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PALEOCLIMATIC EVIDENCE IN APPARENT ^{14}C AGES OF SAHARIAN GROUNDWATERS

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ABSTRACT. Frequency distributions of more than 300 ^{14}C groundwater ages from various regions in northern and southern Sahara reflect the alternating sequence of humid and arid periods in the Sahara during the Holocene and late Pleistocene. A broad frequency maximum between 20,000 and 50,000 years BP indicates a long humid period. During this time span, the northern Sahara received rain from the Western Drift, which is concluded from a west-east decrease of deuterium and oxygen 18 of these groundwaters (continental effect). In the time-slice between 14,000 and 20,000 years BP, groundwater formation was significantly lower due to a cool and (semi-)arid period. In the Holocene, the Saharian climate is characterized by a sequence of dry and wet periods.

^{14}C groundwater ages

Presently, ^{14}C and other isotope data (^{13}C, ^{3}H, D, ^{18}O) from more than 300 groundwater samples from various regions in the Sahara and Sahel-Zone are available (Sonntag and others, 1978; 1980). Figure 1 shows a frequency distribution of ^{14}C ages of 328 Saharian groundwaters. These ages are based on an initial ^{14}C content of 85 percent modern carbon; no carbonate exchange or other age corrections have been made. One sample is represented by a rectangle of unit area. Its width on the time-axis is the $\pm 1\sigma$ dating uncertainty derived from the statistical counting error only. At low dating precision (high age), the area representing one sample is broad and flat; at high precision, it is high and narrow. The frequency distribution reflects the alternating periods of humid and arid climate during the Holocene and late Pleistocene. Most of the artesian and deep groundwaters from Paleozoic till Upper Cretaceous aquifers (mostly Nubian Sandstone) fall into the time interval between 20,000 and 50,000 years BP. The broad frequency maximum in this time interval implies a long humid period during the late Pleistocene. In the following period, between 14,000 and 20,000 years BP, groundwater formation was significantly lower. At that time, the Sahara was cool and (semi-)arid. During the Holocene, Saharian climate was characterized by a sequence of shorter dry and wet periods, which also seem to be reflected in the frequency distribution of groundwater ages, although the significance of the frequency maxima and minima is rather poor. There are several reasons why our frequency distribution cannot be an artifact of groundwater flow: the stable isotope data (see below) shows that the Saharian groundwaters have mainly been formed by local recharge. Therefore, groundwater aging due to flow away from regions of (continuous) infiltration is expected to be of smaller time scale (mean subsurface residence times below 1000 years) than the length of the frequency

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maxima and minima discussed above. Moreover, circuit-model treatment of Saharian groundwater bodies' loading and unloading in the course of alternating humid and arid periods yields ^{14}C time patterns of the subsurface systems which are similar to our frequency distribution of groundwater ages, even in the case of an extremely high groundwater flow dispersion (Sonntag and others, 1980).

As can be seen from regional frequency distributions of ^{14}C groundwater ages (fig 2), the period of low groundwater formation seems to have existed all over the Sahara, even in the southern Sahara. This is supported by other paleoclimatic indicators—time variations of North African lake levels, pollen analyses, etc (Gasse, 1979).

The ^{14}C age spectrum of the southern Sahara includes ^{14}C data of groundwater from the Ferlo Basin (Senegal) (Castany and others, 1974; Kluβmann, pers commum, 1978), the deep groundwater of which (Maastsrichian formation) shows an age increase from the periphery to-

