Tassilian series occur in the vicinity of Abankor. By far the largest is the Tin Seririne synclinal basin some 200 km east of Abankor which covers about 30,000 km^2 within Algeria (see Figure No. 1). The lowest formation is mainly sandstone of Cambro-Ordovician age, over 400 m thick and overlain by 300-400 m of Silurian shales and Devonian sandstones throughout most of the basin. The axis of the syncline is north-south.

Around the margin of the syncline exploratory drilling is proving groundwater in the sandstones at outcrop and beneath a cover of Silurian. Information from 32 exploration boreholes and 21 air-lift pumping tests have clearly established the importance of this aquifer, but only at three sites (In Atei, In Ebeggui and In Azaoua). Exploration is still in progress and approximately 40 more boreholes have been drilled between the three original sites but no detailed information is available beyond the general indication that all have proved groundwater in exploitable quantities.

Data from In Atei, In Ebeggui and In Azaoua have been used to predict the groundwater potential of the whole basin in the Sonarem-Idrotecnico and Burgēap reports. However, despite broadly similar approaches, these two studies have arrived at very different predictions of the consequences of relatively small abstractions of groundwater. The Sonarem-Idrotecnico study concludes that drawdowns of up to 100 m could develop around well fields after only five years of operation at a basin abstraction rate of 19,000 m^3/day. Burgēap on the other hand predict drawdowns of only 20 m after 20 years with a similar abstraction rate and pattern.

While the Sonarem-Idrotecnico analysis suggests that considerable caution is needed in the development of the aquifer and that large risks may be associated with long-term abstraction, the Burgēap analysis suggests that a plentiful supply is available with few risks attached to the development of groundwater for Abankor at a rate of about 5,000 m^3/day even from a single closely spaced wellfield.

Both studies have used mathematical models to examine the supply potential, both start from common ground in terms of the basic information and both share broad concepts regarding the nature of the aquifer system. However, there are important differences in the detail of the models and in the interpretation of certain data which have led to the different results. We have chosen to examine only the most important areas of difference and to use new information we have obtained regarding the characteristics of the aquifer to propose how exploitation of the groundwater resources should develop.

3.4.1 Borehole yields and aquifer properties.

Yields from individual wells are promising, giving from 1 l/sec to about 20 l/sec for depressions in water level up to 50 m. Specific capacities vary from 0.1 l/sec/m to about 0.6 l/sec/m. However, analysis of the pumping test data to derive aquifer properties is rather subjective as the tests were conducted using air-lift and the data are not suitable for detailed analysis. The Idrotecnico and Burgēap estimates are given in Table No. 5. Good agreement is found where transmissivity estimates have been obtained for the same borehole, but this has been possible for only three boreholes and there are no comparative estimates of storage coefficient.

TABLE NO. 5

AQUIFER PROPERTIES DERIVED FROM PUMPING TESTS

		IDROTECNICO		BURGĒAP	
		TRANSMISSIVITY (m^2/day)	STORAGE COEFFICIENT	TRANSMISSIVITY (m^2/day)	STORAGE COEFFICIENT
IN AZAOUA	IH	-	-	173	-
	5H	121	0.00002	-	-
	6H	492	0.0014	518	-
	7H	-	-	432 - 864	0.003 - 0.007
	8H*	3	0.0005	-	-
IN ATEI	7+	190	0.014	-	-
	16	1296	-	-	-
	60	1555	-	1641	0.0004 - 0.0005
	61*	65	-	-	-
	62	1987	0.00002	-	-
	63*	674	0.0013	-	-
	64*	2246	0.0004	-	-
	65*	475	-	778	0.005
	69*	-	-	345 - 432	0.0002 - 0.0004

* Confined conditions

+ Hand-dug well

Both models used these data for steady state simulation. The Burgēap model was based on a uniform transmissivity of 173 m^2/day throughout the basin with storage coefficients of 0.005 and .0002 for water table and confined conditions respectively. The Sonarem-Idrotecnico model on the other hand adopted a uniform value for storage coefficient throughout the basin using a value appropriate to a confined sandstone aquifer (probably 0.0002) and transmissivities were developed using a different approach: permeabilities were obtained from a knowledge of the transmissivity and thickness of the aquifer at test sites and assigned throughout the model network, transmissivities being calculated according to spatial and temporal variations in saturated thickness at each node during each stage of the model run.

Both models predict similar patterns of basin wide changes in water level. The effects of abstraction are shown to be transmitted rapidly throughout the basin producing small but significant falls in water level away from the points of abstraction across the basin between In Atei and In Azaoua, the northern and southern parts of the basin being relatively unaffected. However, deep cones of depression form in the immediate vicinity of the well fields and the Sonarem-Idrotecnico simulation predicted falls up to 20 times greater than those of the Burgeap model.

Part of the difference in drawdown can be attributed to somewhat lower rates of abstraction and generally higher values for aquifer properties in the Burgeap model, but bearing in mind the quality of the pumping test data both interpretations of the aquifer properties are equally realistic. We believe the main difference arises from the alternative methods of dealing with transmissivity in the models. Pumping centres are located close to the model boundary, apparently in the marginal nodes of the Idrotecnico model. Boundary effects will be most noticeable in these locations leading to large falls in predicted levels. With the Idrotecnico approach, where transmissivity is calculated from permeability and saturated thickness, an escallation effect can develop with boundary effects decreasing transmissivity values creating abnormally large drawdowns. Very accurate and precise estimates of the starting permeability, the saturated thickness and the true effects of pumping on the aquifer are needed in order to make an accurate prediction of the behaviour of the aquifer. These are not available, although we believe that it is possible to demonstrate that the basic nature of the aquifer is probably quite different from that envisaged in both studies.

3.4.2 Reservoir Properties

Laboratory tests were made on two samples of core from In Atei in order to assess matrix permeability as a general guide for full production well design. Sample 1 is a partly cemented medium grained sandstone, Sample 2 a weakly cemented coarse grained sandstone. Unfortunately we were unable to determine the geological horizon of the samples. The samples were chosen as being typical examples of the cores examined during visits to six of the exploration sites. The results of the laboratory tests are given in Table No. 6.

TABLE NO. 6

RESERVOIR PROPERTIES FROM CORE ANALYSIS[1]

		Grain Density (g/cm^3)	Effective Porosity (per cent)	Intrinsic Permeability (m/d)
SAMPLE 1	Horizontal	2.647	16.18	3.2×10^{-2}
1	Vertical	2.653	15.99	5.4×10^{-2}
SAMPLE 2	Horizontal	2.636	11.49	5.7×10^{-2}
2	Vertical	2.641	10.64	2.1×10^{-2}

[1] Core Analysis Laboratory, Hydrogeological Dept. Institute of Geological Sciences, London.

The porosity of the finer grained sandstone is rather low due to the secondary cementing material which has probably halved the value. A porosity of 12 percent is however a fairly typical value for a coarse sandstone. Both cores have yielded similar results in the permeability tests (Nitrogen gas permeameter with gas slippage correction) but with reversed horizontal and vertical values. Laboratory tests on sandstone from good aquifers can give intrinsic permeabilities of up to 3,000 m/day; the very low permeabilities of the samples suggest that the cementing materials and the grain packing have almost totally restricted the interconnected pore space. With such exceptionally low permeabilities matrix flow in the aquifer is unlikely, and if these two samples are truly representative then there can be little doubt that fissure flow is responsible for all groundwater movement.

