Die Grüne Vergangenheit der Sahara
The Green Past of the Sahara Desert

Stefan Kröpelin
University of Cologne
Institute of Prehistoric Archaeology

12th Intl. EIKE Conference on Climate Change and Energy
13th International Conference on Climate Change
München, 23-24 November 2018

The *Libyan Desert*
of Libya, Egypt, Chad
and Sudan:

The Earth's
least explored region

Atlas of 1922

Science
189, 460-463 (1975)

WALLACE S. BROECKER
Lamont-Doherty Geological Observatory
and *Department of Geological Sciences,*
Columbia University,
Palisades, New York 10964

Climatic Change: Are We on the Brink of a Pronounced Global Warming?

Abstract. *If man-made dust is unimportant as a major cause of climatic change, then a strong case can be made that the present cooling trend will, within a decade or so, give way to a pronounced warming induced by carbon dioxide. By analogy with similar events in the past, the natural climatic cooling which, since 1940, has more than compensated for the carbon dioxide effect, will soon bottom out. Once this happens, the exponential rise in the atmospheric carbon dioxide content will tend to become a significant factor and by early in the next century will have driven the mean planetary temperature beyond the limits experienced during the last 1000 years.*

The fact that the mean global temperature has been falling over the past several decades has led observers to discount the warming effect of the CO_2 produced by the burning of chemical fuels. In this report I present an argument to show that this complacency may not be warranted. It is possible that we are on the brink of a several-decades-long period of rapid warming. Briefly, the argument runs as follows. The ^{18}O record in the Greenland ice core (*1*) strongly suggests that the present cooling is one of a long series of similar natural climatic fluctuations. This cooling has, over the last three decades, more than compensated for the warming effect produced by the CO_2 released into the atmosphere as a by-product of chemical fuel combustion. By analogy with similar events in the past, the present natural cooling will, however,

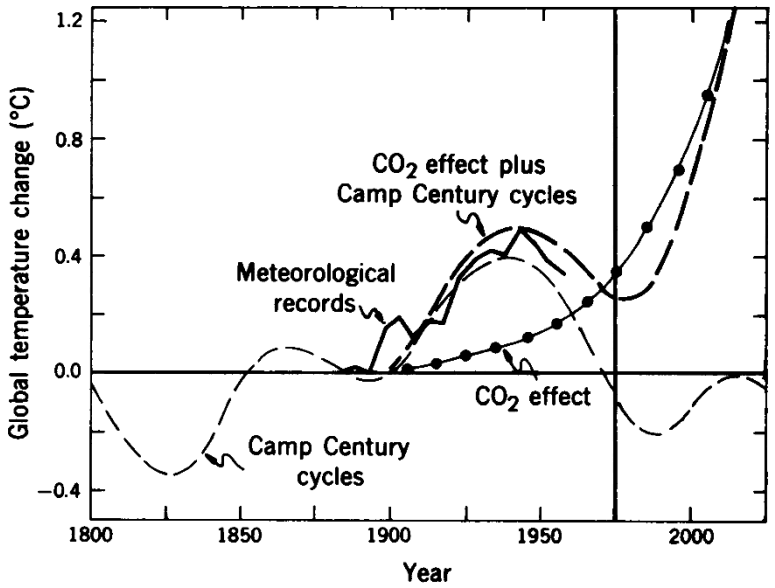
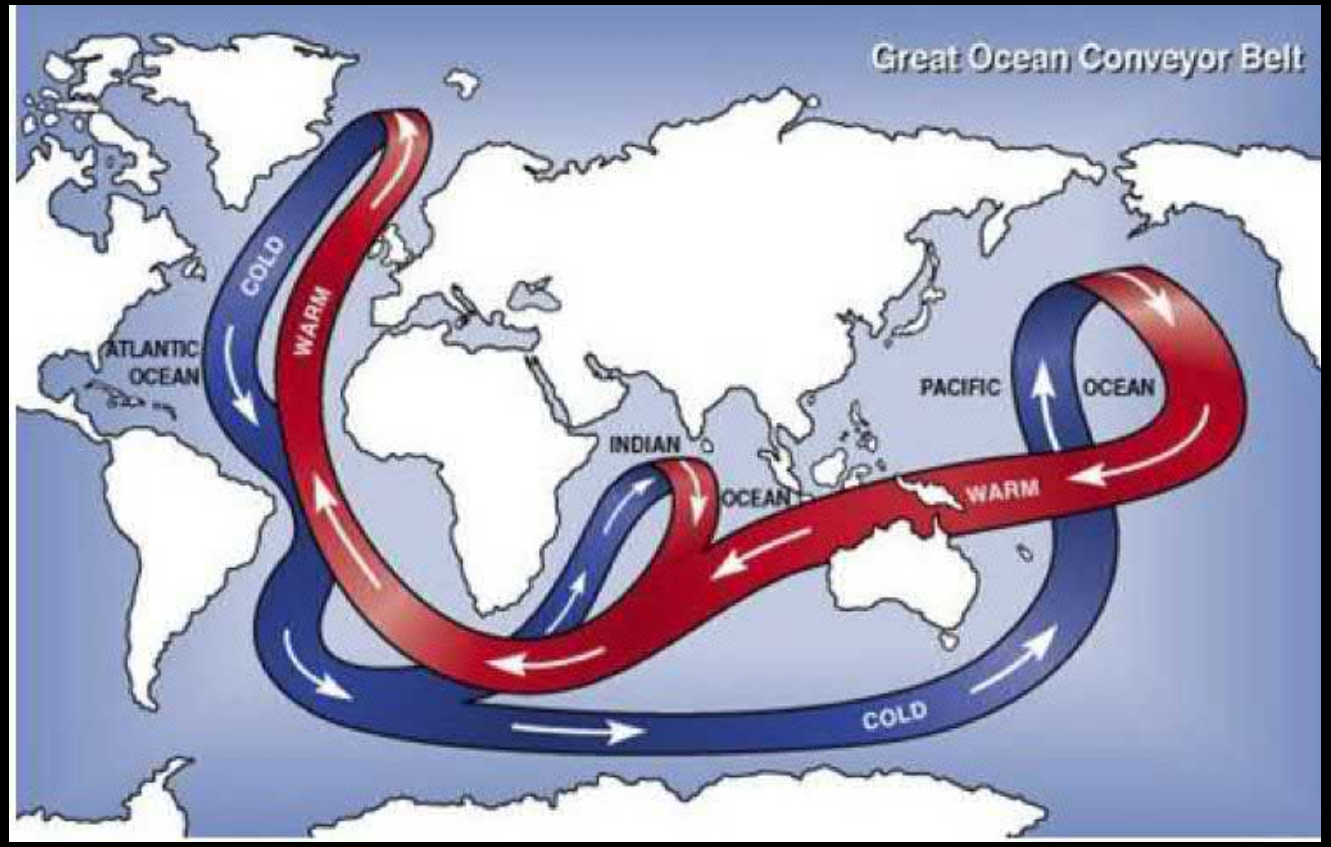


Fig. 1. Curves for the global temperature change due to chemical fuel CO_2, natural climatic cycles, and the sum of the two effects. The measured temperature anomaly for successive 5-year means from meteorological records over the last century is given for comparison.



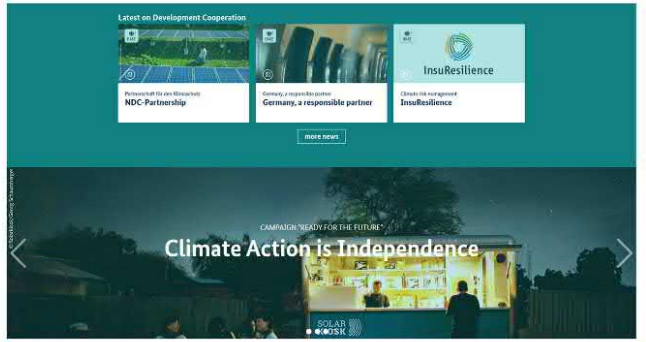
President Clinton presented Broecker with the National Medal of Science, the country's highest scientific award, in July 1996.

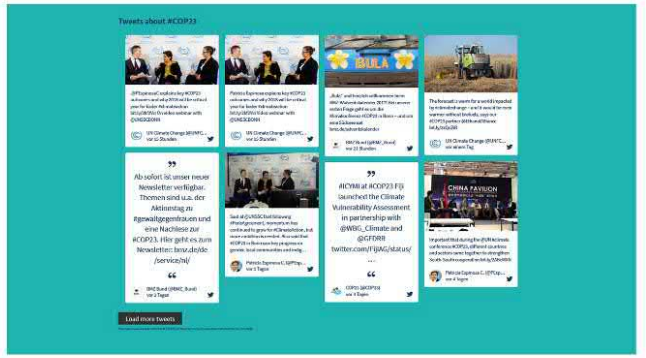
PHOTO: COURTESY WILLIAM J. CLINTON PRESIDENTIAL LIBRARY

COP23 | FIJI

UN CLIMATE CHANGE CONFERENCE

BONN 2017





mobil

DB

„Nur weil man ***Weltmeister*** ist, gehört einem nicht die Welt.“ ***Nico***

11 | 2017 Das Magazin der Deutschen Bahn dbmobil.de

11.2017

CO WER?

KLIMA SPEZIAL

Muss ein übler Ganove sein, dieser Stoff, der unseren Planeten erhitzt. Höchste Zeit zu lernen, wie man mit diesem CO_2 richtig umspringt. Zwölf Fakten über einen flüchtigen Unbekannten

TEXT: DAVID SCHUMACHER

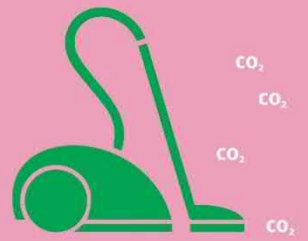
Die Luft, die wir einatmen, besteht nur zu **0,04 Prozent** aus CO_2. Unser Stoffwechsel ist wie ein Minikraftwerk. Folge: Unsere Ausatemluft enthält etwa vier Prozent Kohlendioxid. Fürs Klima also: Bitte flach atmen!

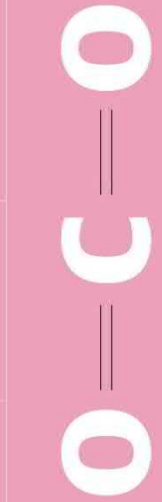
CO_2 ist gut wasserlöslich, ein kleiner Teil davon reagiert zu Kohlensäure. So entsteht das beliebte **Sprudelwasser.**

Ein Erwachsener atmet im Jahr etwa **350 Kilogramm** CO_2 aus. Um diese Menge zu binden, braucht es zehn ausgewachsene Buchen.

Aus abgesaugtem CO_2 (siehe rechts) lässt sich mittels eines Katalysators wieder **Treibstoff** gewinnen. Nachteil: Das verbraucht viel Energie.

Seit Kurzem existieren Geräte, die CO_2 aus der Abluft von etwa **Müllverbrennungsanlagen** und **Kraftwerken** filtern. Wie ein riesiger Staubsauger.





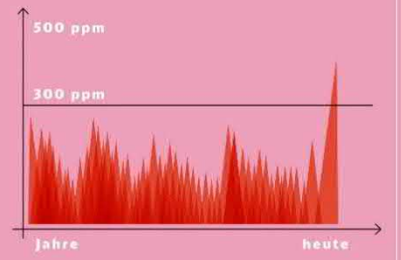
Kohlenstoffdioxid, eine Verbindung aus einem Kohlenstoff- (C) und zwei Sauerstoffatomen (O_2). Im Vergleich zu Krawallgasen wie Methan recht diskret: unbrennbar sowie farb- und geruchlos.

Zwar riecht es nicht, aber bei hoher Konzentration in der Luft sticht CO_2 in der **Nase**

8

Prozent

ist eine kritische CO_2-Konzentration in der Luft: kann auf **Menschen tödlich** wirken.

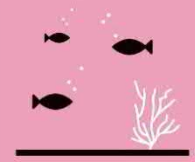


In den zurückliegenden **400 000 Jahren** blieb die CO_2-Konzentration in unserer Atmosphäre stets unter 300 ppm (Teilchen pro Million Teilchen = 0,03 %). Diese Schwelle haben wir dank unserer Industrialisierung im Eiltempo überschritten.

20 Euro pro Tonne CO_2-Ausstoß: So hoch müsste nach Ansicht vieler Ökonomen eine zusätzliche **CO_2-Steuer** mindestens sein, um wirkungsvoll zu sein. Simples Prinzip: Jeder Brennstoff wird besteuert, je mehr CO_2 er freisetzt, desto höher. Am Ende des Jahres ist die staatliche **CO_2-Kasse** voll – und wird an alle wieder ausgeschüttet, etwa per Steuersenkung. Manche trifft es härter, andere gewinnen, aber in der Summe kostet es die Volkswirtschaft nichts. Effekt: Alle Steuerfüchse versuchen, die Belastung zu vermeiden und stoppen so den Klimawandel.

Warnung vom Nachbarn: Die Atmosphäre der Venus weist eine etwa **240 000-mal** höhere CO_2-Konzentration auf als unsere. Folge: Megatreibhaus, **470 Grad** Hitze, auch nachts und an den Polen. Der sonnennähere Planet Merkur ist kühler. Allerdings: Ganz ohne CO_2 wäre die Erde ein Eisplanet.

Hinein ins Nass: CO_2 wird **Aquarienwasser** zugesetzt, als Dünger für die Pflanzen. Warum nicht ein paar Schritte weitergehen? Forscher testen, ob es möglich ist, CO_2 in verflüssigter Form unter den Meeresboden zu pressen – mit ungewissen Folgen. An der Nordseeküste haben sich bereits Bürgerinitiativen dagegen gegründet.



GRÜNE AUSGABE

CO WER?

KLIMA SPEZIAL

Die Luft, die wir einatmen, besteht nur zu **0,04 Prozent** aus CO_2. Unser Stoffwechsel ist wie ein Minikraftwerk. Folge: Unsere Ausatemluft enthält etwa vier Prozent Kohlendioxid. Fürs Klima also: Bitte flach atmen!

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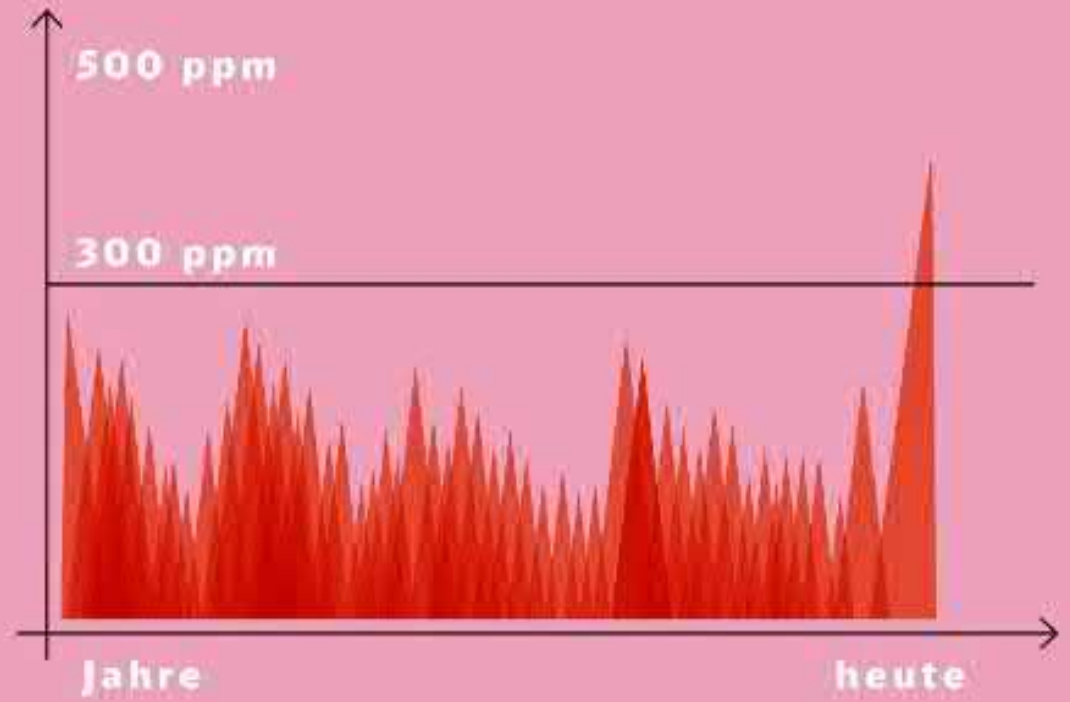


In den zurückliegenden **400 000 Jahren**

385 ppm CO2 = 0.0385 % of total atmosphere

Anthropogenic portion (IPCC) 5 % ≈ 0.002 % of total atmosphere


Hans Joachim Schellnhuber
SELBST
VERBRENNUNG
Die fatale Dreiecksbeziehung
zwischen Klima, Mensch
und Kohlenstoff
"Selbstverbrennung" mein "Lebenswerk"
und "Vermächtnis" an die Menschheit

„Der große Gott von Sefar“ (Tassili n‘Ajjer, Algerien)

WISSENSCHAFTLER FÜRCHTEN Sahara bis Berlin! Hamburg unbewohnbar!