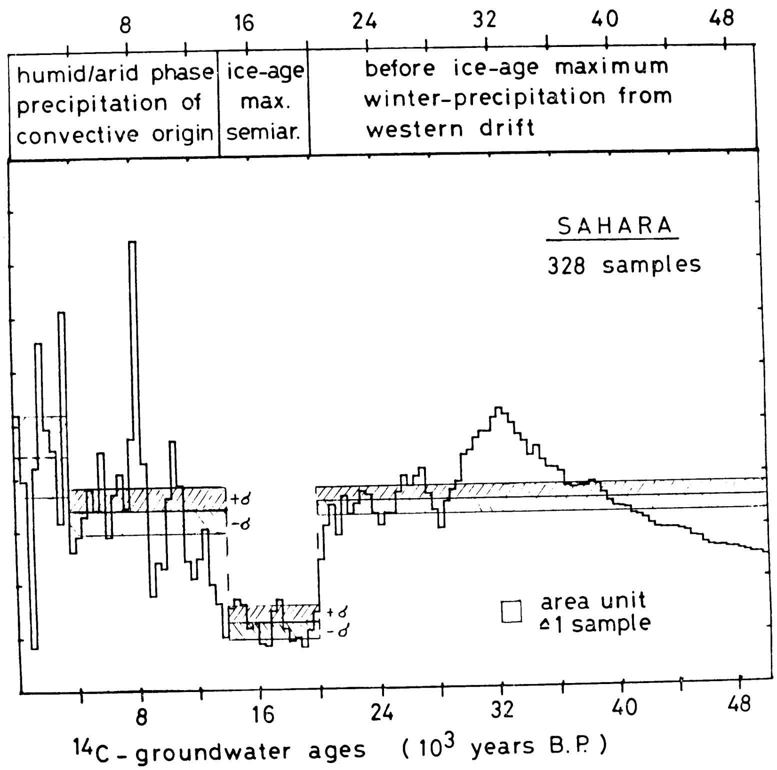

Fig 1. Frequency distribution of apparent ^{14}C ages of Saharian groundwaters based on an initial ^{14}C content of 85 percent modern (no carbonate or other age corrections were made). The unit area representing one sample is always a rectangle; its width on the time axis is the ± 1 sigma dating uncertainty. Therefore, at low dating precision (high age) the area representing one sample is broad and flat, at high precision, narrow and high. The $\pm\sigma$ range on the ordinate indicates the statistical error of the frequency distribution for the individual age periods.