To emphasise the large discrepancy that evidently exists between transmissivity values derived from pumping tests and that implied by the laboratory tests we have determined intergranular transmissivities; that is the saturated aquifer thickness times the mean horizontal permeability corrected for a groundwater temperature of 25° C. The results are shown in Table No. 7, and indicate that matrix flow contributes about 1 percent of the flow implied by the corresponding pumping test results.

TABLE NO. 7

PUMPING TEST AND INTERGRANULAR TRANSMISSIVITY

		Pumping Test Transmissivity (m^2/d)	Saturated Thickness	Intergranular Transmissivity (m^2/d)
IN AZAOUAI	IH	173	c.75	3.8
	5H	121	c.60	3.0
	6H	492 and 518	c.92	4.6
IN ATEI	7	190	1.25	0.06
	16	1296	50	2.5
	60	1555 and 1641	178	8.9
	61	65	88	4.4
	62	1987	69	3.5
	63	674	398	19.9
	65	475 and 778	90	4.5

Although we have no reason to doubt the representative nature of the core samples submitted for testing relative to the cores inspected in the field, we are concerned because we have little information regarding whether these were from the whole aqifer or were perhaps a biassed sample. No details of the lithologies at the cored boreholes are available, nor do we have a measure of the true extent of secondary cementation which was present in most cores we examined, although variable in amounts.

If the laboratory tested samples are representative of the aquifer as a whole, then general concepts regarding the nature of the aquifer must be revised. Briefly, the main points of importance are as follows:

(i) We understand from discussion with SONAREM that no exploration boreholes have been located in major fault zones. Much larger pumping test transmissivities can therefore be expected, the results to date being a measure of the effect of joints or minor faults.

(ii) The storage coefficient in the unconfined zone of the basin may well prove to be underestimated. The matrix condition is conducive to slow drainage and delayed yield effects are likely. Long-term pumping tests will be needed to establish this but increases in storage coefficient of 1 or 2 orders of magnitude are possible.

(iii) If fissure flow dominates, then there is every likelihood that the depth of the aquifer below the ground surface throughout most of the confined part of the syncline is sufficient to reduce the importance of joint and fracture systems. Between In Atei and In Azaoua the top of the aquifer is at depths of 250 m - 500 m below the ground surface and it is even deeper in the southern part of the basin. Transmissivity throughout these deep parts of the syncline could be considerably less than at outcrop or beneath shallow cover.

3.4.3 Groundwater Reserves

The exploitation of the groundwater resources of the basin must be planned on the assumption that there is little if any recharge to the aquifer. Rainfall is less than 10 mm/year and little is known of the runoff in the Wadi Tin Tarabine. Very low concentrations of tritium have been recorded in the groundwater; these indicate a recharge origin at least 25 years ago. No age dating has been made, but the concentration of deuterium and oxygen-18 in water from a borehole in the northern part of the basin shows some resemblance to groundwater in Libya some 5000 to 10,000 years old (see Appendix C).

Groundwater exploitation will therefore consist of mining and an estimate of the potential of the aquifer can be obtained by calculating the volumes of water produced for various amounts of dewatering. We have chosen to use an alternative concept of the aquifer from those used in the Sonarem-Idrotecnico and Burgeap analyses. This is because we believe there is too little data to assume a continuous aquifer throughout the basin, particularly as the deeper parts beneath Silurian and Devonian rocks have yet to be drilled.

Figure No. 2 shows in diagrammatic form our interpretation of the aquifer system. Natural groundwater flow in response to the regional hydraulic gradient may well prove to be concentrated along the eastern and western boundaries of the syncline, and the top of the aquifer having a depth of 250 m below ground level has been taken to be the likely limit of the production unit. The western edge of the syncline between In Atei and In Ebeggui is particularly affected by this structural interpretation and here the source area for a supply to Abankor is limited to a narrow strip some 20 km wide comprising a 10 km wide water table zone and a 10 km wide confined aquifer zone.

In Table No. 8 we have calculated the groundwater yield of the 20 km wide aquifer strip running from In Atei to In Ebeggui and also the yield of an area extending 60 km north of In Ebeggui over a width of 30 km. We have assumed alternative estimates for the storage coefficients in these zones, accepting the Burgeap data to obtain an upper estimate but using lower estimates to arrive at a lower, more cautious assessment of the groundwater availability.

TABLE NO. 8

EFFECTS OF MINING GROUNDWATER

	In Atei to In Ebeggui				North of In Ebeggui			
Assumption:-	Burgēap		Cautious		Burgēap		Cautious	
	1	2	1	2	1	2	1	2
Coefficient of Storage	0.005	0.0002*	0.001	0.0005	0.005	0.0002	0.0005	0.0002
Area (km^2)	300	600	300	600	600	1200	600	1200
Yield per metre drawdown (million cubic metres)	1.50	0.12	0.30	0.30	3.0	0.24	0.30	0.24
Total yield per m drawdown (million cubic metres)	1.62		0.60		3.24		0.54	
Drawdown per year (metres)								
At 5,000 m^3/day	1.1		3.0		0.6		3.3	
At 7,000 m^3/day	1.7		4.5		0.8		5.0	
At 10,000 m^3/day	2.3		6.2		1.1		6.9	

1 Water table conditions

2 Confined conditions

* In this instance we consider the Burgēap figure to be over-cautious

The results serve to illustrate the importance of precise estimates of storage in this form of approach. The alternative assumptions produce a threefold difference in the predicted effect of abstracting from In Atei and a sixfold difference at In Ebeggui. Selection of the storage coefficient values is subjective as the air-lift pump tests have not provided any definitive data. We beleive it prudent therefore to take a deliberately cautions approach and we have not considered the effects of delayed yield, nor have we accepted the most favourable estimates of storage coefficient.

At this stage of planning a supply for Abankor we must accept the largest estimates for dewatering. The results of mining groundwater at rates of 5000 m^3/day, 7500 m^3/day and 10 000 m^3/day from the aquifer between In Atei and In Ebeggui are given in Table No. 8; over a period of 20 years average water levels could fall by up to 60 m, 90 m and 124 m respectively. The average aquifer thickness in this area is probably about 250 m and at the highest rate of abstraction we are thus predicting a dewatering of half of the aquifer. This represents an unreasonable risk when there is no data concerning production zones. A supply of 7 500 m^3/day is probably the maximum that can be contemplated at this stage without considering the possible development of the aquifer both to the north and south of In Ebeggui.

Broad guide lines can be established for the more detailed planning of a well field. If fissure flow is responsible for groundwater movement in the aquifer then production wells must be sited in fault zones. It is obvious from the reports we have studied that the syncline is structurally complex and that extensive N-S faulting occurs. Unfortunately no details of the geophysical exploration or of the geological interpretation of such data have been made available. However, the optimum siting for a well field and the number and disposition of the production boreholes can probably be determined from existing detailed information held by SONAREM. Evaluation of this data should be the first step in a Stage 2 study.