In der ganzen Welt diskutierten Wissenschaftler die Ergebnisse der Schock-Studie: Sie fürchten furchtbare Überflutungen, den Verlust ganzer Städte!

„Die Zukunftsprojektionen aus dem Bericht legen nahe, dass wir bis 2100 an den deutschen Küsten einen zehn bis zwanzig Zentimeter höheren Meeresspiegelanstieg haben könnten als an anderen Meeresküsten", sagte Prof. Stefan Rahmstorf (47) vom Potsdam-Institut für Klimafolgenforschung.

Er ist einer der Mitautoren der Studie. „Aus geologischer Sicht ist es völlig unproblematisch, wenn der Meeresspiegel um einen Meter steigt", sagte er. „Das ist nur sehr schlecht für uns, weil wir die Städte dort gebaut haben, wo bislang die Küstenlinien gewesen sind."

Der veränderte Regenfall überfordert die Gewässer: „Unsere Flussläufe sind darauf ausgerichtet, die Wassermassen aufzunehmen, die erfahrungsgemäß in den letzten Jahrhunderten immer wieder vorgekommen sind. Wenn sich das ändert, bekommen wir Probleme wie beim Hochwasser 2002 in Dresden."

Prof. Hans Joachim Schellnhuber (56), Klima-Chefberater der Bundesregierung, hat ebenfalls an der Studie mitgearbeitet. Er ist sicher: „Bei einer Erderwärmung um fünf Grad kann langfristig die Sahara bis nach Berlin reichen."

Der Klimaforscher weiter: „Hamburg bräuchte Sperrwerke, um das Wasser fernzuhalten. Das wäre zu machen. Große Probleme bekäme London, weil es näher am Meer liegt und sehr niedrig. Ähnlich ist es in allen großen Flussdeltas der Erde, zum Beispiel Ganges, Nil und Niger."

Er fürchtet: „Eine einigermaßen lebenswerte Zivilisation, wie wir sie heute kennen, wäre für die dann acht oder neun Milliarden Menschen aber nicht mehr möglich. Es würde wohl ein Klima der Gewalt herrschen. Die Welt, die jetzt schon explosiv genug ist, würde noch heftigere Auseinandersetzungen erleben."

Dr. Hermann E. Ott (45) vom Wuppertal-Institut für Klima, Umwelt und Energie sieht ebenfalls mit größter Sorge auf die deutsche Küste: „Das Abschmelzen der Polkappen macht auf lange Sicht Städte wie Rostock, Hamburg und Kiel unbewohnbar. Was mit den Inseln wie Sylt passiert, kann man sich vorstellen."

Können wir überhaupt noch etwas retten? Klimaforscher Prof. Dr. Martin Claßen (51), Max-Planck-Institut für Meteorologie: „Selbst, wenn wir alle Emissionen stoppen würden – das Klima erwärmt sich weiter. Die Treibhausgase halten sich über 100 Jahre in der Atmosphäre."

Samstag, 3. Februar 2007 29/5 0,50 €
4198061700505 60005
Bild

3.2.2007

Xavier und die Wetterextreme: Kippt unser Klima?

Deutschlands prominentester Klimaforscher stellt fest: *"Das Jahr 2017 zeigt uns auf bitterste Weise, warum die Wissenschaft seit Jahrzehnten vor dem Klima-Chaos warnt. Die Elemente Feuer, Wasser und Luft wenden sich nun gegen uns, weil wir den Planeten aus dem Gleichgewicht bringen."* Wenn der Klimawandel nicht gebremst würde, so der Direktor des Instituts für Klimafolgenforschung, gäbe es irgendwann Bedingungen, die sogar Hurrikans in Europa möglich machen könnten. Außerdem stehe zu befürchten, *"dass in den nächsten Jahrzehnten die Sahara nach Europa vordringt"*, prophezeit Prof. Hans Joachim Schellnhuber, der die Bundesregierung und den Papst in Klimafragen berät.

Das Erste

11.10.2017

arte

20.11.2018

Klimafluch und Klimaflucht
Massenmigration - Die wahre Umweltkatastrophe

Der Tschadsee in der Sahelzone ist seit den 60er Jahren wegen der zunehmenden Hitze bereits um 90 Prozent geschrumpft. Im Laufe dieses Jahrhunderts wird er vermutlich ganz verschwunden sein. Die ca. 40 Millionen Menschen, die noch immer von ihm leben, werden gezwungen sein, weiter in Richtung Süden zu migrieren, dorthin, wo es noch mehr Regen gibt. Eine Katastrophe mit Ansage.

Google News 24.11.2018

Google News

Nach Themen, Orten und Quellen suchen

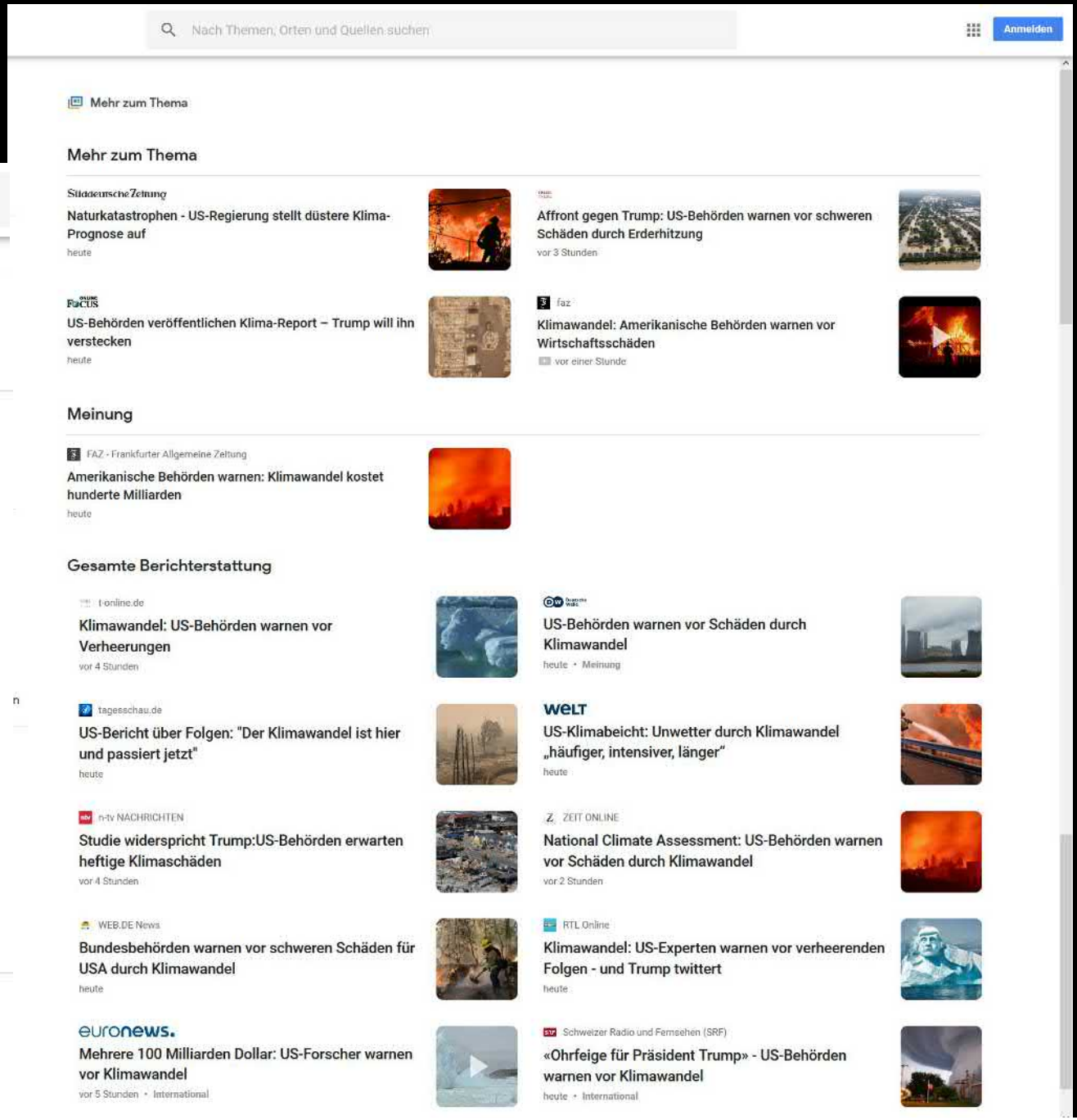
Schlagzeilen

Naturkatastrophen - US-Regierung stellt düstere Klima-Prognose auf

Süddeutsche Zeitung • heute

- **US-Behörden veröffentlichen Klima-Report – Trump will ihn verstecken**
  FOCUS Online • heute
- **Klimawandel: Amerikanische Behörden warnen vor Wirtschaftsschäden**
  faz • vor einer Stunde
- **Klimawandel: US-Behörden warnen vor Verheerungen**
  t-online.de • vor 4 Stunden
- **Studie widerspricht Trump:US-Behörden erwarten heftige Klimaschäden**
  n-tv NACHRICHTEN • vor 4 Stunden

Mehr zum Thema



BLOG: **KLIMALOUNGE**

Wie erkennt man echte Klimaexperten?

6. September 2018 | Von **Stefan Rahmstorf | 76 Kommentare**

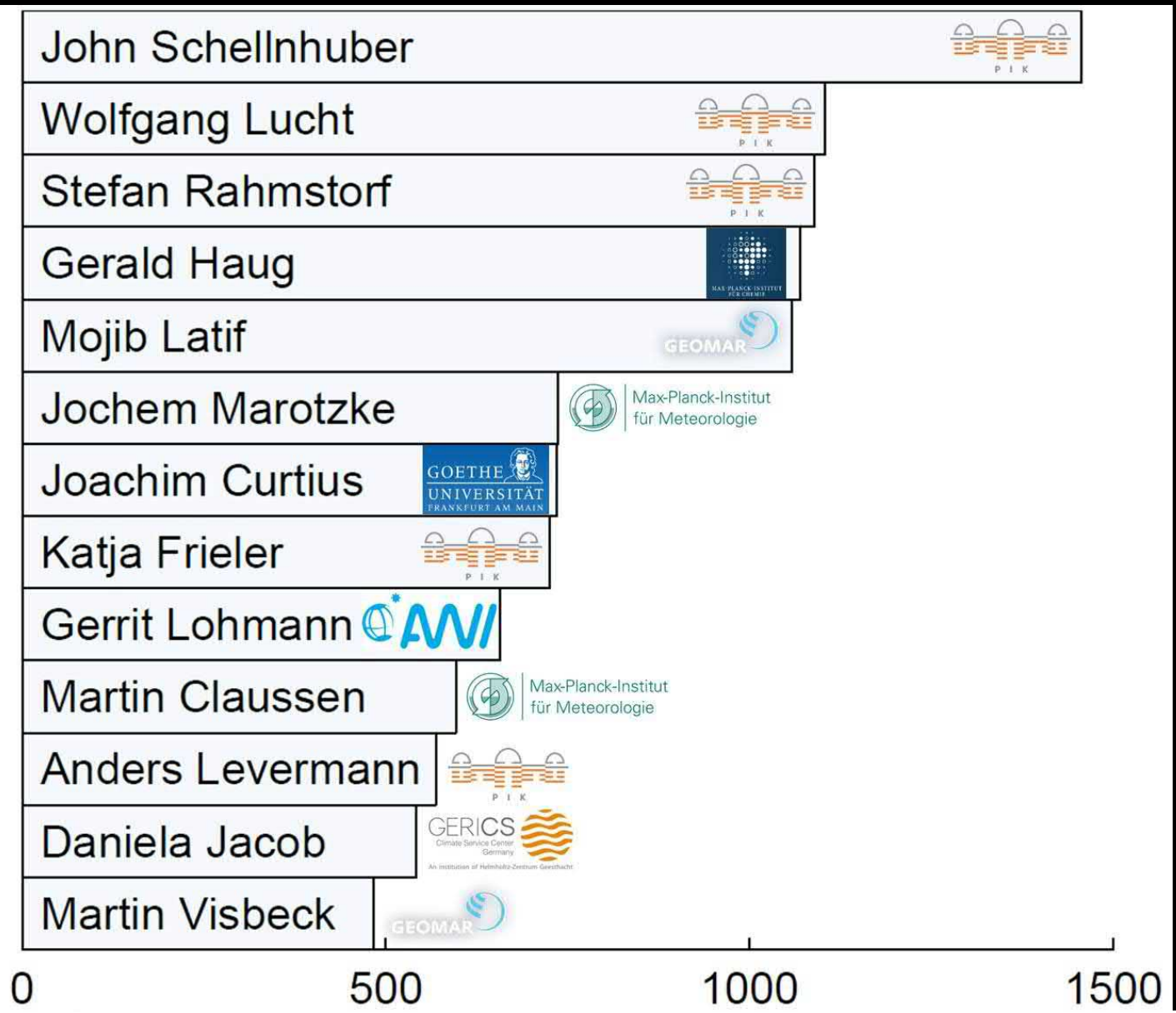
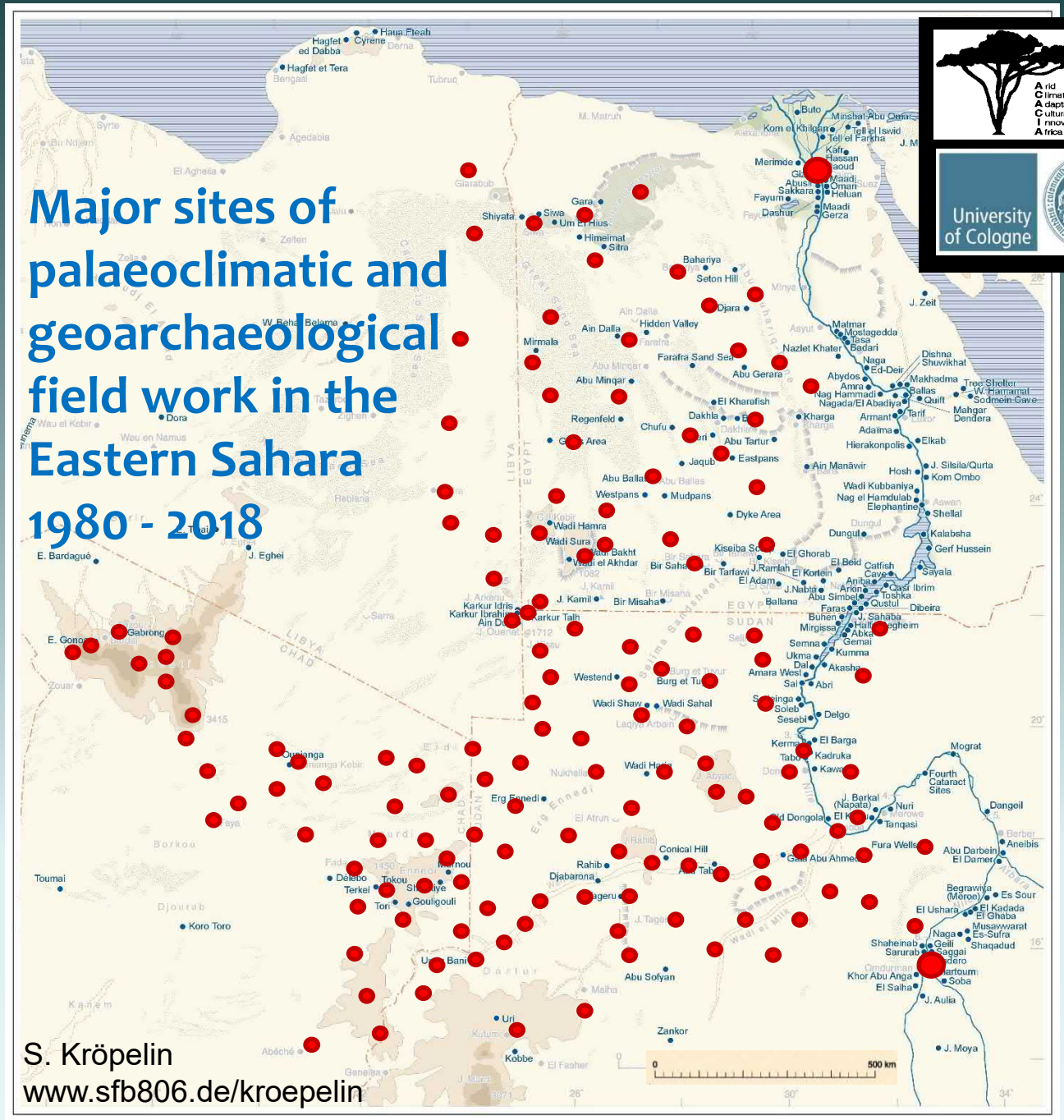


Abb. 1 *Die Häufigkeit, mit der die Studien einiger prominenter deutscher Klimaforscher laut Datenbank Web of Science im Jahr 2017 zitiert wurden. Insgesamt sind 2017 zum Suchbegriff „climate change" 20.000 Studien erschienen.*