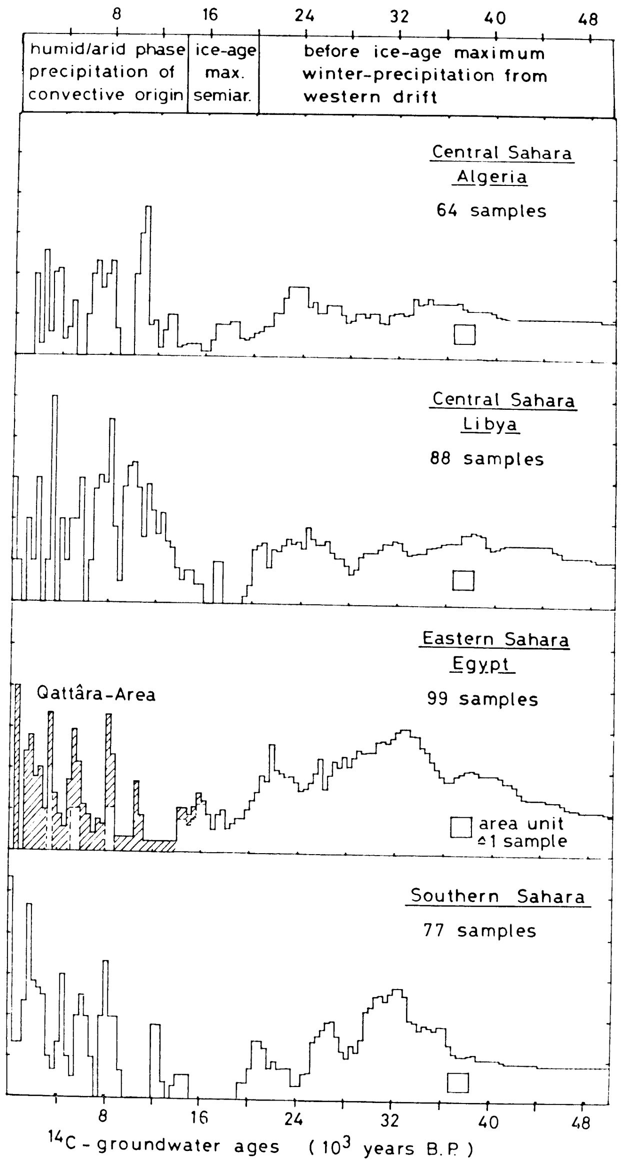

Fig 2. Frequency distributions of ^{14}C groundwater ages from different regions of the Sahara. The southern Sahara diagram includes the Sahel Zone. Algeria and southern Sahara contain data taken from (Gonfiantini and others, 1974; Castany and others, 1974; Mabrook and Abdel Shafi, 1977).

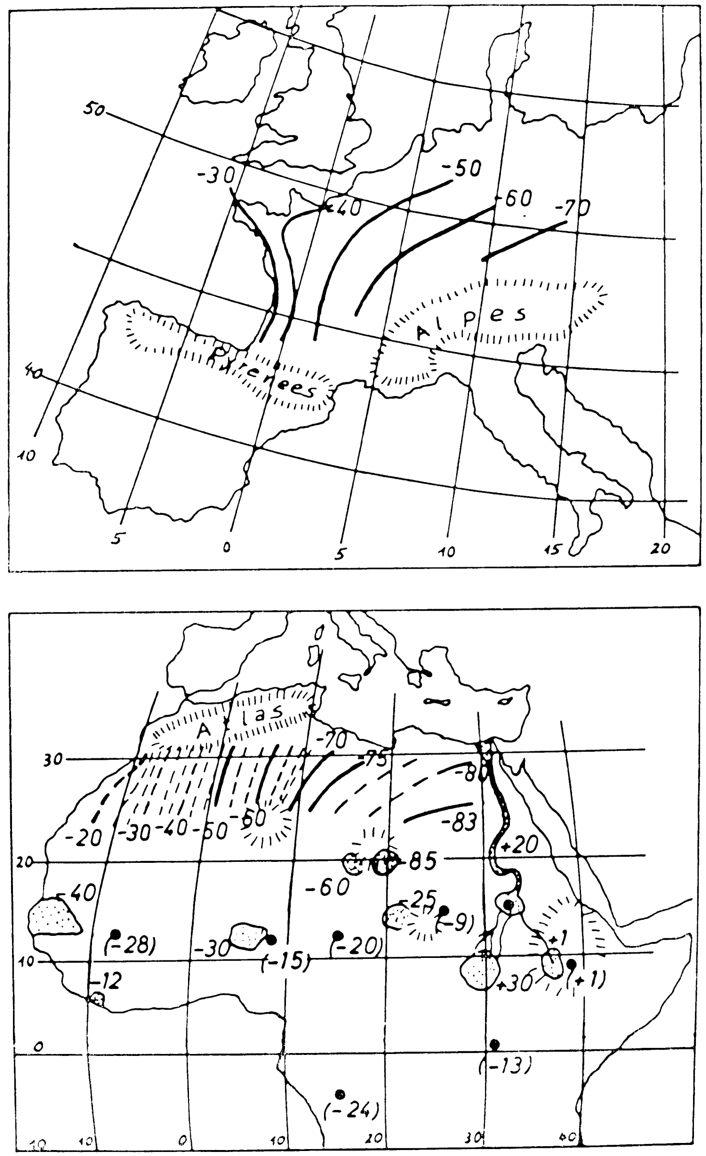

Fig 3. Isoline presentation of δD of modern European and fossil Saharian groundwaters, respectively, data of Gonfiantini and others (1974) included. For Central Africa the mean δD of modern and fossil groundwater (in the dotted areas) and of mean weighted annual precipitation (heavy full dots, numbers in brackets) is shown.