Production yields of 15 l/sec (1300 m^3/day) can be expected from the fault zones. Borehole spacing is difficult to assess as this will depend on the nature and distribution of the faulting. It would be prudent to assume that it may be necessary for boreholes to be spread along the margin of the basin for up to 60 km.

In conclusion we comment upon the selection of In Atei as a source of supply for Abankor. It appears to have been chosen because test pumping has indicated the best aquifer properties at the site. This may be because of the proximity of the test boreholes to faulting. If there is a depth effect to the confined parts of the basin then the area to the north of In Ebeggui where the aquifer is relatively shallow over a large area would be a better location for a well field. Stage 2 studies must be directed toward a detailed structural interpretation of the whole western margin of the syncline. On the basis of our analysis of the consequences of mining there is little to choose between In Atei and In Ebeggui and the extent and frequency of faulting will probably be the critical factor in deciding the best location.

3.4.4 Water Quality

Chemical analyses published by SONAREM indicate a very good quality of water at In Atei and In Ebeggui (Table No. 9). However, the sulphate content appears to be very variable and reaches extremely high concentrations at In Azaoua in the east.

TABLE NO. 9

CHEMICAL QUALITY OF GROUNDWATER FROM TIN SERIRINE BASIN

(milligrams per litre)

	IN ATEI Borehole 16	IN ATEI Borehole 17	IN EBEGGUI Borehole 18	IN AZAOUA Borehole 20
pH	7.0	7.1	7.5	6.7
Potassium/Sodium	72.7	83.0	47.1	390.7
Calcium	40.0	28.0	31.3	24.0
Magnesium	17.1	26.8	10.7	7.3
Carbonate	-	6.0	5.8	-
Bicarbonate	152.5	122.0	166.7	146.4
Chloride	51.5	49.7	17.2	38.6
Sulphate	118.1	162.1	50.2	749.0
Nitrate	15.1	16.5	5.1	0.9

3.4.5 Other Cambro-Ordovician areas

We have not considered other areas of sandstone such as Tin Missaou as potential sources of supply for Abankor in view of their relatively small areal extent, lack of exploration, and distance from the mine.

3.5 Groundwater at Silet

In our overall assessment of the potential of the various groundwater sources for supply to Abankor we consider Silet to offer the only possible alternative to Tin Siririne. Currently a well into basalt gravels in the wadi bed at the village provides the mine supply by tanker. The well is one of several dozen which are reported to give permanent supplies apparently unaffected by periods of drought. The quality of the water is excellent (Table No. 10) but chemically quite distinct due to relatively large concentrations of sodium and bicarbonate.

TABLE NO. 10

SAMPLE OF WATER FROM SONAREM WELL SILET

This sample is practically clear and bright in appearance and is free from colour. The reaction is on the alkaline side of neutrality and the hardness of the water is very moderate, with an excess of alkalinity over total hardness. The amount of mineral and saline constituents in solution is moderate and metals were not detected.

These results indicate, from the aspect of the chemical and mineral analysis, a wholesome water suitable for potable purposes.

(Table No. 10 Continued)

TABLE NO. 10 Continued

SAMPLE OF WATER FROM SONAREM WELL SILET

RESULTS IN MILLIGRAMMES PER LITRE

Appearance: Bright with a few particles.

Turbidity (Formazin, A.P.H.A. units): Less than 0.5

Colour (Hazen): NIL — Odour: NIL

pH: 8.3 — Free Carbon Dioxide: Absent

Electrical Conductivity Reciprocal Megohms (Micro-Siemens) per cm at 20° C.: 520 — Dissolved solids driec at 180°C.: 390

Chlorine in Chloride: 26 — Alkalinity as Ca CO_3: 250

Hardness as Ca CO_3: Total 150 — Carbonate 150 — Non-carbonate 0

Nitrogen in Nitrate: 0.5 — Total Organic Carbon: ...

Nitrogen in Nitrite: Absent — Permanganate Value 4 hrs. at 27°C.: ...

Ammoniacal Nitrogen: Less than 0.5 — Residual Chlorine: ...

Albuminoid Nitrogen: ...

Iron Absent — Zinc Absent — Copper Absent — Lead Absent — Manganese Absent

Cadmium: Not detected <0.001 — Fluorine in Fluoride 0.5 — Silica 50

("Absent" refers to a detection limit of 0.03 of each metal unless otherwise stated)

MINERAL ANALYSIS (after filtration if necessary) (milligrammes per litre and millequivalents per litre)

Cations	mg/l	me/l	Anions	mg/l	me/l			
Ca	27	1.36	$*CO_3$	150	5.00	Calcium Carbonate	68	1.36
Mg	20	1.64	SO_4	33	0.69	Magnesium Carbonate	69	1.64
Na	78	3.38	Cl	26	0.73	Sodium Carbonate	106	2.00
K	3	0.08	NO_3	2	0.04	Sodium Sulphate	49	0.69
						Sodium Chloride	40	0.69
						Potassium Chloride	3	0.04
						Potassium Nitrate	4	0.04
						Silica	50	
Total		6.46			6.46		389	6.46

*(Usually present as bicarbonate)

The drainage basin to the village of Silet is only 34 km^2 according to the 1:20 000 topographic maps and is therefore most unlikely to be able to provide sufficient recharge to support the large village water requirements. The tritium content of the groundwater is very low indicating that the water originated mainly as recharge prior to 1952 (Appendix C) and it is evident that an aquifer system with at least a 25 year storage feeds into the gravels. Lavas and tuffs of the basalt massif between Silet and Tamanrasset are the most likely source of the groundwater from an extensive catchment area.

We know nothing of the nature of the aquifer system or of its distribution and there is no way in which the total resource can be calculated from existing information. Our interest in the source is partly due to the command of an obviously large storage volume but mainly because the underground flow through the wadi at Silet may well exceed the village abstractions. Any surplus resources could be developed and used at Abankor.

At the moment the SONAREM well provides 18 m^3/day to Abankor pumping for 30 minutes with a depression in water level of 1 m. It is most unlikely that increasing abstraction to 100 m^3/day will significantly affect other users in the short-term as the extent of the storage in the system probably guarantees this. The long-term exploitable resource is the difference between consumptive use in the village and the groundwater flow through the wadi. These should be determined in the Stage 2 investigations.

3.6 Proposals for Stage 2 Groundwater Investigations

3.6.1 Tin Seririne Basin

The principal objective of the Tin Seririne investigations would be to establish the location and design of a production well field for the main supply to Abankor and Tingaouine.

Initially an assessment should be made of the structure of the western margin of the aquifer from the completed geophysics (aeromagnetic and surface) and the detailed geological logs of the existing boreholes. We would also recommend that further laboratory testing of cores should be undertaken to confirm the results obtained from the In Atei samples. Existing cores could be used; random samples taken every 5 - 10 m from two fully penetrating boreholes would give a good indication of the role of the matrix of the aquifer.