Arid Climate, Adaptation and Cultural Innovation in Africa

Centre National d'Appui à la Recherche CNAR

University of Cologne

Comité technique de la mise en œuvre de la Convention de l'UNESCO sur le Patrimoine Mondial au Tchad

DFG Deutsche Forschungsgemeinschaft

B.O.S. / *Settlement history of the Eastern Sahara*
University of Cologne (1980 - 1992)

SRP 69 *Arid zones*
Universities of Berlin (1980 - 1995)

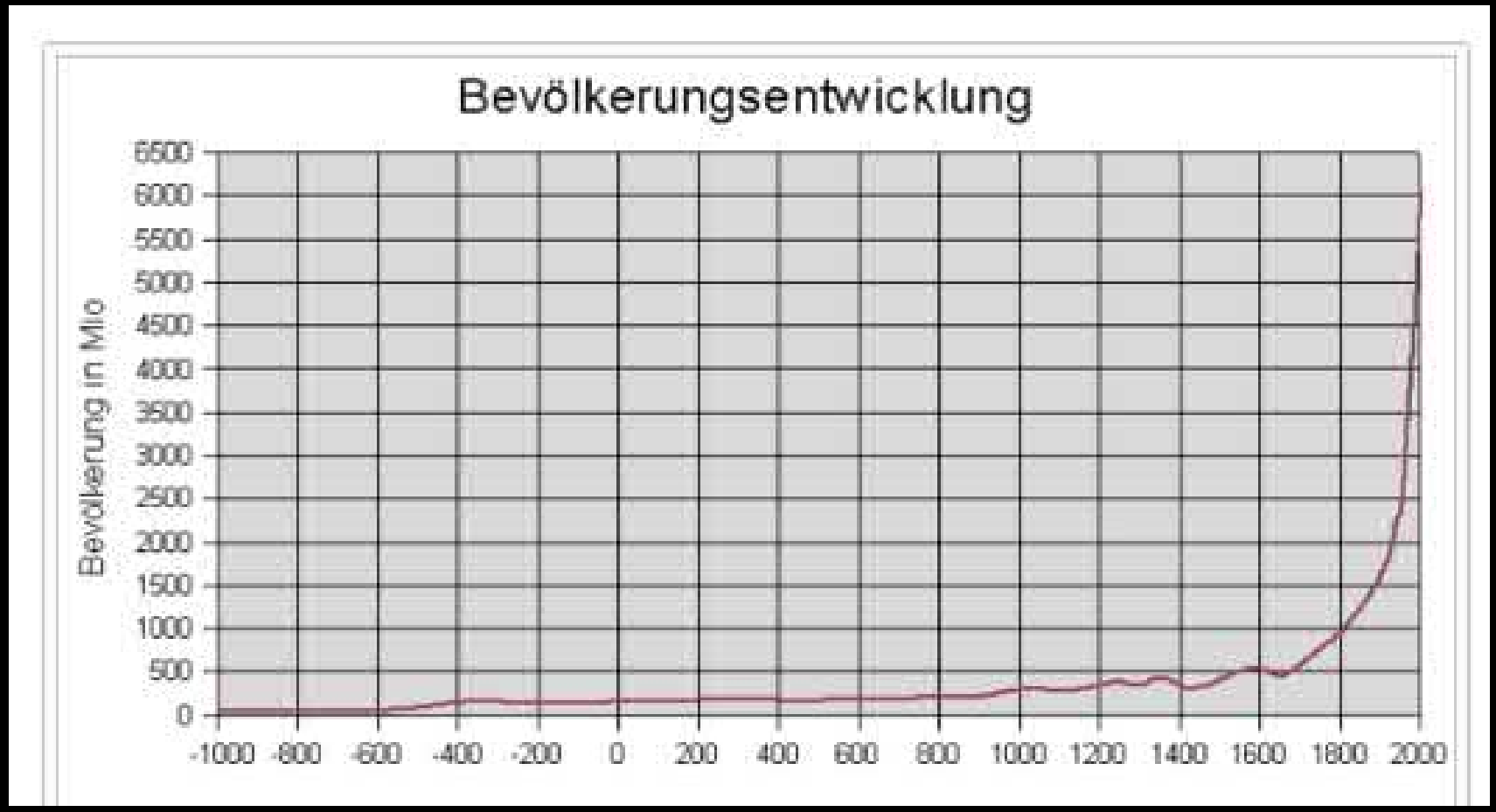
CRC 389 *ACACIA*
University of Cologne (1995 - 2008)

CRC 806 *Our Way to Europe*
Universities of Cologne, Bonn and Aachen (2009 - 2021)

WIKIPEDIA
Die freie Enzyklopädie

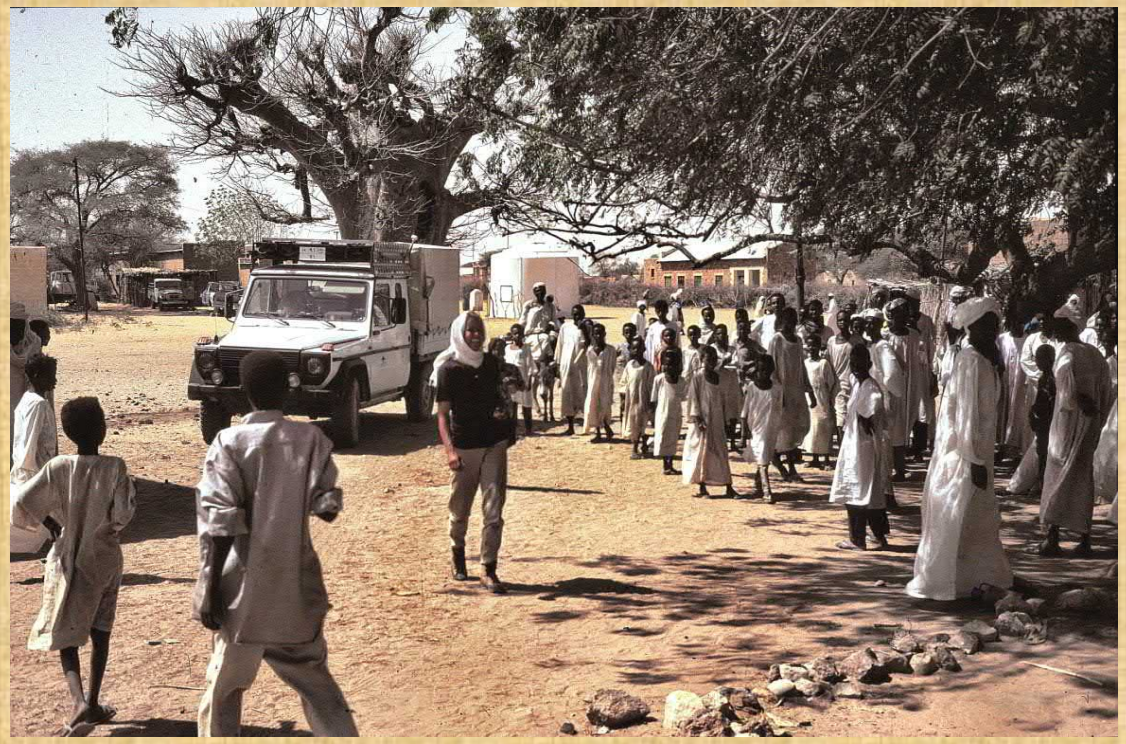
Artikel | Diskussion

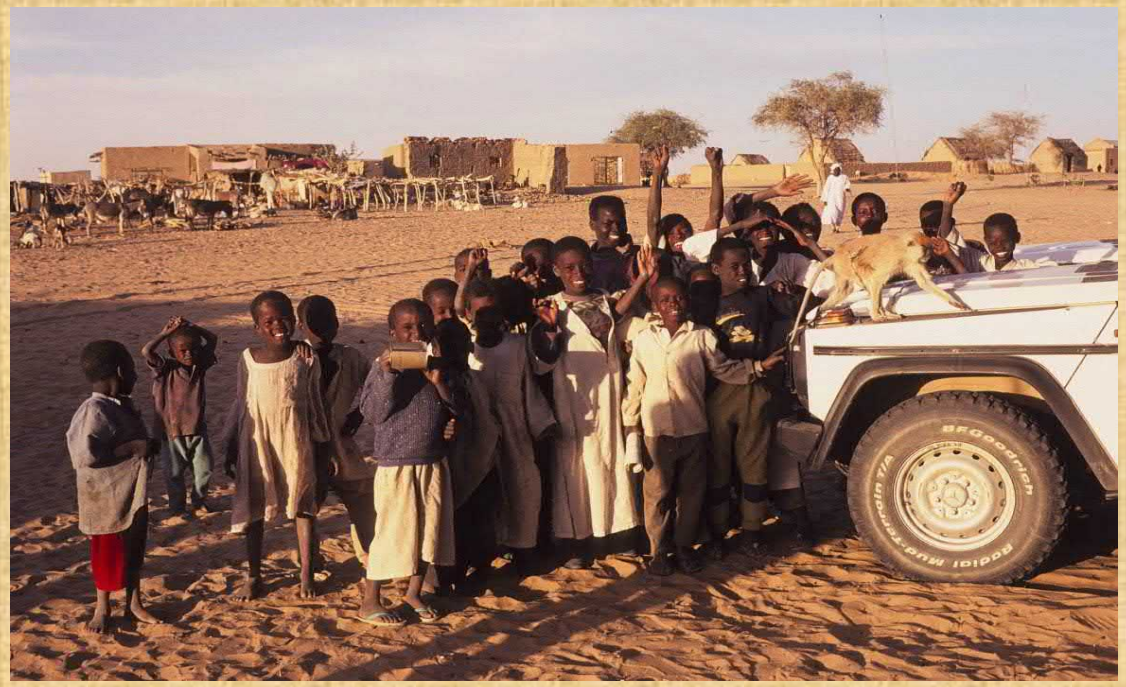
Weltbevölkerung



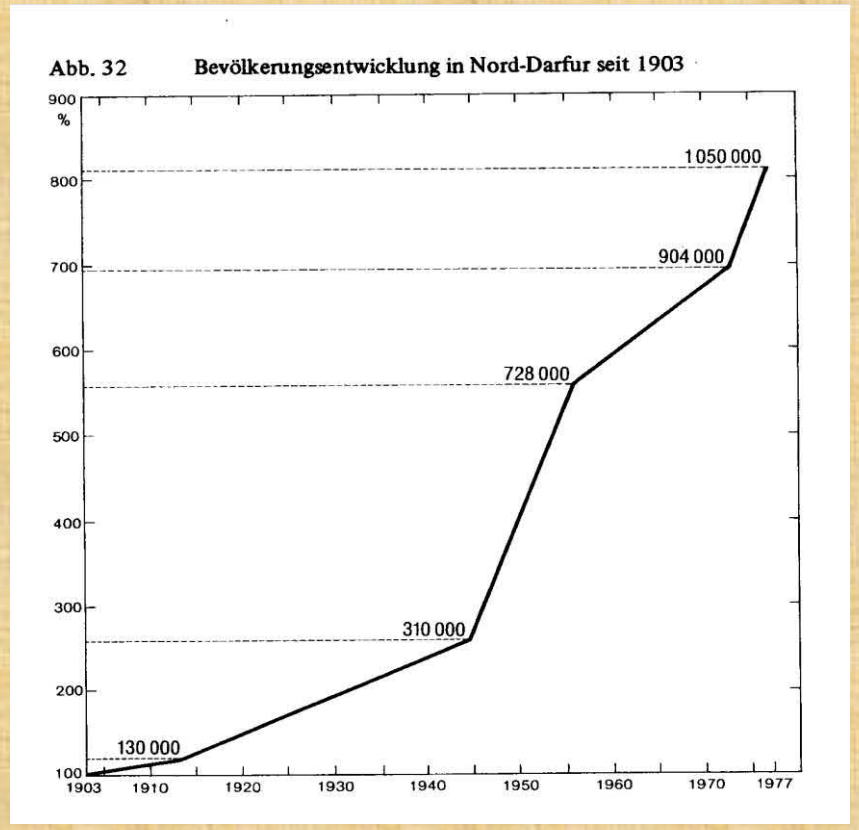
Weltbevölkerung nach Kontinenten (in Mio.)[14]

	2016	2030	2050
Asien	4437	4946	5327
Afrika	1203	1681	2527
Amerika	997	1117	1220
Europa	740	744	728
Ozeanien	40	51	66
Welt	7418	8539	9869





(1995)

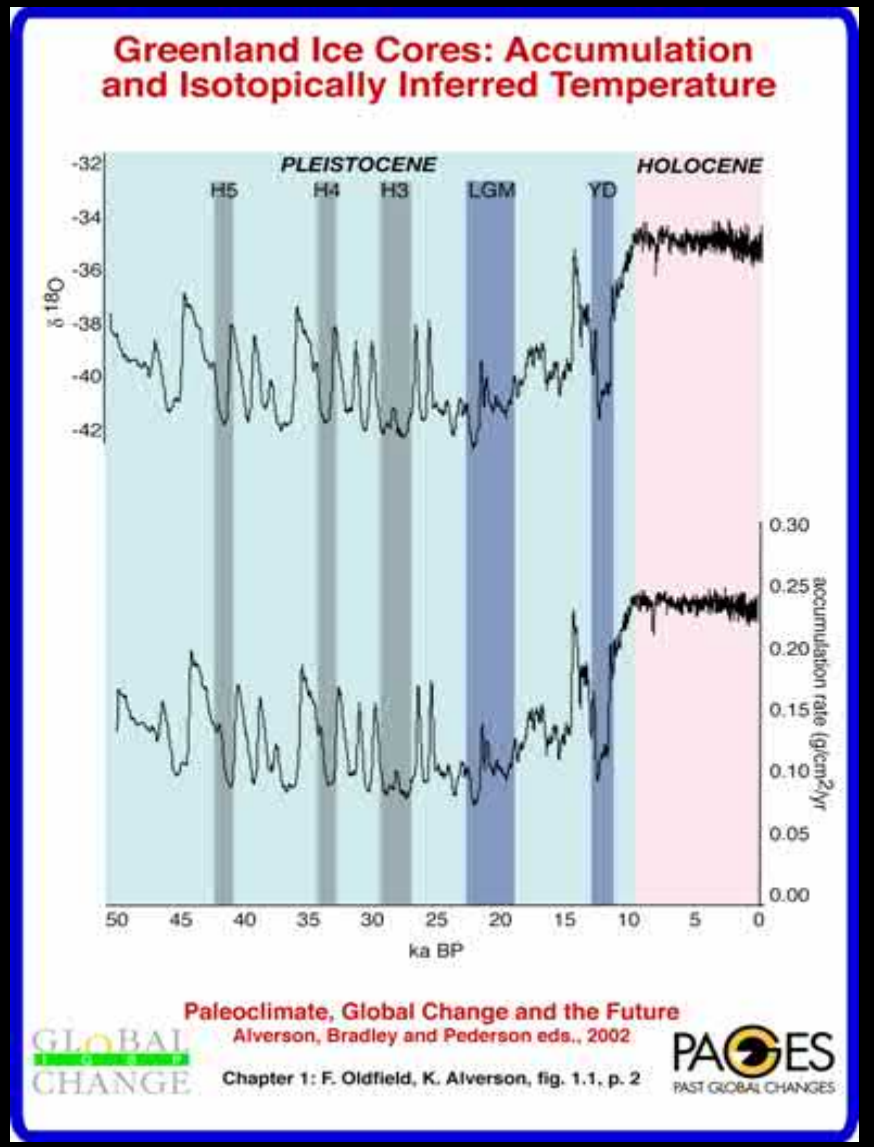


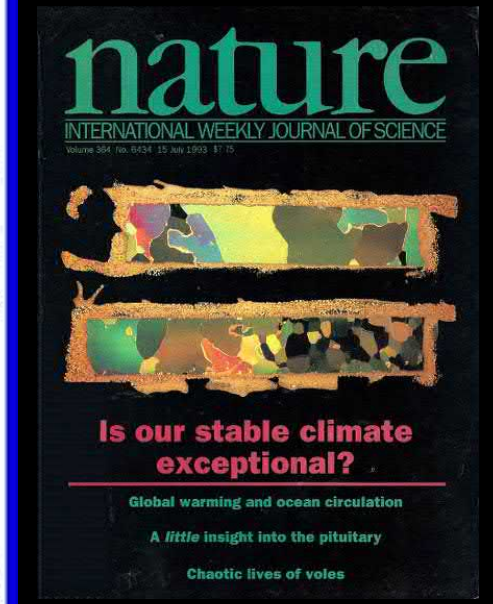
(Ibrahim 1980)

During the past 60 years, the population of Darfur has increased from 1.3 million to about 9 million