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wards the basin center. This indicates groundwater from the Senegal and Gambie Rivers at the periphery into the basin. We believe that the deep groundwater of the Ferlo Basin is mainly recharged by these rivers. Our conclusion is supported by hydrochemical data (Castany and others, 1974; Klußmann, pers commun, 1978) and by uniform D and ^{18}O data ($\delta D \cong -40‰$). From the point of view of continental effect, the heavy stable isotope content of the Ferlo Basin waters is too low to be attributed to local rainfall. It would, however, correspond to expected rainfall in the catchment areas of the two rivers. A frequency minimum between 14,000 and 20,000 years BP in the ^{14}C age spectrum of Ferlo Basin groundwaters would, thus, indicate reduced flow rate of the Senegal and Gambie Rivers during this time period.

Continental effect in deuterium and oxygen 18

Saharian groundwaters, primarily those older than 20,000 years BP, show a significant west-east decrease in D and ^{18}O. The decrease is similar to that found in modern European groundwater and winter precipitation (Sonntag and others, 1976). In Europe, the decrease is known as the "continental effect" caused by isotopic depletion of wet Atlantic air masses in the course of progressive rainout under equilibrium isotopic fractionation. The continental effect in fossil Saharian groundwaters indicates that the Sahara received rain from the Western Drift in the past. Figure 3 shows an isoline presentation of the deuterium data of fossil Saharian and modern European groundwaters. ^{18}O shows the same pattern due to a linear correlation between D and ^{18}O content (see below). The Western Drift influence seems to have only reached down to 20 degrees northern latitude. At lower latitudes, the stable isotope data shows a meridional variation indicating the tropical convective origin of these groundwaters.

Since groundwater normally does not change its D and ^{18}O content, the significant spatial variation in these isotopes indicates that Saharian groundwaters were mainly formed by local infiltration. Long-range groundwater movement, as previously assumed (Ambroggi, 1966), might only exist along stable isotope isolines (eg, Tibesti via Cufra and Farafra to Bahariya). A significant ^{14}C age increase along these lines, however, has not yet been found.

Figure 4 shows the linear correlation between deuterium (δD) and oxygen 18 ($\delta^{18}O$)[1] content of the fossil Saharian waters and modern European groundwaters. European groundwaters fall on the Meteoric Water Line (MWL): $\delta D = 8 \cdot \delta^{18}O + 10$, which at $\delta^{18}O = 0$, cuts the D axis at a deuterium excess of $d = 10‰$. Spread of the data points around the regression line is due to our present analytical precision of $\pm 1‰$ for deuterium.

Saharian waters fall on a line parallel to the MWL with a smaller deuterium excess of $d \cong 5‰$. We believe the smaller d was caused in the past by a lower moisture deficit (higher relative humidity) in the ocean air (Münnich and others, 1978; Merlivat and Jouzel, 1979).

[1] D and ^{18}O content presented as ‰ deviation δ from that of Standard Mean Ocean Water (SMOW).

A simple model treatment of the continental effect, based on progressive rainout of a closed wet air-mass system by Rayleigh condensation (no vertical vapor exchange, and no exchange between rain and vapor assumed), yields an estimate for the west to east variation of paleo-precipitation across the Sahara. Assuming 600mm mean annual paleo-precipitation at Agadir, about 250mm would be obtained for the Murzuq Basin. This value agrees with the precipitation estimate that Pachur (1979) obtained from ^{14}C dated fluvial and limnic sediments.

At present, we are trying a general vapor model that considers the vertical distribution of the stable isotopes D, ^{18}O in atmospheric water vapor, and the isotope exchange between local rain and this vapor. This model is expected to yield improved estimates for local paleo-precipitation considering local paleo-temperature data derived from the noble gas content of groundwater (Mazor, 1972; Bath, Edmunds, and Andrews, 1978).