The drilling and test pumping of two trial production boreholes in fault zones should form the second step. The precise location of these boreholes can probably be determined from the structural analysis. If possible they should be sited in the vicinity of existing boreholes which can then be used for observation purposes during pump testing. The boreholes should be at least 300 mm diameter probably to 300 m depth and be fitted with pumps capable of delivering up to 30 l/sec.

Provision should be made for short-term multiple stage testing of about 24 hours duration at each of four stages up to the maximum capacity of the borehole or the pump. These should be followed by up to four weeks abstraction at a constant rate to determine aquifer properties.

We would also recommend the use of fluid conductivity and temperature logging equipment during the testing to investigate fissure flow characteriestics.

Provision should be made for the construction of three observation boreholes to support each of the trial production bores if these have to be sited in faults at some distance from existing boreholes. During testing water must be piped at least 500 m from the production wells and if possible discharged out of the basin or away from any outcrop areas.

3.6.2 Silet

At Silet, the investigations would examine how large a supply could be obtained without interfering with existing users. We do not see this as a likely source for a 20 year supply to the mine although it must be considered particularly if the Hichem and Daira Nord sites indicate exploitable quantities of water. (see 3.6.3.)

A local survey of the wadi should be undertaken to estimate the consumptive use of the village and determine the thickness and aquifer properties of the wadi gravels. A detailed geophysical survey using shallow seismic methods should be carried out along 2 km of the channel to determine the configuration of the gravels. The aquifer properties of the gravels can be determined by test pumping the SONAREM well, two shallow boreholes to 30 m should be constructed for observation purposes and a topographic survey made to establish the hydraulic gradient throughout the village.

3.6.3 Hichem and Daira Nord

Stage 2 should also include exploration of the groundwater encountered in the mineral boreholes at the Timg'aouine-Abankor prospect. The Hichem and Daira Nord sites appear to be worth re-drilling unless the steeply dipping (70°) mineral bores remain and can be yield tested.

3.6.4 General

Following the completion of the field work outlined above we would wish to consider whether further work would be necessary.

This could involve the following inter alia:

(i) A mathematical model of the western strip of the Tin Seririne aquifer.

(ii) Additional water samples with particular reference to sulphate concentrations.

(iii) Additional stable isotopic determinations with particular reference to the identification of flow pathways in the system.

APPENDIX A

ITINERARY OF VISIT TO ALGERIA

Tuesday, 22nd March

Depart from London 1230

Arrive Algiers 1830

Collected reports and maps from Constructors John Brown Limited.

Wednesday, 23rd March

Depart from Algiers 0300

Arrive Tamanrasset 0930

Discussions with Charter Consolidated Limited.

Visit to Tamanrasset for field stores.

Thursday, 24th March

0640-1600 Tamanrasset to Tin Siririne via Fort Motylinski and Bachir camp (276 km).

(i) Traverse down the Wadi Ighaghar showed recent runoff (probably September 1976) for a distance of about 100 km. Wadi contained few gravels or rounded boulders. Generally fine sand becoming silty and then muddy. Flow appeared to have been shallow - say 1-2 ft.

(ii) Journey into the Basin of Tin Siririne through extensive outcrops of Cambro-Ordovician sandstones. Little evidence of any runoff in these areas.

(iii) Visited drilling site (Portadrill) to south of Tin Siririne camp and took water sample.

Geological log:

0-6.8 m sand

6.8 - 67.3 m Silurian shales

67.3 - 291 m Sandstone - heavily cemented

Granite gneiss

Air lift test 5.5 l/sec

water encountered 67.3 m

RWL 62.75 m.

(iv) Discussion at Tin Siririne camp with geologists of the Russian team exploring the aquifer.

Friday, 25th March

0540–1730 Tin Siririne camp to Bachir via In Ebeggui and In Atei (378 km)

(i) Visit to borehole 50 km W of camp (21° 40'N, 6° 47'E).

(ii) In Ebeggui borehole at 125 km

Examined cores - black shales with graptolites underlain by white quarz grit with purple bedded stringers in top 2 m. (21° 8'N, 6° 16'E).

(iii) Borehole 38 km North of In Atei at 151 km (20° 51'N, 6° 15'E). coarse grits with well developed joints.

(iv) Borehole 10 km north of In Atei at 180 km (20° 37'N, 6° 13'E), reputed to give 1000 l/min on air lift.

(v) In Atei boreholes at 189 km. (20° 31'N, 6° 14'E).

The journey westwards took a route across the plains underlain by sandstones and shales(?). Route mainly stony desert between extensive areas of high sand dunes. No vegetation, no bedu or toureg wells, no sign of ancient settlement.

The journey southwards along the Wadi Tagrira was close to the Devonian escarpment. Small, unimportant wadi again devoid of vegetation. The westerly Cambro-Ordovician scarp formed a strong feature. Erosion of the Silurian shales forming a N-S erosion channel with few bedrock exposures.

The Wadi Igharghar crosses the sandstone scarp and joins the Wadi Tagrira immediately north of In Ebeggui. The wadi floors the valley between the two sandstone scarps and not to the west of the Cambrian-Ordovician outcrop as implied by other maps. This is the site of an ancient village. A traverse across the sandstone outcrop to the underlying basement showed evidence of differential erosion of thick beds (up to 20 m) rather than of alternating 10 cm bands as implied by the discussion of previous evening. Jointing is well developed, lower and upper horizons most eroded.

Despite some vegetation and a well at In Atei there was no evidence of permanent settlement of the site.

The journey to Bachir was made to the west of the sandstone outcrop via the In Ebeggui mining prospect 60 km north of In Atei (now abandoned). In Ebeggui to Bachir (125 km) along minor wadis and part of Wadi Igharghar. The western scarp of the Tin Seririne basin rises up to 250 m above the wadi beds. Few crossing points exist onto the plateau: In Atei, In Ebeggui and the Wadi Ingharghar being the three principal crossings.

Saturday, 26th March

0600-1115 Bachir-Tamanrasset (162 km).

Visited well supplying Bachir camp at 73 km.

Sunday, 27th March

0700-0950 Visit to sources of supply at Tamanrasset.

(i) Well in basement near Wadi Tamanrasset at Tihegouine where the wadi disappears into a rocky defile for 20-30 km. No sign of gravel water at this site. Water sample collected.

(ii) Sample taken from Sonarem borehole in wadi bed near base camp.

(iii) Visited foggera and wells at upstream end of town.

(iv) Visited standby sources at Tehendi 7 km N.E. of town. Multiple wells through alluvium into weathered zone of basement. Permanent supply from basement only.

(v) Visited and sampled Source Chapuis (Tahabort).

1500-1700 hours. Visit to Met. Office at Tamanrasset. Unable to provide 1974-1977 rainfall data without written authority from Oran where records are kept.

Monday, 28th March

0715-1320 Tamanrasset to Timg'aouine (224 km).

(i) Visited Co-operative farm at Amsel on a tributary of the Wadi Tamanrasset. Flow from gravels 3-5 l/sec through failed dam downstream of several hectares of irrigated farmland.