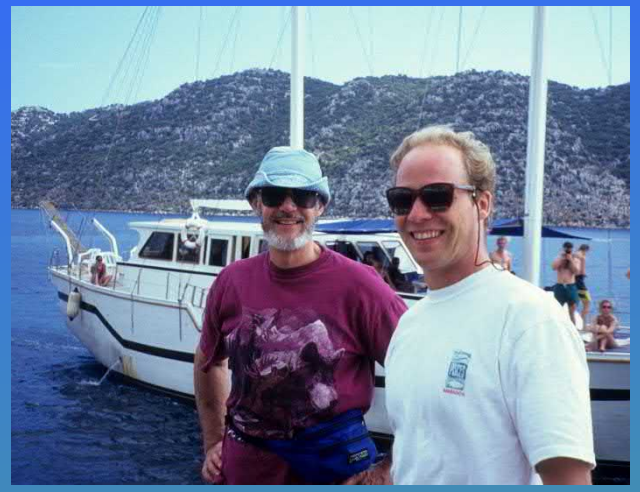
Terrestrial paleoclimatology of the habitable continents
vs.
Paleoclimatic proxies from ice and ocean cores

Vostok, Antarctica





15 July 1993



PERGAMON

Quaternary Science Reviews 19 (2000) 347–361

QSR

Abrupt onset and termination of the African Humid Period: rapid climate responses to gradual insolation forcing

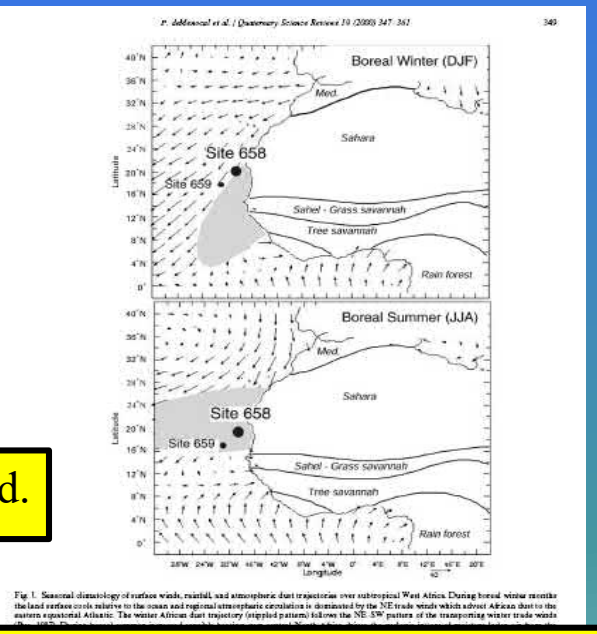
Peter deMenocal[a,*], Joseph Ortiz[a], Tom Guilderson[b], Jess Adkins[a], Michael Sarnthein[c], Linda Baker[a], Martha Yarusinsky[a]

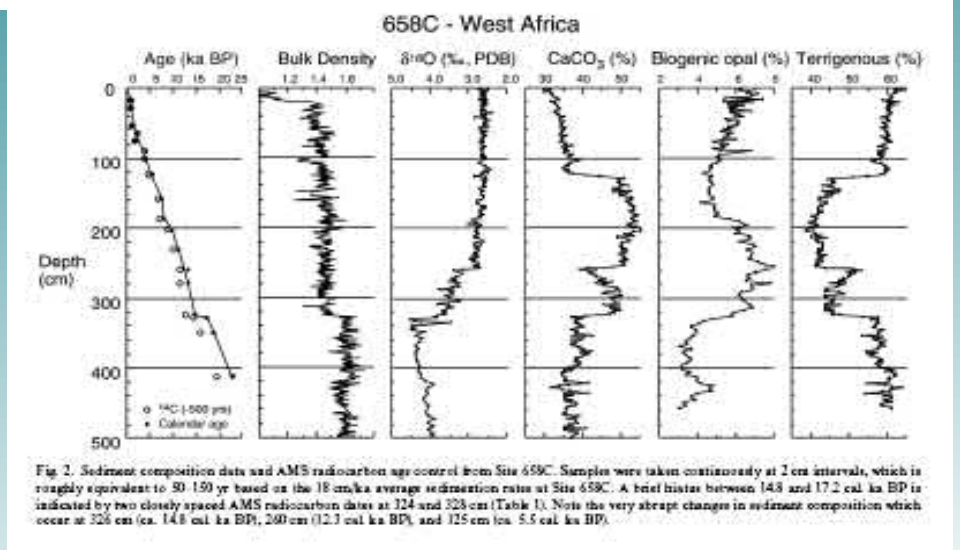
[a]Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA
[b]Center for Accelerator Mass Spectrometry, Lawrence-Livermore National Laboratory, Livermore CA 94551, USA
[c]Institute Fuer Geowissens Chafter, Universitaet Kiel, Kiel, Germany

14.8 and 5.5 cal. ka BP associated with the African Humid Period, when the Sahara was nearly completely vegetated and supported numerous perennial lakes; an arid interval corresponding to the Younger Dryas Chronozone punctuates this humid period. The African Humid Period has been attributed to a strengthening of the African monsoon due to gradual orbital increases in summer season insolation. However, the onset and termination of this humid period were very abrupt, occurring within decades to centuries.

14.8 and 5.5 cal. ka BP (*) associated with the African Humid Period.

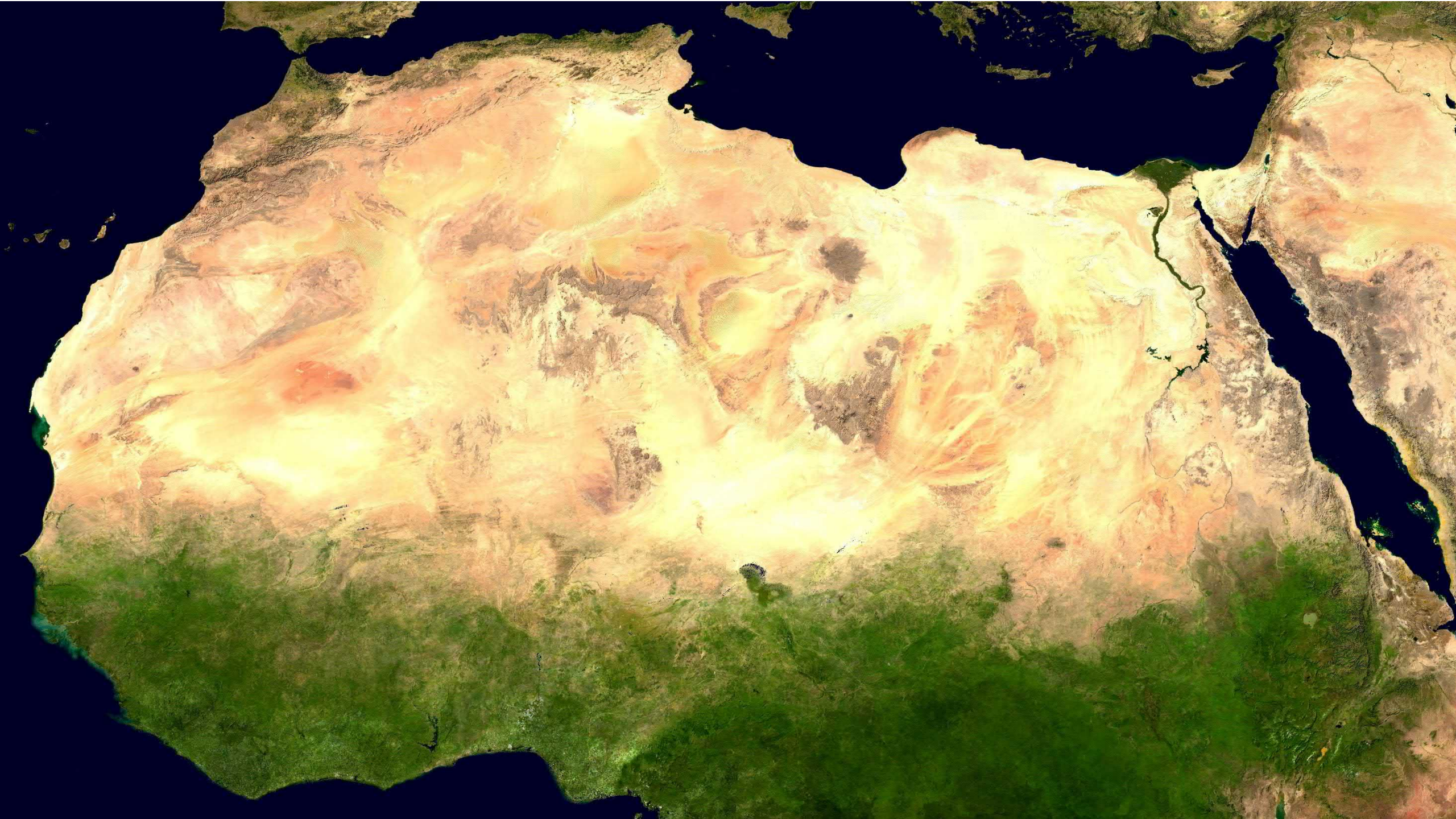
The onset and termination of this humid period were very abrupt, occurring within decades to centuries.





* 12,800-3,500 BCE

Nato Advanced Research Workshop, Kemer, 9/1994

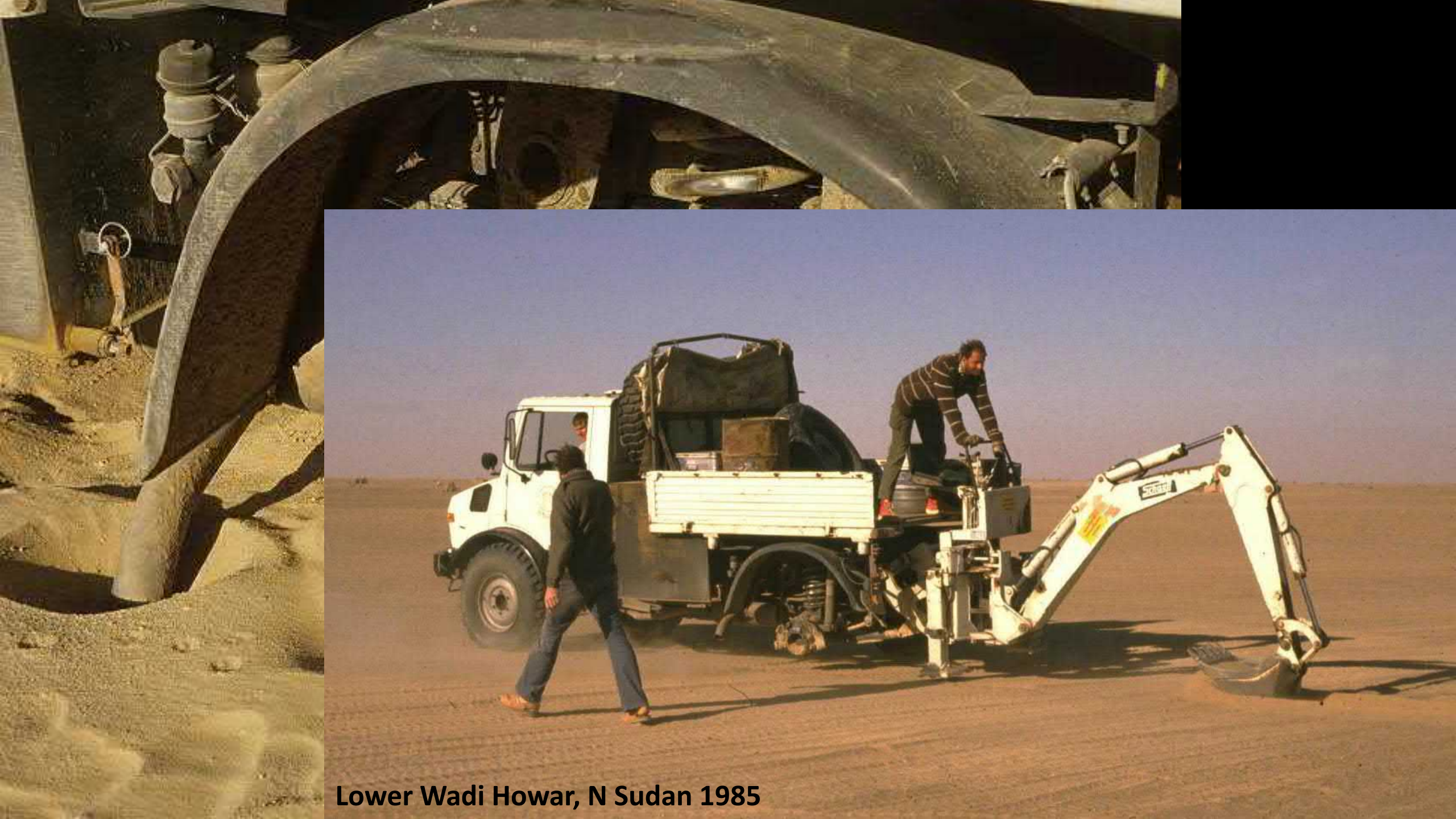


Sahara - USA

(~9 mio km²)

Hamada south of Laqiya, N Sudan 1983


Tieroko, Tibesti, NW Chad 2016



Lower Wadi Howar, N Sudan 1985

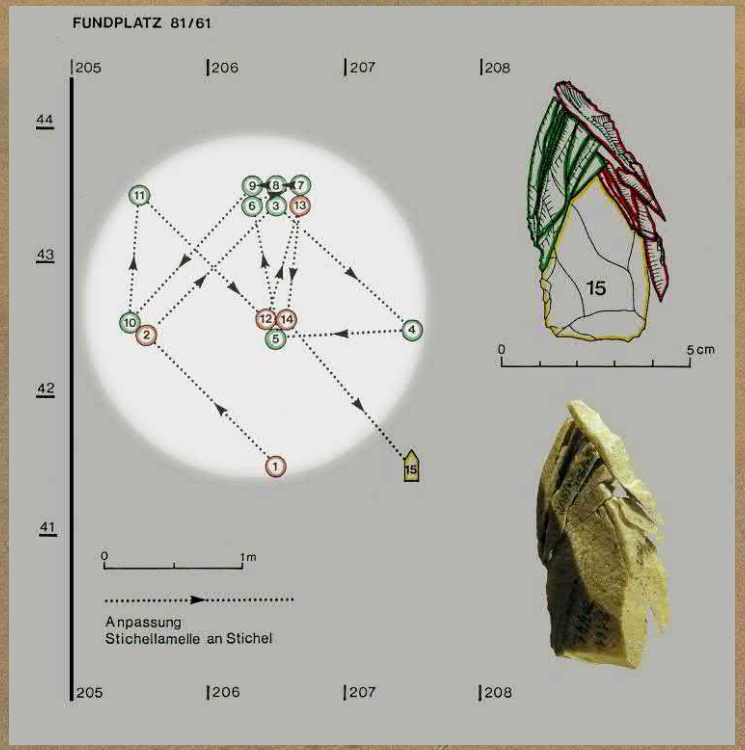
Emi Koussi, Tibesti, NW Chad 2015

Era Kohor, Emi Koussi, Tibesti, NW Chad 2016

Mourdi, N Chad 2003

Great Sand Sea, SW Egypt (1996)

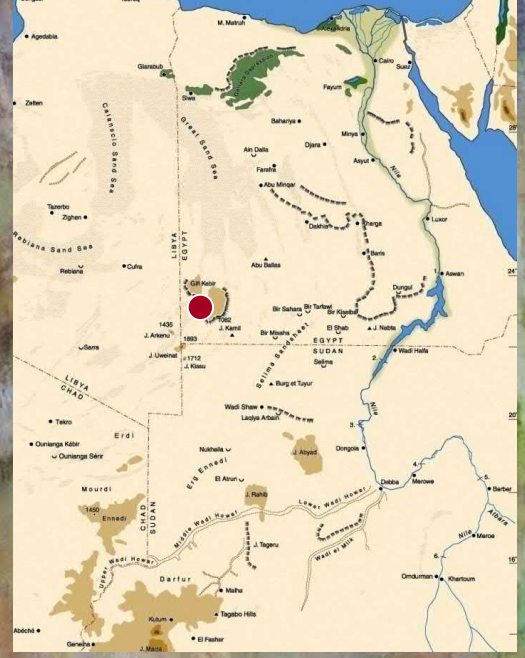
Great Sand Sea, SW Egypt, 24.5° N (1995)