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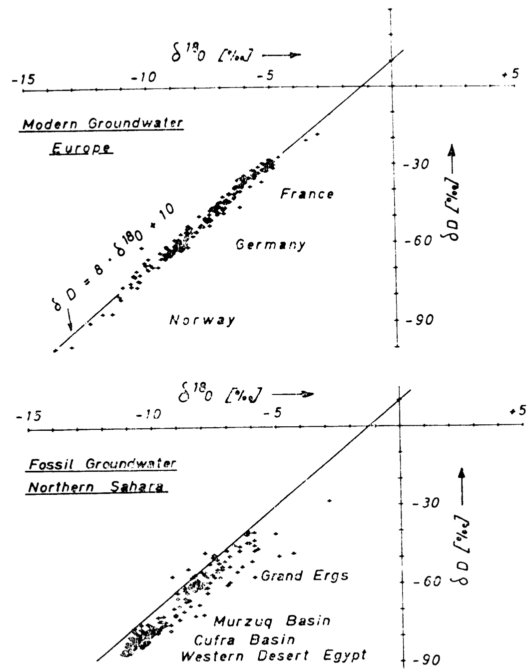

Fig 4. δD versus $\delta^{18}O$ diagram of modern European and fossil Saharian groundwaters. The isotope data from the Grand Ergs were taken from Gonfiantini and others (1974).

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DISCUSSION

Fritz: I would like to ask a question one should not ask. However, in the light of the previous presentation on ^{39}Ar, what would you suggest could be the significance of your data if the ^{14}C ages were too high by a factor of 10 or so. We should note, that "conventional" ^{13}C *and* chemical corrections do not suffice to bring ^{39}Ar and ^{14}C ages given by Dr Loosli into agreement, and have to assume that this would also be the case for your samples.

Münnich: It looks to me that if we, on the basis of argon-39, would have to compress the time scale by about an order of magnitude most of the arguments of this paper break down.

Rudolph: If the ^{14}C ages would be too high by a factor of 10 the significant changes in atmospheric circulation (shift of west-wind belt, etc) would have to be placed within the Holocene instead of late Pleistocene, which would contradict current paleoclimatic ideas.

Oeschger: Comment regarding the ^{39}Ar-^{14}C-discrepancy: it may be that the ^{14}C ages are in some cases too old by a factor of 5 to 10 due to exchange with dead carbonate or due to a chromatographic effect. Even if this were the case, ^{14}C measurements still could be very valuable, eg, combined with an "age stretching factor" determined by comparison with ^{39}Ar ages.

Muller: With regard to your statistical treatment of the groundwater "dates" from the Sahara, I suspect that a distribution of these values could reflect an artifact of the nature of the sampling. For example, consider the 100 odd ^{14}C analyses which I have obtained in the south central Sahara north of Lake Tchad. The vast majority appear to have apparent ages less than 5000 years. Added to your 380 dates, they would skew your distribution so that the last few millennia would appear to be a pluvial, which is highly unlikely. Therefore, do you not think that with so small a data set, the frequency distribution (of "dates" obtained at points which are clearly not randomly distributed in the Sahara) is not representative of natural variations, but is an artifact of the sampling?

Rudolph: We were also surprised that the frequency distribution of ^{14}C ages of Saharian groundwaters reflected the climatic history derived from other paleoclimatic indicators as well. One may doubt whether the groundwaters in this presentation are representative for the whole groundwater population of the Sahara or not. We are aware that the "true" ^{14}C groundwater age distribution might differ from our spectrum. The point, however, is that we see no reason not to believe in the significant frequency minimum between 20,000 and 14,000 years BP.

Muller: Could you not increase the confidence in your value of 85 percent modern initial activity assumed for the groundwater dates if it would be supported by some geochemical model such as those of Tamers, Pearson, Mook, Fritz and Reandon, Wigley and others, or more recently, Fontes and Garnier?

Rudolph: We are not yet convinced of all these models which yield reliable ^{14}C groundwater ages only in particular cases. A new model is needed which is based on a better understanding of the processes involved in carbonate geochemistry in soil and aquifer systems. As long as such a model is not available, it is better to treat the ^{14}C data in the same way, for example, to use empirical initial ^{14}C values for various soil types.