(ii) Visited Sonarem exploration borehole at 142 km - Amselka. A recent dry borehole into the bed of the Wadi Tamanrasset on a major fault zone.

(iii) Visited Abankor BH 15 (source of supply to mine April 1971 - May 1973), now disused. Sited in gravels of Wadi Tamanrasset at termination of the thick alluvial deposits (18 m) of the basin.

1500-1830 Meeting with mine geologist at Timg'aouine and visit to Abankor.

Tuesday, 29th March

0600-1500 Timg'aouine - Silet - Tamanrasset.

(a) Traverse due north revealed active wadi channels in Wadi Tinef well to south of similar conditions in Wadi Tamanrasset. Minor tributaries rising from basalt area of Silet carry vegetation and fine gravels.

(b) Immediately before Silet several westward draining wadis crossed in coarse gravel channels. Many scour channels and relatively abundant vegetation.

(c) At Silet 30-40 wells and 5 foggeras in active wadi channel. Sonarem supply from 5' diameter well providing 14,000 l in 30 mins for drop in water level of 1 m. Well sampled for quality. Foggera examined, reputedly largest in the area - flow about 2 l/sec. Carbonate sedimentation taking place. pH 6.8. Wells reputed never to go dry.

(d) Return to Tamanrasset via Abalessa to north of basalt massif. Meteorological site run by school teacher not working. Wadis show signs of recent runoff throughout the basalt area. Few soils in the massif, heavy dust storms blowing silt from the occasional wadi bed.

<u>Wednesday, 30th March</u>

Depart from Tamanrasset 0700

Arrive Algiers 1500

<u>Thursday, 31 March</u>

0800-1200 Visit to Sonarem office in Algiers.

<u>Friday, 1st April</u>

Depart for London 0730

APPENDIX B

LIST OF PUBLICATIONS

The following reports and maps were made available and have been studied for the preparation of this Report:

REPORTS

1. Etude et mise en valeur des eaux souterraines (Burgeap).

2. Résultats des travaux hydrogéologiques exécutés au Hoggar 1970-73. (SAMYLINE, KOVALENKO, YANKOVSKY, LEONTIEV, MAWIMOU).

3. Rapport sur les résultats des travaux de recherche et de prospection hydrogéologiques exécutés dans la région de Tamanrasset en 1973-75. (LEONTIEV, MAXIMOU, CHILOV).

4. Rapport Géologique et hydrogéologique concernant les travaux de Recherche exécutés pendant la campagne 1974-75 Zones Assfe - In Azaoua. (VICTOR, ALEXANDRU, VASILE, SORIN, CONSTANTIN).

5. Rapport de programmation, groupe mixte, SONAREM, Idrotecnico Etude Hydrogéologique du Hoggar Octobre 1975.

6. Rapport de synthése, groupe Mixte.

MAPS

NF.31 V - VI - XI - XII - XVII - XVIII - XXIV

NF.32 I - II - XII - VIII - XIII - XIV - XIX

The following information was requested but had not been received at the time of completing this Report:

1. Details of boreholes at Silet

2. Geological logs of boreholes at In Atei and In Ebeggui

3. Geological maps of In Atei and In Ebeggui

4. Details of Borehole No; 1 at Abankor

5. Details of boreholes at Amselka

6. Details of drilling undertaken by SONAREM between In Atei and In Ebeggui

7. Rainfall data for 1974-1977.

APPENDIX C

ISOTOPE STUDIES

C.1 INTRODUCTION

Direct observations regarding the origin of the groundwaters and the time and place of recharge are not available. Sonarem-Idrotecnico attempted to gain some idea of past events by examining the isotopic composition of various sources. They used tritium, a radioisotope of hydrogen present in the atmosphere in large quantities due to thermo-nuclear testing to indicate recent recharge to aquifers, and a natural heavy isotope, oxygen-18, to provide information about the source of recharge.

The interpretation of such results is greatly enhanced by information concerning a second natural heavy isotope of water, deuterium. We therefore sampled four important sites during our field reconnaissance and arranged for deuterium and oxygen-18 determinations to be made. Samples were obtained from the following locations:

1) Borehole 101A, exploration borehole into main aquifer at the Tin Seririne base camp.

2) Abankor, Borehole 15; the original source of supply for the mine from Pre-Cambrian basement.

3) Silet, SONAREM well now supplying the mine by tanker from Basalt gravels.

4) Tamanrasset supply borehole in wadi bed at Sonarem camp.

The tritium concentrations in two of the samples have also been determined; at B.H. 101A to provide information for the northern part of the Tin Seririne syncline not previously sampled, and from B.H. 15 at Abankor previously sampled for tritium by SONAREM but exhibiting large variations in chemical quality.

Our analyses were undertaken at the Carbon-14/Tritium Measurement Laboratory of the Atomic Energy Research Establishment, Harwell.

C.2 USE OF STABLE ISOTOPES IN GROUNDWATER STUDIES

In order to present and interpret the results it is useful to provide some explanation of the occurrence and use of the isotopes in hydrological studies. These explanations are not intended to be complete summaries of the techniques but are a guide to the major conclusions which may be drawn from the information collected.

Deuterium (D) and oxygen-18 (^{18}O) occur in small quantities in all natural waters. In groundwater the concentrations are determined predominently by the composition of the rainfall which provides the recharge to the aquifers. Many factors control the isotopic composition of the rainfall. The water vapour producing rainfall changes its composition and becomes more depleted in D and ^{18}O with distance from oceanic source, seasonal variations due to temperature increase these concentrations in summer, but they also decrease with altitude. Since there are no isotopic data for Hoggar rainfall we have used published information for stations to the south and southwest of the area in the path of the air masses bringing in moist air from the southern Atlantic Ocean.

The two stations Kano (Nigeria) and Bamko (Mali) have records predominently of summer rainfall during the same months in which the Hoggar experiences its main storms. The isotopic compositions of the rainfall are illustrated in Figure No. 3, a conventional diagrammatic presentation of the data, where the isotopic compositions are expressed in the usual per mil deviation of the isotope ratio from that of a standard[1].

[1] The standard of reference is SMOW (Standard Mean Ocean Water) and the data are expressed by:-

$$\delta = \frac{R-R_{SMOW}}{R_{SMOW}} \; 10^3 \; {}^o/oo$$

where R refers to the isotope ration of $^{18}O/^{16}O$ or of D/H

Generally rainfall which has not been subjected to rapid evaporative concentrations shows a good linear relationship of the general form;

$$\delta D = 8\delta^{18}O + Y$$

The excess of deuterium, y in the equation, may vary but is normally +10 in northern hemisphere where rainfall exhibits a composition lying somewhere along the curve $\delta D = 8\delta^{18}O + 10$ (the World Meteoric Rainfall Line).

The Kano and Bamako rainfall show two unusual isotopic charateristics:

1. The δD - $\delta^{18}O$ relationships are complex approaching a general line of slope 8 in some months but in others being charaterised by slopes of about 6. Thus in summer (July to September) when the isotopic concentrations are lightest ($\delta^{18}O$ -2 to -10°/oo and δD -10 to -80°/oo) the composition fits the curve $\delta D = 8\delta^{18}O + 10$. Early summer and autumn rainfall at the beginning and at the end of the rainy season have higher concentrations ($\delta^{18}O$ = +19 to -2°/oo and δD = +90 to -10°/oo) which fit a line of about $\delta D = 6^{18}O$.