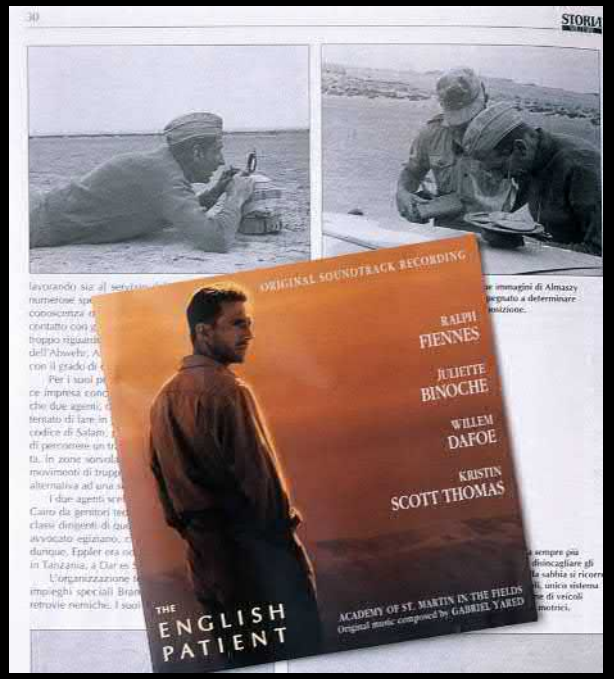
Great Sand Sea, SW Egypt 1981

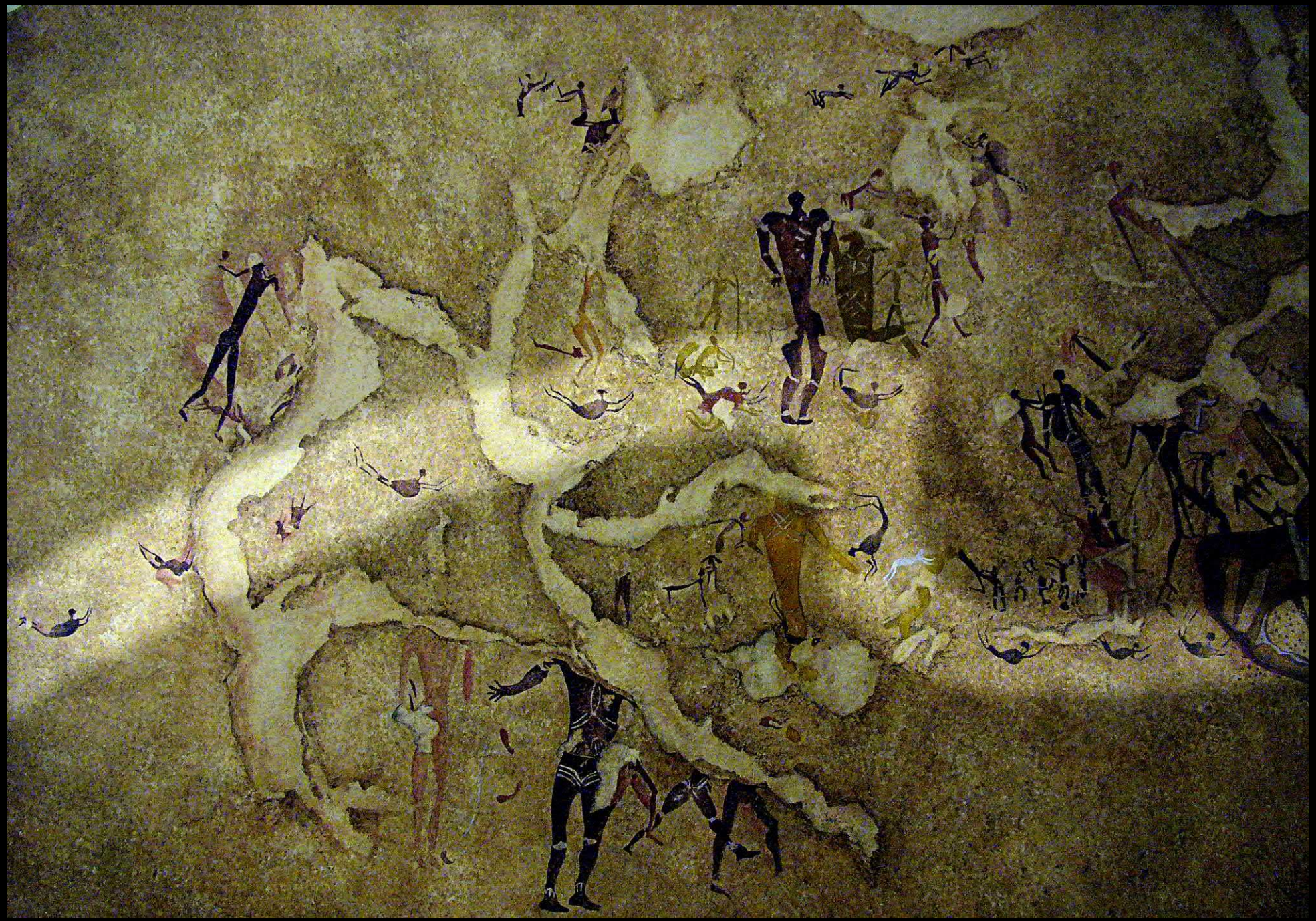
Early Wadi Shaw, NW Sudan, 7800-5600 BCE (1983)

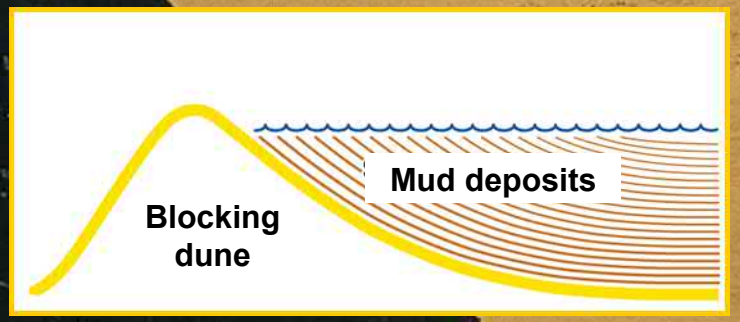
Gilf Kebir Plateau
SW Egypt
(23°N)




DER ENGLISCHE PATIENT


ORIGINAL SOUNDTRACK RECORDING
RALPH FIENNES
JULIETTE BINOCHE
WILLEM DAFOE
KRISTIN SCOTT THOMAS
THE ENGLISH PATIENT
ACADEMY OF ST. MARTIN IN THE FIELDS
Original music composed by GABRIEL YARED





Wadi Bakht, Gilf Kebir

Wadi Bakht, Gilf Kebir
SW Egypt, Tropic of Cancer

Kröpelin,
Palaeoecol. Africa 18 (1987),
Africa Praehistor. 2 (1989),
Catena Suppl. 26 (1993),
Africa Praehistor. 18 (2005), etc;
Linstädter & Kröpelin,
Geoarchaeology 19 (2004)

ANTIQUITY
a review of world archaeology
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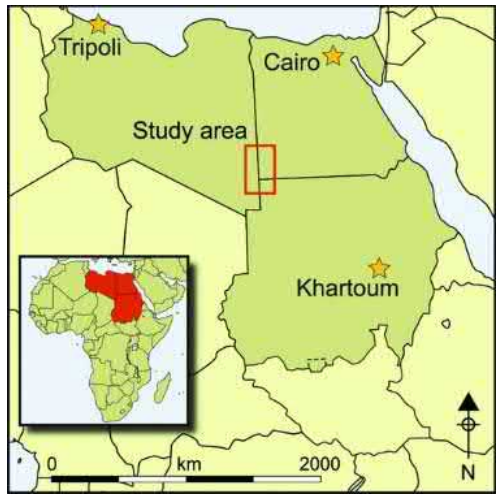

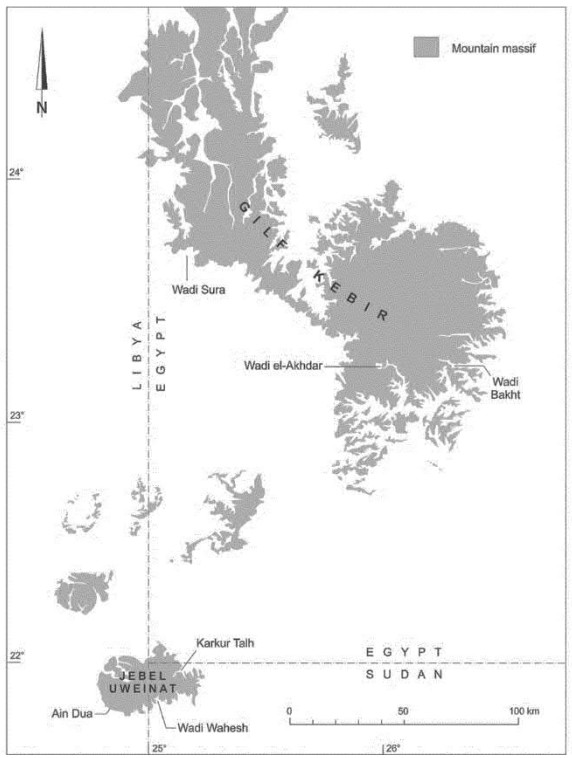

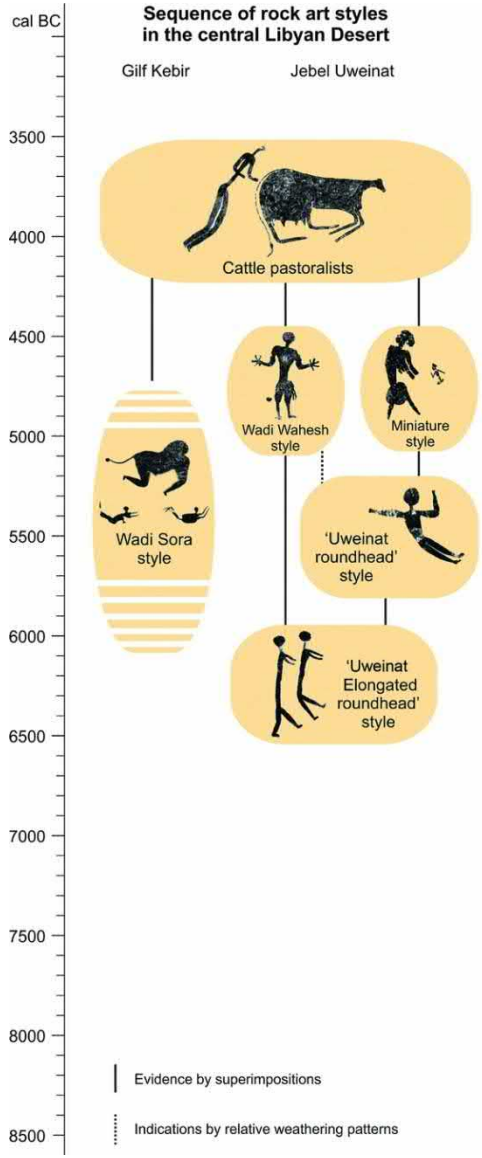

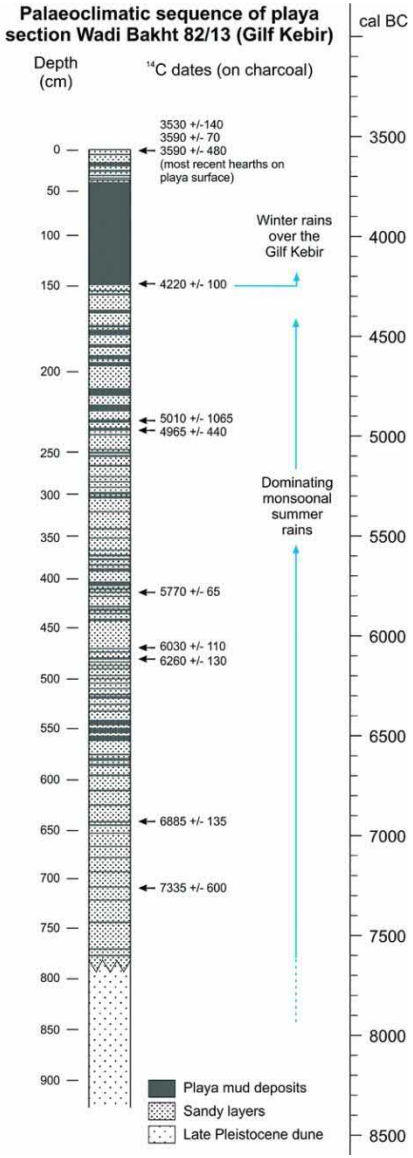

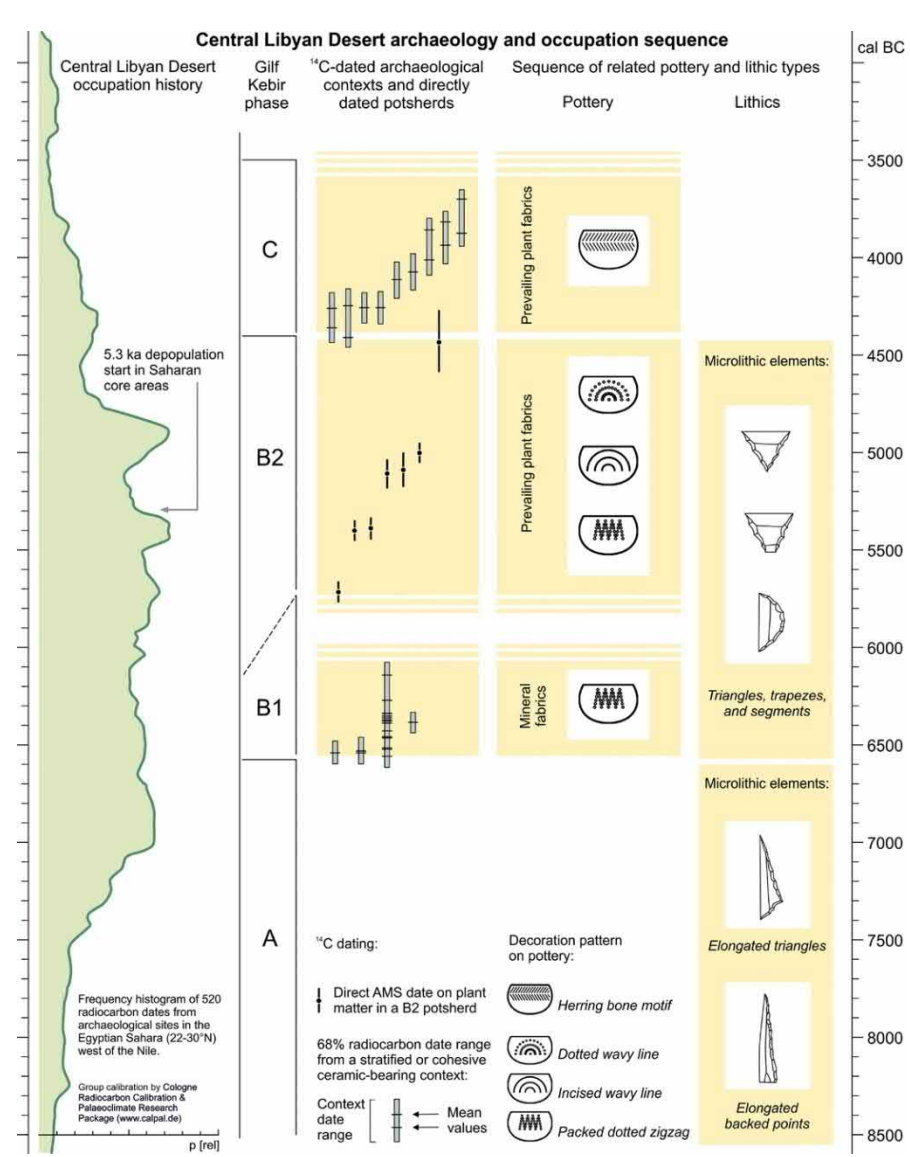

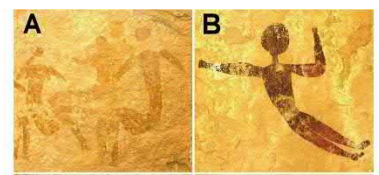

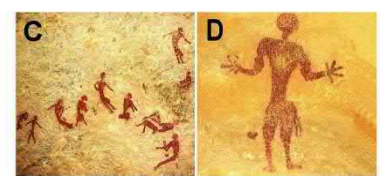

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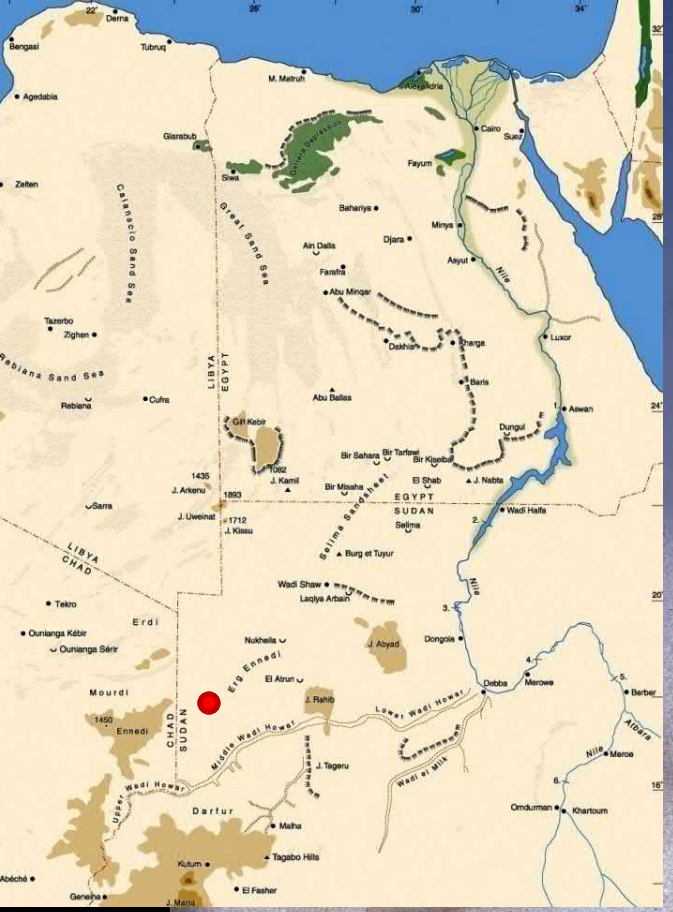