2. The range of isotopic concentrations are exceptionally large. The lowest concentrations are in August rainfall ($\delta^{18}O$ = -10.7°/11 and δD = -78°/oo), the heaviest generally in April rainfall with the greatest concentration in a September storm at Bamako ($\delta^{18}O$ = +18.9°/oo and δD = +91°/OO).

Hoggar rainfall can be expected to have isotopic concentrations similar to that of summer rainfall at Kano and Bamako. Although the greater elevation of the land and the longer distance to be traversed by the humid air masses would tend to lead to lighter isotopic contents, the extremely high temperatures will probably cause a compensatory enrichment and we are predicting that Hoggar rainfall will closely resemble that at Kano and Bamako.

Groundwater commonly has a stable isotope content corresponding to the long-term average of the isotope content of recharge and any short-term variability is damped through mixing in the aquifers and by dispersion during recharge. However, if the groundwater is affected by evaporation from shallow aquifers then its isotopic composition will fall below the source line. An example of such an effect is shown in Figure No. 3. Point A represents an original recharge composition of $\delta^{18}O = -5^{\circ}/oo$ and of $\delta D = -30^{\circ}/oo$. Continuous evaporation can change its composition which will alter in the manner demonstrated by the curve A-A'.

C.3 THE USE OF TRITIUM IN GROUNDWATER STUDIES

Prior to 1952, the natural level of tritium in the atmosphere was of the order of 5-10 tritium units (TU)[1]. However, since 1952 large quantities have been introduced into the atmosphere by thermonuclear testing raising the concentration to a peak of many hundreds of units in 1963. Its special value in groundwater studies is in indicating recent recharge to aquifers. As a radioactive isotope it undergoes natural decay at a rate described by a half-life of 12.3 years which is the time required for one half of the atoms to decay. Since 1952, or two half-lives, any natural tritium trapped in groundwater will have decayed to about 3 TU or less, hence any water containing significant quantities of tritium includes modern recharge.

In broad terms 0-3 TU shows groundwater originating as recharge before 1952. Concentrations of 10 TU or more show post 1952 recharge, while 3-10 TU suggest mixed waters of both ages.

Tritium in rainfall at Bamako provides base data for prediction of Hoggar rainfall levels. Concentrations for the period 1964-1971 are published by the International Atomic Energy Agency. They show levels of up to 1100 TU in 1964 falling to about 400 TU in 1965, and to 300 TU in 1966. Between 1967 and 1971 the tritium content of rainfall at Bamako gradually fell from about 150 TU to 100 TU. There are no published data since 1971 but levels have probably remained at about 100 TU although very recently they may have declined to 50 TU.

[1] Tritium concentrations are expressed in absolute units where 1TU corresponds to one atom of tritium in 10^{18} atoms of hydrogen.

Groundwater originating as rainfall on the Hoggar in 1964 will now have a tritium content of about 400 TU, 1965 recharge will contain 200 TU and 1966 recharge about 150 TU. Values of about 75 TU will be from recharge associated with 1965-1971 rainfall although recharge since 1972 may contain up to about 100 TU.

C.4 INTERPRETATION OF RESULTS

The isotope concentrations are given in Table 11 which shows close agreement between the Sonarem-Idrotecnico results and our own.

TABLE NO. 11

ISOTOPIC COMPOSITION OF GROUNDWATER

LOCATION AND SOURCE		$\delta^{18}O$ ‰	δD ‰	TRITIUM TU
TIN SERIRINE SYNCLINE				
Recent exploration borehole 101a	(2)	- 9.5	- 70	?
IN AZAOUA				
borehole	(1)	- 10.1	-	2.5
well	(1)	- 9.7	-	2.8
IN ATEI				
borehole	(1)	- 9.6	-	2.5
well	(1)	- 10.6	-	2.5
IN EBEGGUI				
borehole	(1)	- 10.0	-	2.7
FAULT ZONES IN BASEMENT				
Tinef borehole	(1)	- 9.3	-	3.3
Amselka borehole	(1)	- 10.0	-	2.4
Abankor borehole	(1)	- 4.7	-	3.1
	(2)	- 4.5	- 44	?
WADI ALLUVIUM				
Wadi Tin Amzi borehole	(1)	- 3.8	-	120.8
Wadi Tamanrasset borehole	(2)	- 4.9	- 27	-
Wadi Silet well	(1)	- 5.1	-	5.9
	(2)	- 4.9	- 30	-

Note
(1) Sonarem-Idrotecnico analyses
(2) Samples collected during reconnaissance March 1977
? Result not yet available

C.4.1 Tritium

The tritium content of groundwater from the Cambro-Ordovician sandstone at Tin Seririne and from fault zones in the Pre-Cambrian basement indicate a recharge origin prior to 1952. Essentially the results show extremely small tritium concentrations but the levels are so low that these must be attributed to sample contamination.

The sample from a well into gravels at Silet has a slightly higher concentration, sufficient probably to discount contamination, but enough to indicate a mixed origin mainly of pre-1952 water with a small amount of more recent recharge. This is a most interesting and important result. The village of Silet has three foggara and perhaps 30 wells in a wadi bed draining a topographic catchment of only 34 km^2. This tiny drainage basin does not appear capable of containing an aquifer with 25 year storage in the basalt gravels that occur upstream of the village. The primary source must therefore be a main basalt aquifer with a contributing area considerably larger than that of the surface catchment. In our opinion this is an indication of an aquifer potential second only in the area to the Cambro-Ordavician sandstone of the Tin Seririne basin.

The precise identity of the Tin Amzi alluvial borehole is not certain. However, we interpret the tritium content of 121 TU as being either a mixture of a little 1964-1966 water with a large volume of more recent water, or entirely modern water from a post 1971 storm. Up-to-date tritium analyses for rainfall are needed for a more precise interpretation. Generally we expect similar or slightly lower concentrations of Tritium in all flood recharged wadi gravels in the Hoggar to an elevation of about 1500 m, i.e. downstream as far as say Tamanrasset.

C.4.2 Oxygen-18 and Deuterium

For interpretation of the stable isotope data we rely on the plot of the concentrations on a $\delta^{18}O$ - δD diagram. Figure No. 3 shows the four samples collected during our field reconnaissance relative to the rainfall data discussed previously.

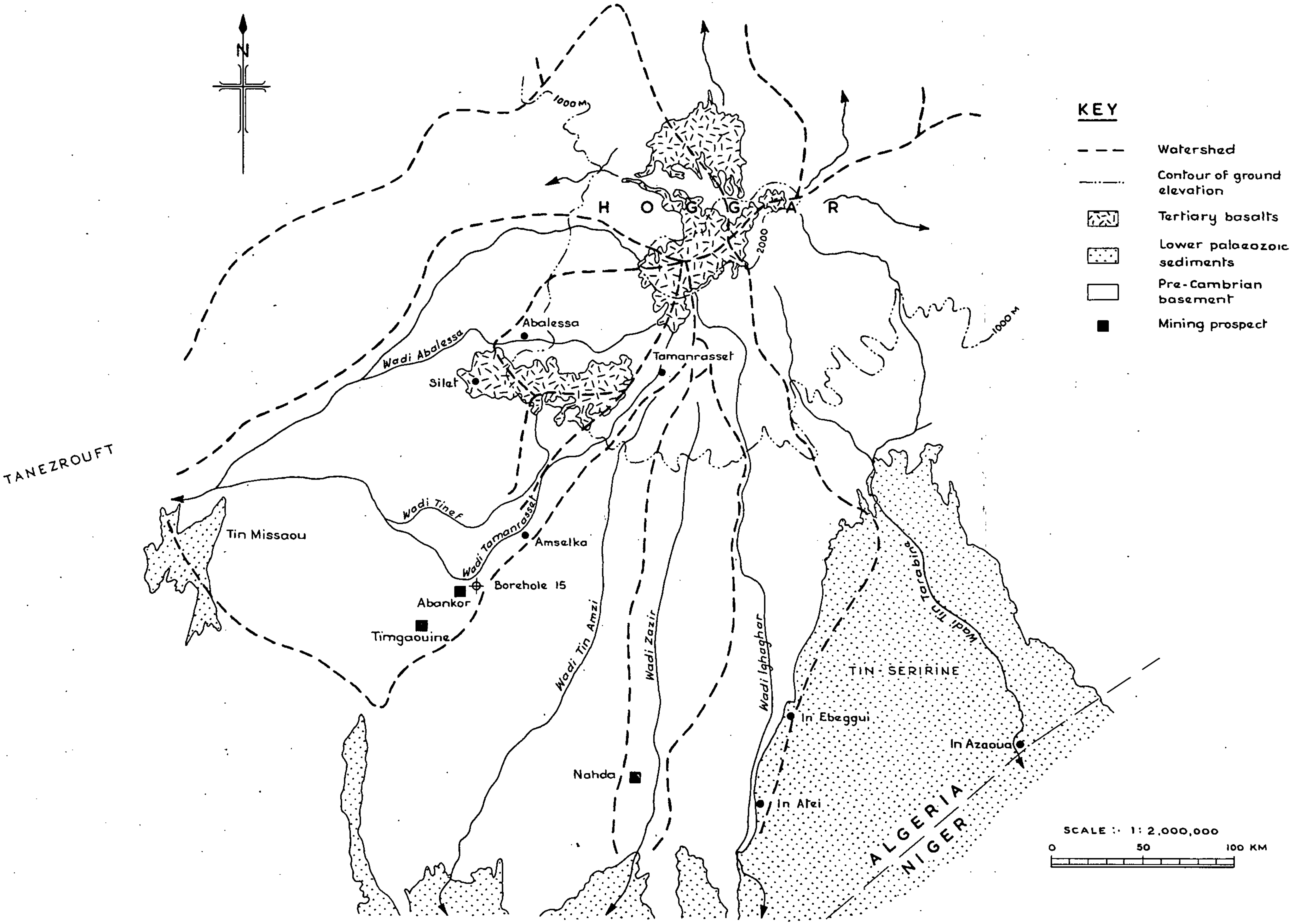
The Silet and Tamanrasset samples have similar compositions to the rainfall and can be interpreted as originating with little evaporative concentration. In the case of the Silet sample, with a largely pre-1952 age, a deep basalt origin is indicated. Recharge was from rainfall where climatic conditions were similar to those which exist today. From this we infer a recharge age up to a few hundred years ago. The Tamanrasset sample should be modern, a tritium determination would confirm this, and we anticipate that all recently recharged groundwater will have similar oxygen-18 and deuterium concentrations.

The Abankor analysis shows a sample enriched in $\delta^{18}O$ relative to D and it plots just outside the main rainfall field in the $\delta^{18}O$-- δD diagram. The origin is a little uncertain but it could have evolved by evaporative concentration from rainfall having a composition of $\delta^{18}O = -8^{o}/oo$ and $\delta D = -53^{o}/oo$ i.e. from Kano-Bamako type rainfall of the lightest isotopic concentration. By comparison the oxygen-18 (and tritium) levels in the Tinef and Amselka samples (also from faulted basement) appear to be similar to the Tin Seririne groundwater. We therefore hesitate to postulate further regarding the origin of the water at Abankor.

The age and origin of the groundwater from the sandstones of the Tin Seririne syncline is most important in terms of the future exploitation of the aquifer. The stable isotopic composition from borehole 101A is lighter than that of all but two of the rainfall samples, and furthermore the oxygen-18 analyses of SONAREM indicate similar or light concentrations in groundwater at In Azaoua, In Atei and In Ebeggui. This suggests recharge from a rainfall of different composition to that of the Kano-Bamako type. Sonarem-Idrotecnico propose recharge originating high in the Hoggar to account for the low oxygen-18 concentration of $-10^{o}/oo$ in the sandstone. We sampled the borehole in the wadi bed at Tamanrasset to obtain a measure of the isotopic composition of runoff, and hence rainfall, for the Hoggar and our contention that it currently resembles that at Kano-Bamako is based upon that result. Unless there is a marked altitude effect in the Hoggar reducing the isotopic content of rainfall to about $\delta^{18}O = -12^{o}/oo$ and $\delta D = -80^{o}/oo$, then it is unlikely that the sandstone groundwater has originated as recharge during the past few hundred years.