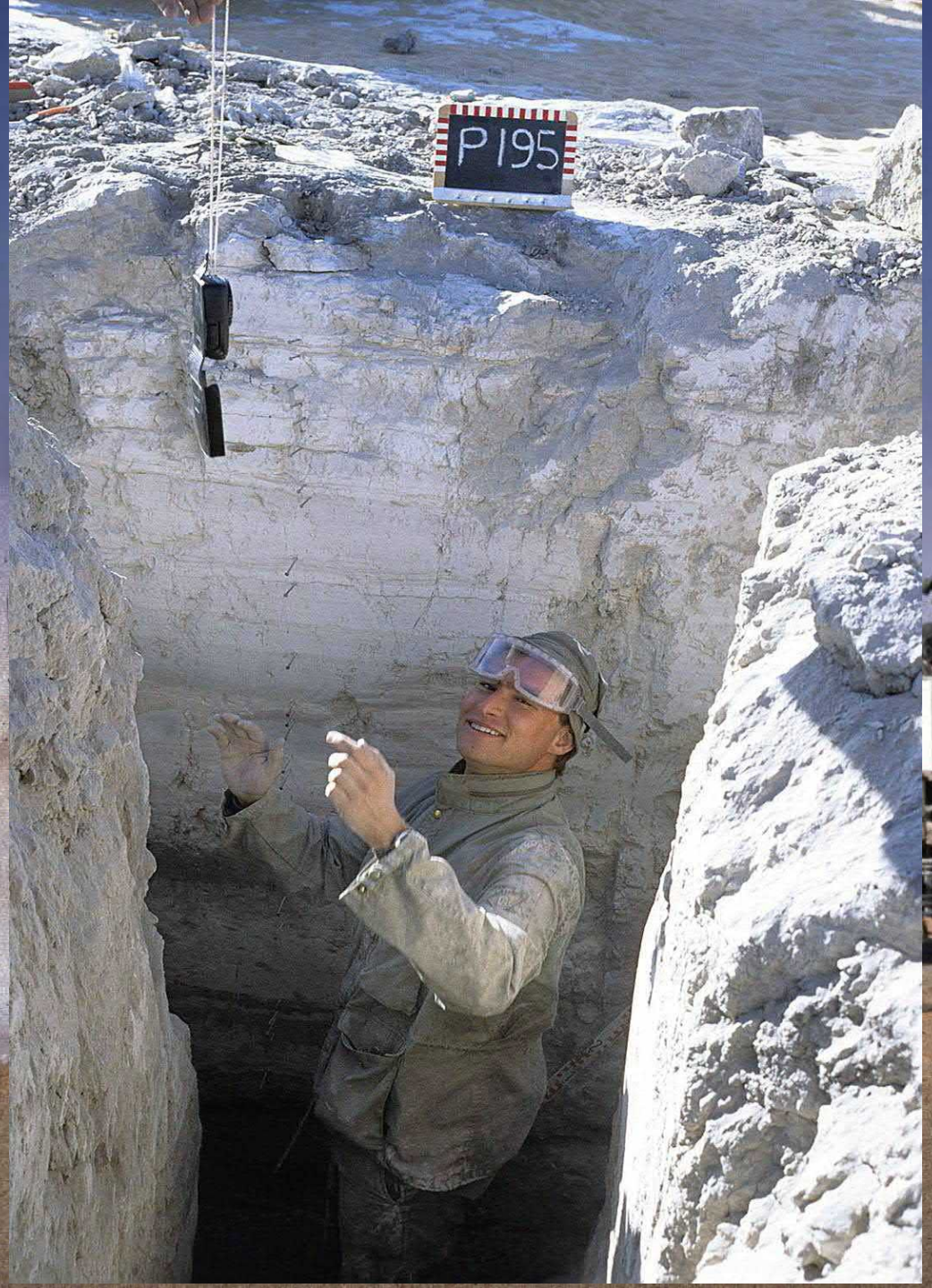

West Nubian Paleolake NW Sudan, 1985

West Nubian Paleolake
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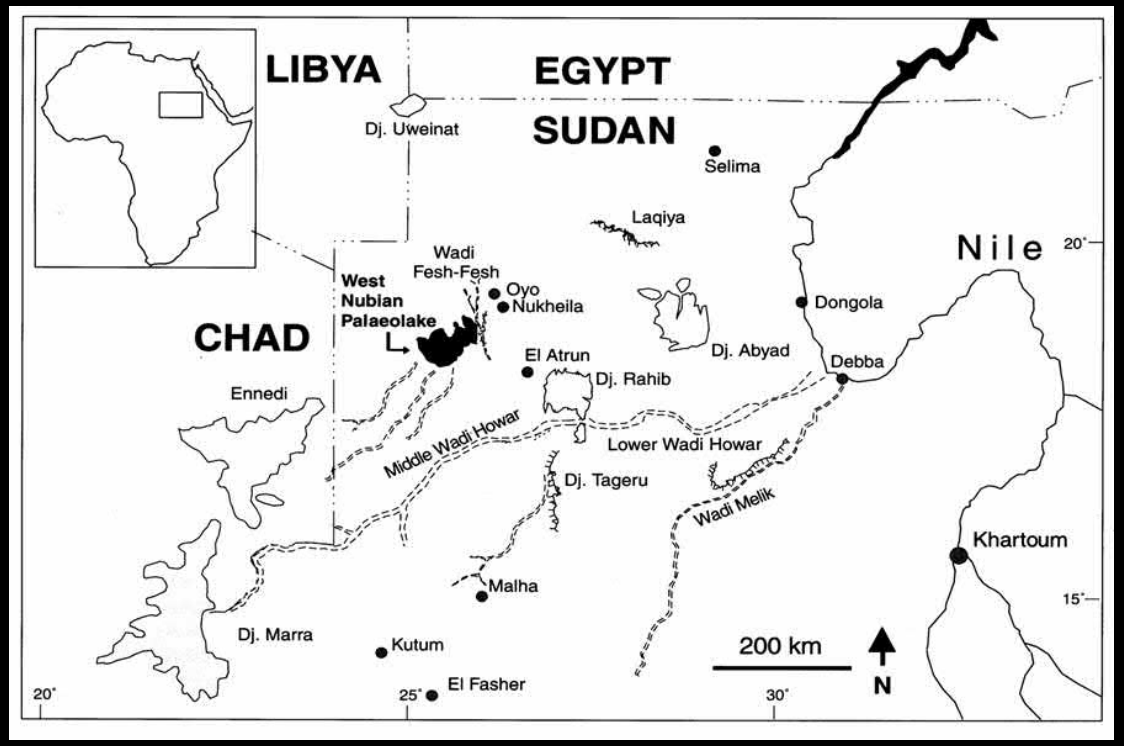

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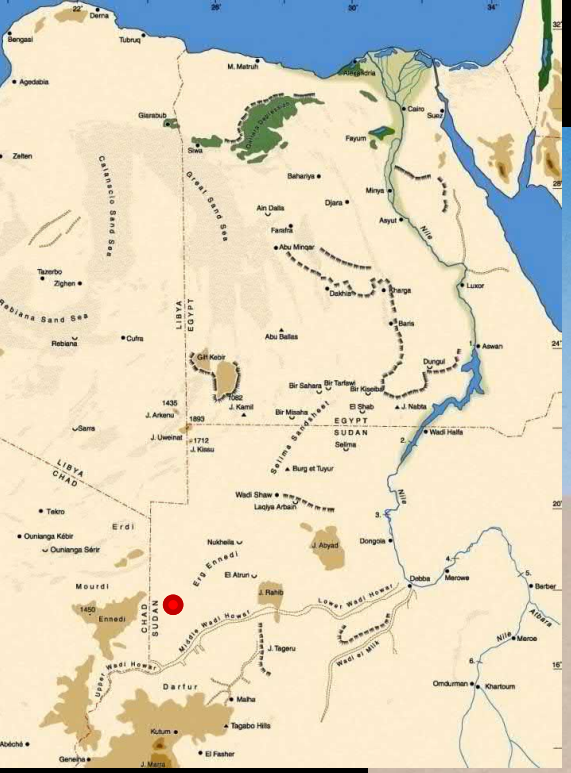


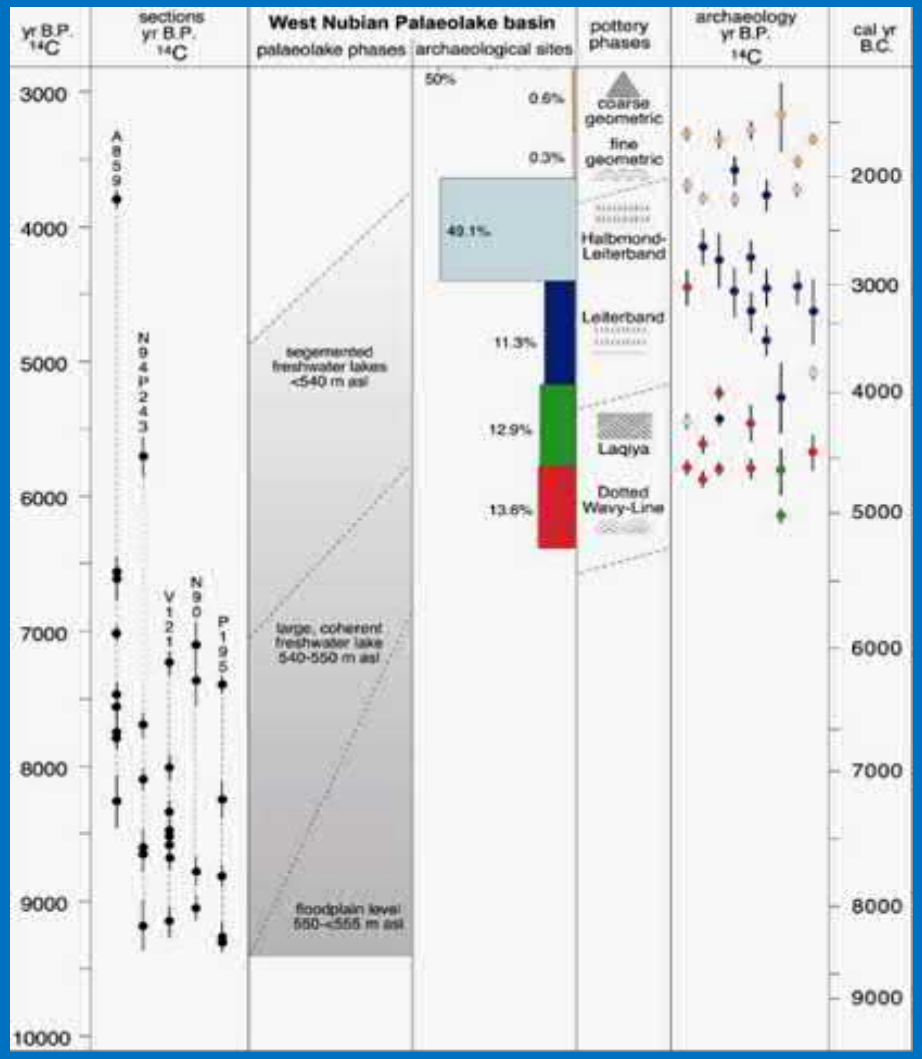
West Nubian Paleolake, NW Sudan

17° N - 25° E

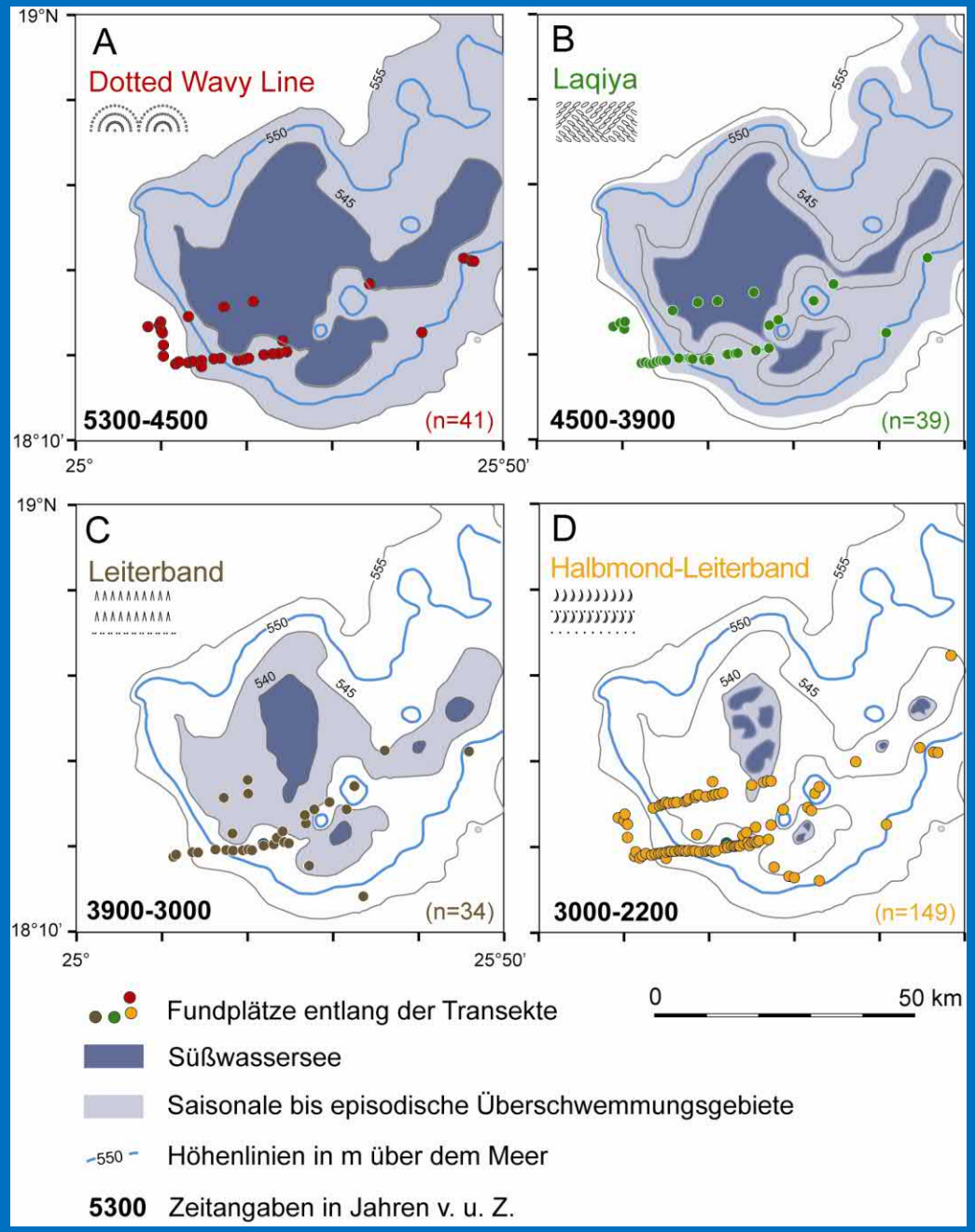
(1995)

Neolithic site at former shore of West Nubian Paleolake (1995)

Environmental change and archaeology: Lake evolution and human occupation



(Hoelzmann, Keding, Berke, Kröpelin & Kruse, Palaeo3, 2001)



(Kröpelin, *Nova Acta Leopoldina* 108, 2009)

The Lower Wadi Howar (17-18° N): once the Nile's largest tributary from the Sahara

Wadi Howar: Paleoclimatic Evidence from an Extinct River System in the Southeastern Sahara

H.-J. PACHUR AND S. KRÖPELIN

Field research into the climatic history and shifting of the East Saharan desert has furnished evidence that during Quaternary time the present extremely arid western part of Upper Nubia (northern Sudan) was temporarily linked to the Nile by way of a hitherto unknown 400 kilometer long tributary. From about 9500 to 4500 years ago, lower Wadi Howar flowed through an environment characterized by numerous ground water outlets and freshwater lakes. Savanna fauna and cattle-herders occupied this region, which today receives at most 25 millimeters of rainfall per year. At that period the southern edge of the eastern Sahara was some 500 kilometers further north than today and ground water resources were recharged for the last time.

DURING THE PAST 10 YEARS PALEOclimatic research undertaken in the eastern Sahara has revealed the existence of two major late Pleistocene to mid-Holocene drainage networks that once interrupted the state of internal drainage of this vast region. One network is a 800 km long watercourse in eastern Libya (*1*). This drainage system, however, might have been influenced by increased rainfall in the Tibesti Mountains, which cover an area of some 100,000 km^2 at an average elevation of 2000 m above sea level. For this reason, further fieldwork was conducted in the expanses between the Great Sand Sea of Egypt and the Sahel zone in northern Sudan, which have an elevation of only 500 to 600 m and are located far away from any high mountains (Fig. 1b). The investigations yielded evidence on another major relict drainage system in the southeastern Sahara: lower Wadi Howar.