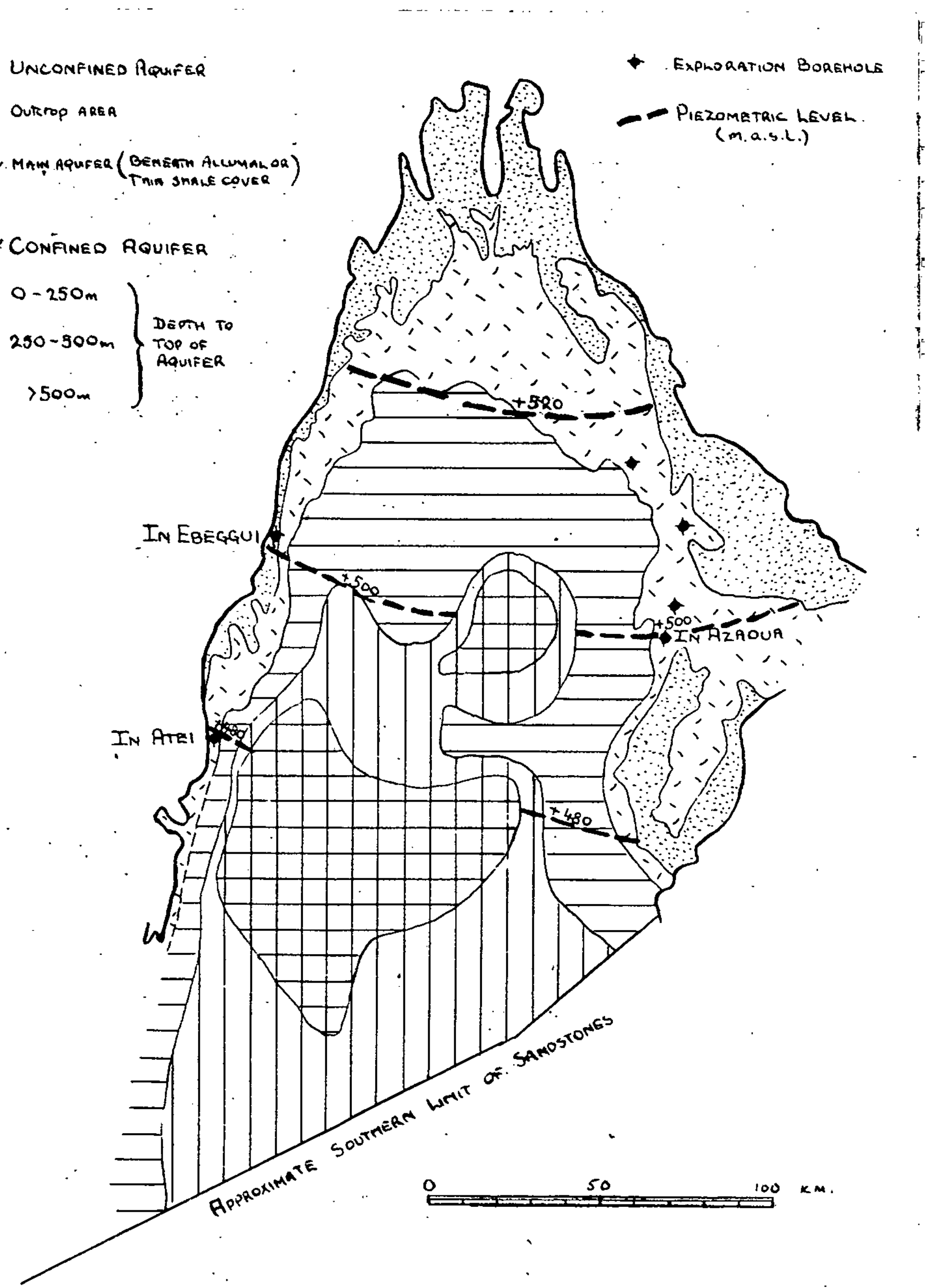
In Figure No. 3 we also show the composition of groundwaters from the Kufra area in Libya[1]. These groundwaters have been shown by carbon age dating to be 5,000 - 10,000 years old and are believed to have originated from rainfall in a cool, temperate climate similar to present day conditions in northern Europe. Although not identical in composition, the Tin Seririne sample bears a close similarity to these "fossil" groundwaters. Age dating of the sandstone groundwater is necessary to resolve its origin. However, we would suggest from the isotopic data that it could be a fossil supply or perhaps a mixture of very ancient groundwater with some more recent but not necessarily modern water.

[1] Unpublished data provided by Dr. M. Edmunds, Institute of Geological Sciences, Hydrogeological Department, London.



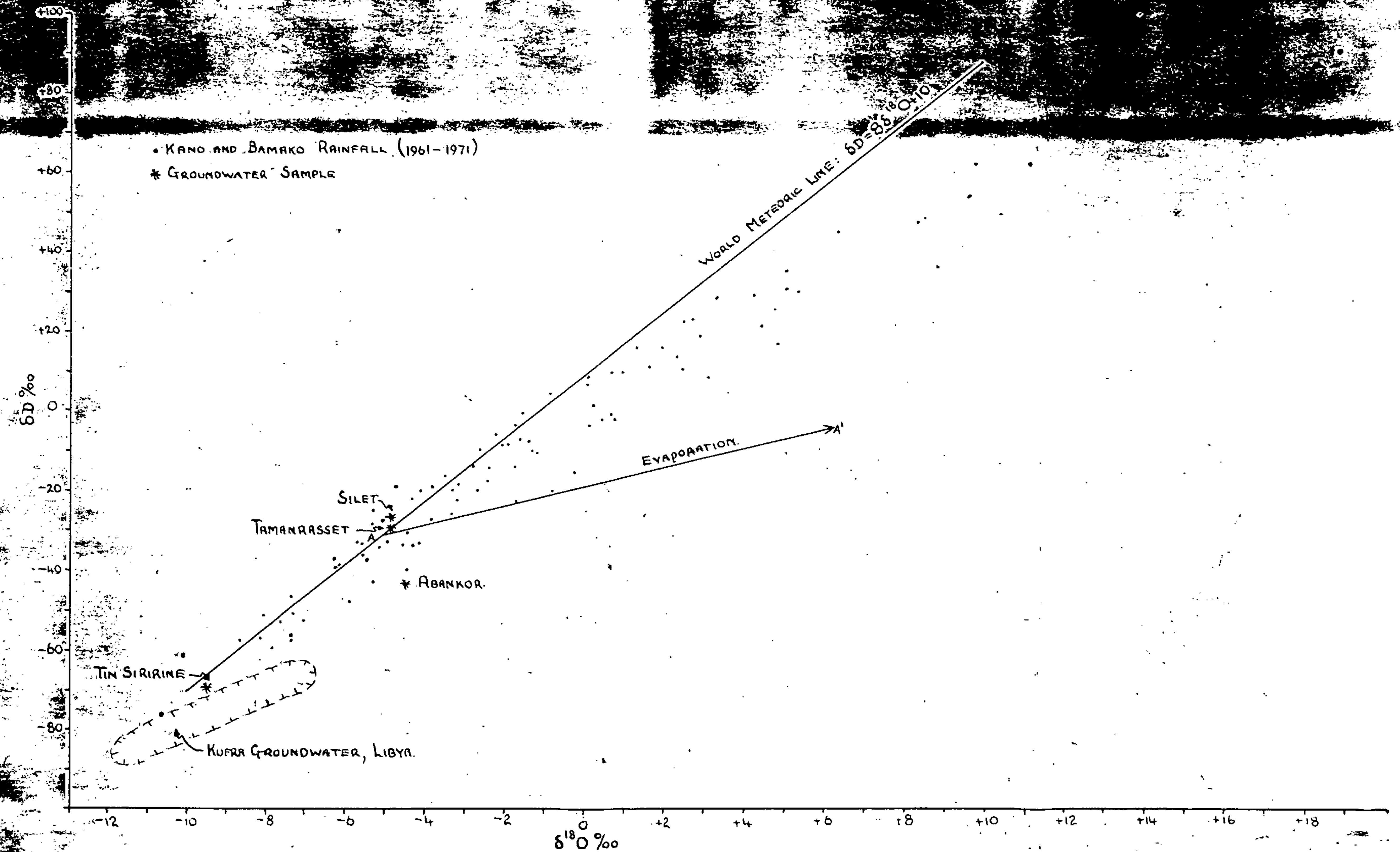
LOCATION PLAN

FIGURE I



CAMBRO-ORDOVICIAN AQUIFER - TIN SERIRINE SYNCLINE

FIGURE 2



ISOTOPIC COMPOSITION OF RAINFALL AND GROUNDWATER

FIGURE 3