Wadi Howar issues from the mountainous region between Gebel Marra and Ennedi and traverses the southern fringe of the Sahara for a length of 640 km. All topographic maps of the area show the end of the wadi bed at 17°30′N and 27°25′E south of Gebel Rahib. Here the wadi is already defunct and its course is marked only by linear tree vegetation, sustained by a ground water table some 6 to 10 m below the surface (*2*). Speculations on a possible eastward connection to the Nile during the Tertiary (*3*) and interpretations of satellite imagery (*4*) were verified by ground checks. Evidence was found that the lower Wadi Howar drained this 400 km wide area (present rainfall, 25 mm/year) and entered the Nile between the third and fourth cataracts, opposite Old Dongola (*5*). Thus, Wadi Howar constituted the largest tributary to the Nile from the Sahara between the Mediterranean Sea and the Atbara River, with a length of more than 2700 km.

At Rahib the former riverbed is blocked by a 15-m high and 5-km wide dune barrier (Fig. 1a, locality 3). It overlies a sequence of sandy pebbly alluvium, fossiliferous lake marl, cross-bedded dune sand, and calcrete. The lacustrine deposits at the base gave a radiocarbon date of 9430 ± 85 years ago (Hv 12380), indicating high variability in climate and geomorphology during the early and middle Holocene in this region.

Further to the east the lower Wadi Howar crosses a peneplain with numerous granite outcrops capped by lacustrine calcretes at the old wadi banks. This section, stretching about 185 km, consists of a series of interconnected shallow depressions, which display fossil lake beds up to 10 km in diameter and dated at 5640 ± 70 and 7260 ± 70 years ago (Hv 14434 and Hv 14438) (Fig. 1a, localities marked 4). These deposits indicate pools remaining on the floodplain of the wadi after seasonal flooding and thus enabling an occasional overflow of one sheet

Special Research Project Arid Areas, Department of Physical Geography, Geomorphological Laboratory, Free University, D-1000 Berlin (West) 41, Germany.

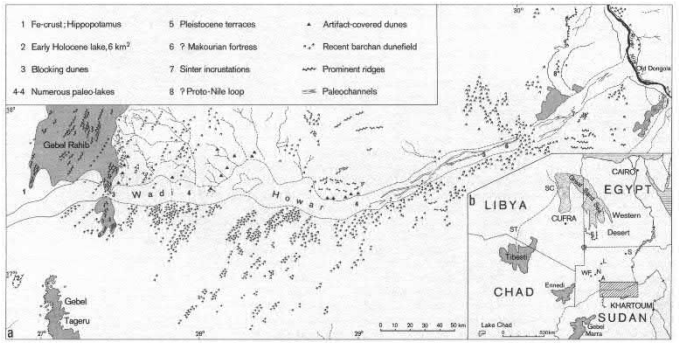


Fig. 1. (**a**) Generalized topographic map of the lower Wadi Howar showing reconstructed paleodrainages and selected features (source of data, LANDSAT imagery and field investigations). (**b**) Outline map of the eastern Sahara indicating mapped area and other localities mentioned in text. ST, Serir Tibesti; SC, Serir Calanscio; S, Selima; L, Laqiya Arbain; WF, Wadi Feshfesh; N, Nukheila; and A, El Atrun.

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semilacustrine sediments provided a radiocarbon age of 3825 ± 115 years (Hv 14433). Lacustrine deposits, however, dated at 6580 ± 100 years ago (Hv 14429), mostly occur as erosional remains on the gentle slopes suggesting subsequent fluvial activity.

Over the last 70 km Wadi Howar approaches the Nile Valley at an apparent low gradient and with no indication of any major incision. Above the level of the Late Quaternary deposits, however, a presumed Proto-Nile riverbed (*9*) has been identified 50 km west of the present-day river (Fig. 1a, locality 8). Its glaring white mantle of quartzose gravels stands out both in the field and on satellite imagery. This probably early Pleistocene Nile loop was as much as 10 km wide and 60 km long. Its chronological position constitutes a maximum age for the major fluvial erosion cutting the banks of the 12 km wide floodplain before the junction with the Nile.

The concept of Wadi Howar as an indicator of a significant shift in the rainfall regime of the eastern Sahara is valid only if proof can be furnished that its lower course was not an exotic river like the modern Nile—that is, a teleconnection from the headwaters, but was fed by substantially increased local rainfall. The following evidence supports this point of view. In the near vicinity of the wadi (Fig. 1a, locality 2) the groundwater table rose considerably, causing the formation of a lake more than 6 km^2 in area; its lake chalk contains both freshwater Mollusca and Ostracoda and was radiocarbon dated to 9195 ± 95 years ago (Hv 13563) at the base and 7985 ± 90 years ago (Hv 13564) at the top. The close network of now defunct tributary wadis with broad gravel belts east of Gebel Rahib likewise points to paleo-discharge characteristics essentially different from those of today. Further evidence is the formation of 50 m wide calcareous sinter incrustations above the wadi bank with a radiocarbon age of 7825 ± 100 years (Hv 13565); they were supplied by springs fed by infiltrated local rainfall (Fig. 1a, localities 7).

Furthermore, the 12-m rise in the water table at El Atrun, 90 km to the north (Fig. 1b), could not have been induced by the upper Wadi Howar. Giraffe bones in the lake chalk were dated at 7370 ± 80 years ago (Hv 13566). The ferrous sulfite–bearing lake mud, laminated at the base and dated at 9180 ± 200 years ago (UZ 2270), is more than 7 m thick at the deepest part of the basin; hence, the lake was probably deeper than 19 m. Also, extensive field studies in February 1985 and January 1986 revealed a 180 km long relict drainage network west of Nukheila Oasis (Wadi Feshfesh, Fig. 1b) that was fed by local rainfall. A more than 10 km wide basin belonging to this ancient river valley contained a continuous sequence of 3 m thick calcareous diatomite with radiocarbon ages of 7780 ± 90 years at the base and 3805 ± 65 years at the top (Hv 14446 and Hv 14441). This inner Saharan archipelago of brackish to freshwater lakes was possibly linked to the Mourdi depression (*10*).

At Nukheila, only 40 km east of this Holocene river, rhinoceros bones were found in lacustrine marls (*11*). The lake marl terrace here is located 6 m above the present level of the hypersaline ground water fed–lake. The pollen-bearing algal muds of the Oyo complex (*12*) also belong to this archipelago of early to mid-Holocene lakes and correspond to those at El Atrun and Selima. The latter existed between about 9200 and 4500 years ago (*13*). Finally, the fossiliferous lake chalk sequences 80 km northwest of Laqiya Arbain dated between 7500 and 6500 years ago fit into this picture (*14*).

It is now clear that there is substantial evidence of a rainfall regime supporting an early Holocene ground-water recharge and that this evidence culminates in the lower Wadi Howar (18°N). It was surrounded by the early Holocene Sahel zone, which stretched about 500 km further north than today. Since the number of paleoclimatic indicators decreases northward of Wadi Howar, we conclude that rainfall was due to tropical influences from the south. These findings show parallels to paleoclimatic evidence from the central and western Sahara. Lake Chad (14°N) as well as the Mali lakes (21°N) record high levels and humid phases between 9500 and 4500 years ago (*15*, *16*).

The extreme summer aridity (*17*) of the Sahara was suspended in early Holocene time. At present it is due to the sinking air masses in the delta of the tropical easterly jet stream, which in turn is caused by high summer temperatures in the central Asian mountains. Should the proposal of a persistent glaciation in the Tibetan mountains during the early Holocene prove correct (*18*), summer paleorainfall in the eastern Sahara could be explained by a continuing weakening of the easterly jet stream.

Table 1. Vertebrate and invertebrate taxa identified from sites and sections of Holocene age in the lower Wadi Howar between Gebel Rahib and Nile River, Northern Sudan.

T

Sa
Addax nasomaculat
Alcelaphus buselaph
Arricanthis niloticus
Bos sp. (big bovide
Bubalus bubalis (bu
Bufo regularis (toad
Crocodylus sp. (croc
?Dicerorhinus bicornis (bl
Equus africanus (wi
Gazella dorcas (dor
Geochelone pardalis
Giraffa camelopardal
Hippopotamus amph
?Hippotragus equinus
Hippotragus equinus
Loxodonta sp. (elep
Phacochoerus aethiop
Struthio camelus (os
Tragelaphus sp. (an
Do
Bos primigenius (do
Capra aegragus (go
Ovis ammon (sheep
Gastropo
Anisus dallonii
Biomphalaria pfeiffe
Bulinus forskali
Bulinus truncatus
Cleopatra bulimoide
Gabbiella senaarien
Gyraulus costulatus
Lanistes carinatus
Lymnaea natalensis
Melanoides tuberculi
Pila wernei
Segmentorbis angust
Valvata nilotica
Gastrop
Curvella sp.
Gastrocopta sp.
Helicidae sp.
Limicolaria flammea
Streptostele sp.
Succinea sp.
Succinea oblonga
Vertigo antivertigo
Zonitoides nitidus
Zootecus insularis
Bivalvi
Aspatharia arcuta
Aspatharia rubens
Caelatura aegyptiac
Corbicula fluminalis
Mutela nilotica
Ostrac
Candona sp.
Cyprideis sp.
Cypris sp.
Darwinula sp.
Encypris sp.
Heterocypris sp.
Metacypris sp.
Strandesia sp.

*Savanna and dome
mann, Tübingen.
§Gastropoda and Biva
dorf. ‖Ostracoda:

REFERENCES AND NOTES

1. This Holocene wadi flowed across Serir Tibesti in southern Libya (present rainfall, 2 mm/year) into Serir Calanscio (present rainfall, 20 mm/year) (Fig. 1b). Along its course calcitic lake deposits, radiocarbon dated to 8800 to 5000 years ago, were formed in freshwater lakes. In Egypt's Western Desert however (1 to 2 mm of annual rainfall), silty clayey semi-lacustrine sediments prevail in deflation hollows at numerous sites, mainly at the base of escarpments, during the period between 10,000 and 4,000 years ago; this reflects a west to east decrease in rainfall at a latitude of 28°N in the early Holocene. See H.-J. Pachur, *Berl. Geogr. Abh.* 17, 62 (1974); C. V. Haynes, in *Desert Landforms of Southwest Egypt: A Basis for Comparison with Mars*, F. El-Baz, T. A. Maxwell, Eds. (NASA CR-3611, Washington, DC, 1982), p. 91.
2. K. S. Sandford, *Geogr. J.* **85**, 412 (1935).
3. D. Newbold, *Sudan Notes Rec.* **7**, 43 (1924); R. Said [in *The Geological Evolution of the River Nile* (Springer, New York, 1981)] does not even preclude the Wadi Howar as a possible source of the late Pliocene Paleonile about 2 to 4 million years ago.
4. Geological Map of the Sudan 1:2,000,000 (BRGM, Orléans, 1981); B. Meissner and H.-J. Schmitz, *Berl. geowiss. Abh. (A)* **47**, 87 (1983). The region under discussion here was not covered by the Columbia Shuttle Imaging Radar (SIR-A) which revealed subsurface valleys in the Selima Sand Sheet about 400 km further north [J. F. McCauley *et al.*, *Science* **218**, 1004 (1982)].
5. The capital of the Early Christian kingdom of Makouria about A.D. 550. On the south bank of Wadi Howar, 150 km west of the Nile, there is a hitherto unknown rectangular fortress about 150 m in diameter with stone walls more than 5 m thick, discovered in 1984 by an archeological expedition from the University of Cologne. We could fix the location by satellite Doppler positioning at 17°48′24″N, 29°59′18″E (Fig. 1a, locality 6). The locations of the capital and this fortification indicate the importance of the lower Wadi Howar as a transit route to Chad as late as the sixth century A.D.
6. It must be emphasized that some of the skeletons found were not buried, but embedded in the completely undisturbed sediment. For that reason death may have been accidental, possibly due to drowning.
7. B. Gabriel, S. Kröpelin, J. Richter, E. Cziesla, *Geowiss. unserer Z.* **3**, 105 (1985).
8. Charophyta were identified by I. Soulié-Märsche, Montpellier.
9. K. W. Butzer and C. L. Hansen, *Desert and River in Nubia* (Univ. of Wisconsin Press, Madison, 1968).
10. The Ptolemaic world map (about A.D. 150) shows marshes inhabited by tortoises in this region. Actually we found tortoise and giraffe remains in calcareous mud deposits reaching thicknesses of about 3 m and containing freshwater Mollusca and Ostracoda.
11. H.-J. Pachur and H.-P. Röper, *Berl. geowiss. Abh. (A)* **50**, 249 (1984).
12. J. C. Ritchie, C. H. Eyles, C. V. Haynes, *Nature (London)* **314**, 352 (1985).
13. The early Holocene lake at Selima was 14 m deep and occupied an area of more than 11.5 km^2. There is a complete sedimentary sequence ranging from lake sands, algal mud, freshwater chalk, rhythmites, aragonitic lake chalk, and diatomite to sulfatic, highly saline sediments.
14. B. Gabriel and S. Kröpelin, *Palaeoecol. Africa* **16**, 295 (1984).
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19. R. Kuper, *Beitr. Allg. Vgl. Archäol.* **3**, 215 (1981).
20. The investigations were sponsored by the Deutsche Forschungsgemeinschaft and the Free University of Berlin within the framework of the Special Research Project "Geoscientific Problems in Arid Areas." We wish to acknowledge the help given us by the Sudanese colleagues from the Geological and Mineral Resources Department, Khartoum. Fieldwork in Egypt was carried out under the auspices of the General Petroleum Company, Cairo. Special thanks are due to M. A. Geyh, Hannover, for radiocarbon dating. Furthermore, we thank B. Gabriel, Berlin, and R. Said, Washington, DC, who read the manuscript and made useful suggestions.

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Technical Comments

Neuronal Coding and Robotics

Apostolos P. Georgopoulos *et al.* (*1*) present a study of neuronal coding of direction of arm movements in monkeys. They show that a group of neurons exist in the motor cortex which have firing rates that can be combined vectorially to predict the direction of arm movement.

In robotics, an analogous problem exists, called kinematic inversion (*2*). The issue is to decide how to drive the motors of a robot arm so as to drive the hand in a particular direction in Cartesian coordinates. The problem is interesting because the individual joint actuators do not contribute uniquely to any one Cartesian direction. Instead, their contributions are "broad" in the sense of (*1*): several motors contribute to motion along a single Cartesian direction. Furthermore, each motor must, in general, vary its contribution during a motion because the geometric relations between single motor contributions and ultimate hand direction vary as the arm moves and changes shape.

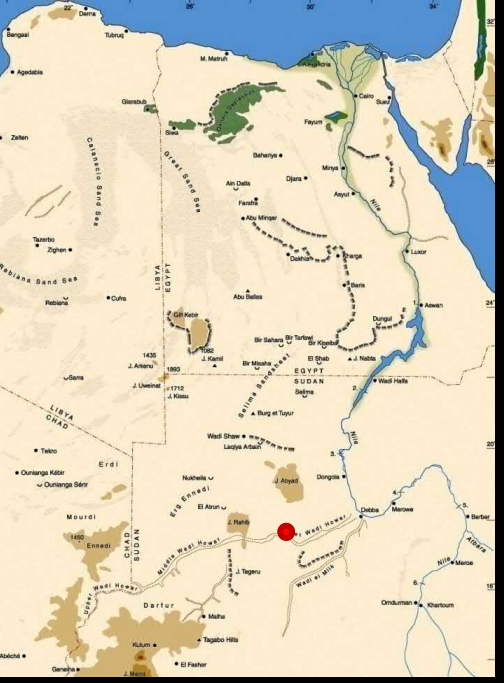
To be more precise, the problem in (*1*) is called the velocity control problem in robotics, wherein the controller must choose velocities for the joint actuators in order to obtain a velocity vector for the hand in Cartesian coordinates. This Cartesian velocity vector corresponds to vector $\mathbf{M}$ in (*1*). This problem was solved (*3*), as follows: Let X represent a position and V a velocity, respectively, in Cartesian space. Let Θ represent a vector of arm joint positions and Ω a vector of arm joint velocities. We say that Θ and Ω exist in joint coordinates. Then V and Ω are related by

$$V = J(\Theta)\,\Omega \qquad (1)$$

where J is called the Jacobian matrix of the arm and consists of partial derivatives of Cartesian axis motions with respect to joint axis motions. In general, J is 6×6 because Cartesian motions comprise three translations and three rotations, and arms able to make such motions must have at least six joints. The velocity control problem is solved by writing

$$\Omega = J^{-1}(\Theta)\,V \qquad (2)$$

The robot's control computer takes in V commands, reads Θ, calculates J and J^{-1}, and finally calculates Ω and sends it to the motors as individual command velocities.



The Lower Wadi Howar (17-18° N): once the Nile's largest tributary from the Sahara

Wadi Howar: Paleoclimatic Evidence from an Extinct River System in the Southeastern Sahara

H.-J. PACHUR AND S. KRÖPELIN

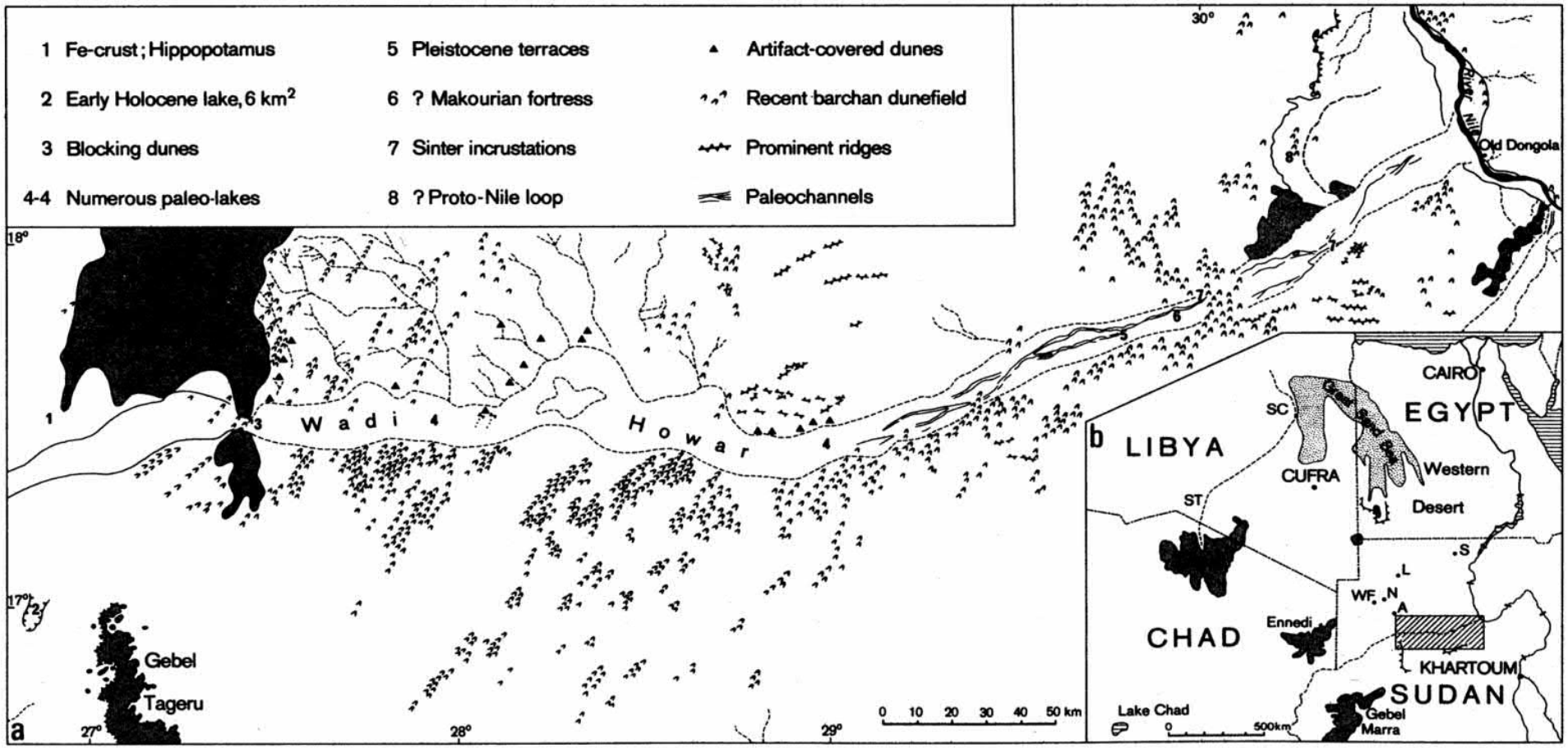


Fig. 1. (**a**) Generalized topographic map of the lower Wadi Howar showing reconstructed paleodrainages and selected features (source of data, LANDSAT imagery and field investigations). (**b**) Outline map of the eastern Sahara indicating mapped area and other localities mentioned in text. ST, Serir Tibesti; SC, Serir Calanscio; S, Selima; L, Laqiya Arbain; WF, Wadi Feshfesh; N, Nukheila; and A, El Atrun.

Lower Wadi Howar

Jabarona 84/13, Middle Wadi Howar

New petroglyph sites in the Southern Libyan Desert (Sudan-Chad)

*Stefan Kröpelin**

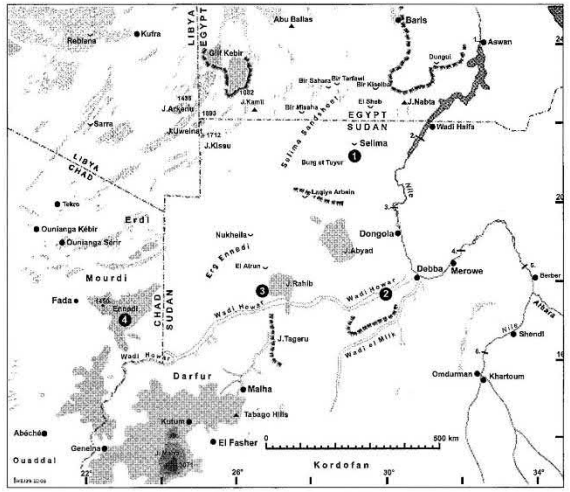
ng the annual geoscientific missions in the Eastern Sa- of Western Egypt, Northwest n and Northeast Chad con- ed since the early 1980s, a ber of rock art sites have observed which were not re- ed before. Some examples Sudan, where rock art is rel- ly scarce with the exception bel Uweinat, and Chad shall ortly presented here.

Selima

so-called «Dry Selima» is a tional depression beneath an rpment about 60 km south of na oasis, in the far north of n. We named it that way be- e of its vicinity to Selima, the lack of a well or near- ace groundwater and any tation (Fig. 1). Surprisingly gh, Dry Selima remained oticed until 1990 although airy-tale oasis of Selima was yn to Europeans at least e Charles Poncet's and the rian Pater Krump's visits in /1700. Maybe the powdery esh that covers the southern slope of the depression prevented camel people and vehicle drivers to proceed to the site.

According to the geological evidence, consisting of 4 metres of thinly laminated diatomaceous sediments, a relatively large groundwater-supported freshwater lake existed here during the early Holocene humid phase about 8970-6700 BP (Pachur and Wünnemann, 1996). It filled the lower parts of the wind-carved basin, which is dissected by elon-

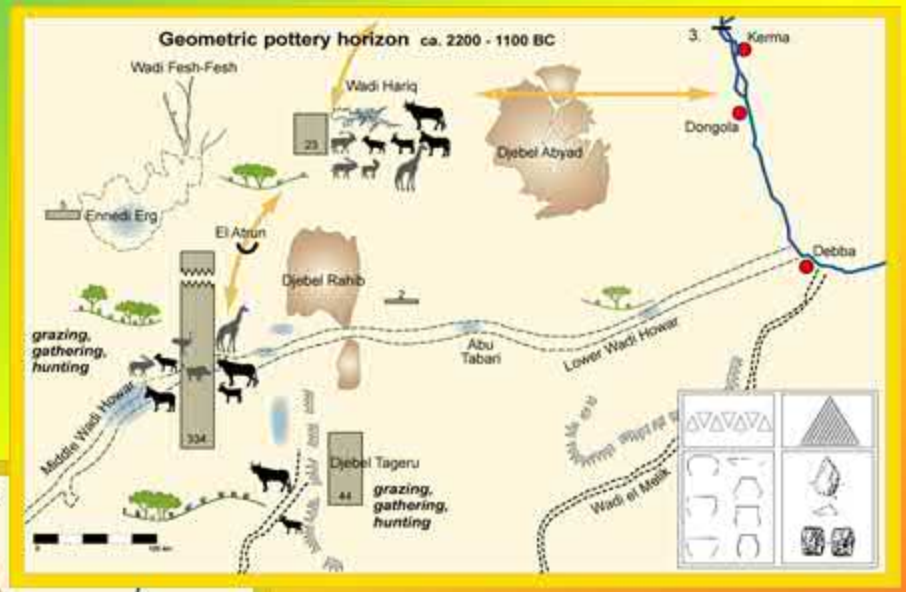
Fig. 1. Map of the Southern Libyan Desert with location of rock art sites. (1) Dry Selima, (2) Lower Wadi Howar, (3) Zolat el Hammad, (4) Central Ennedi.



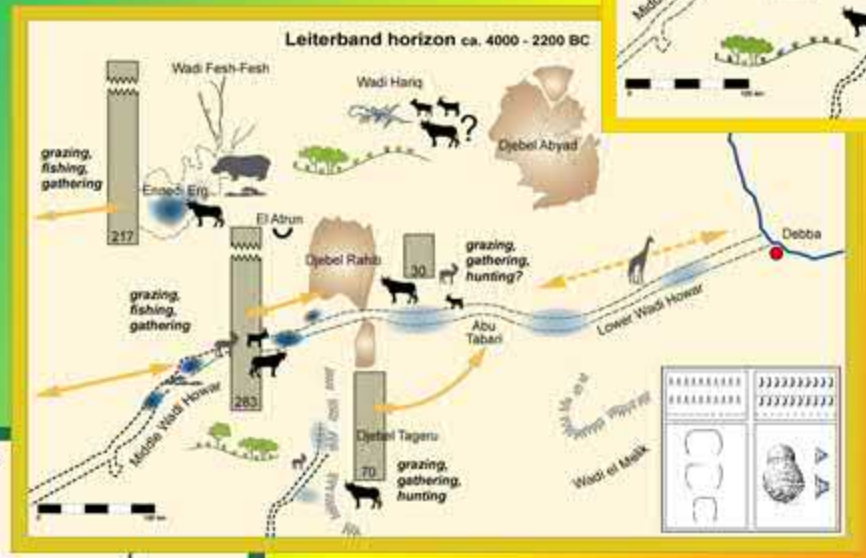
*Collaborative Research Project ACACIA
Universität zu Köln
Jennerstr. 8
D-50823 Köln

Zolat el Hammad, Wadi Howar, ca. 8000 BCE

Environmental change and prehistoric settlement in the Wadi Howar region from 5200 to 1100 BCE



2200 -1100 BCE



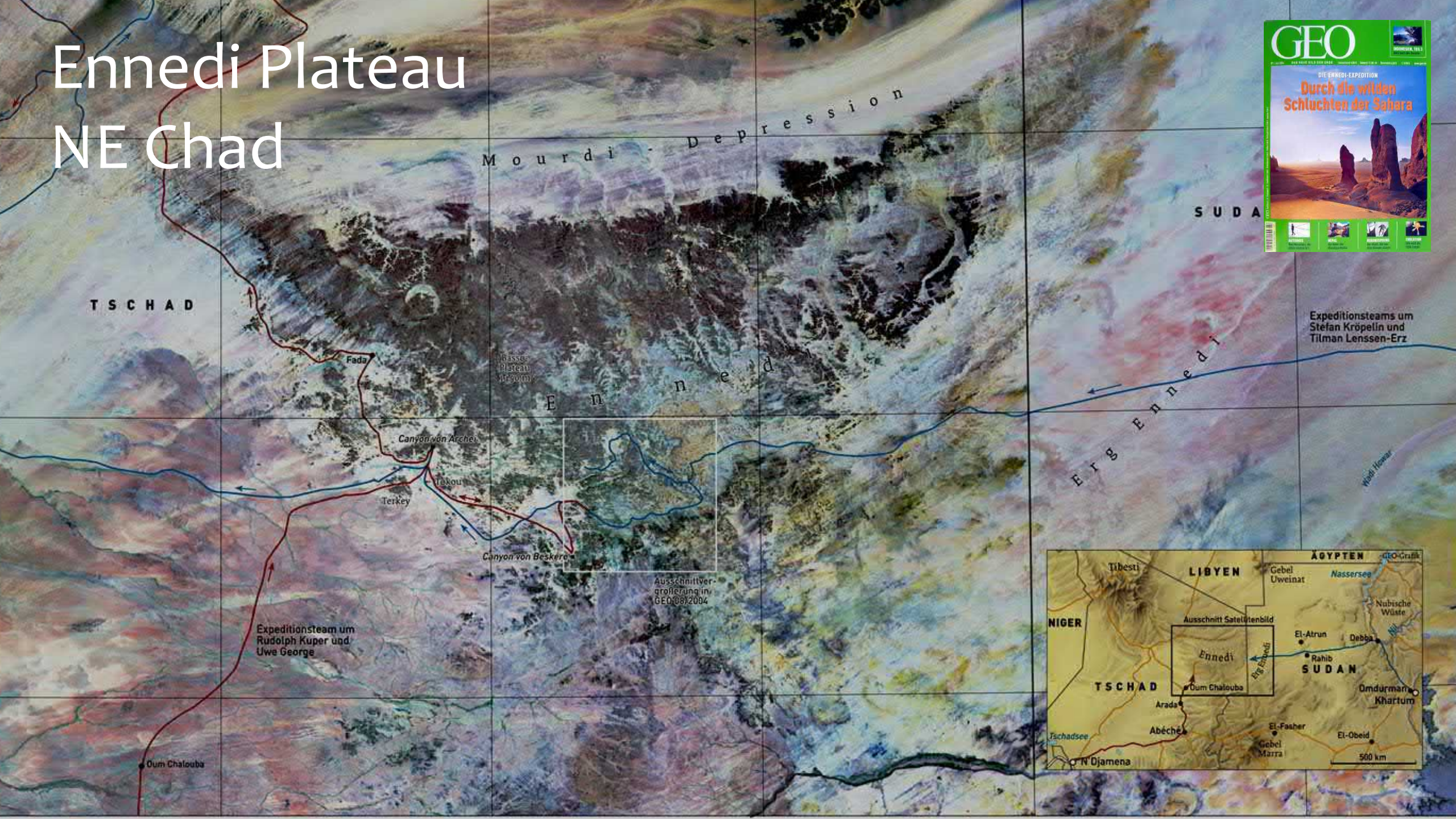
4000 - 2200 BCE

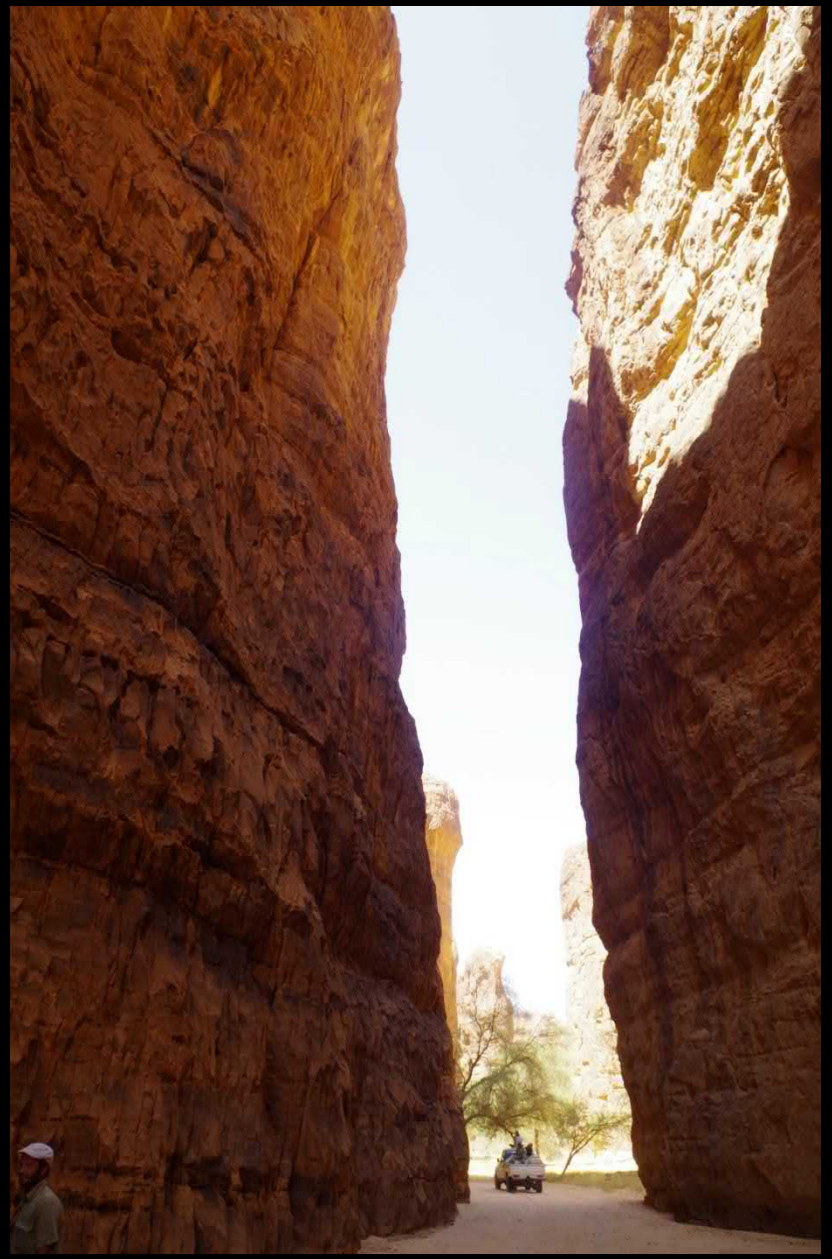
5200 - 4000 BCE

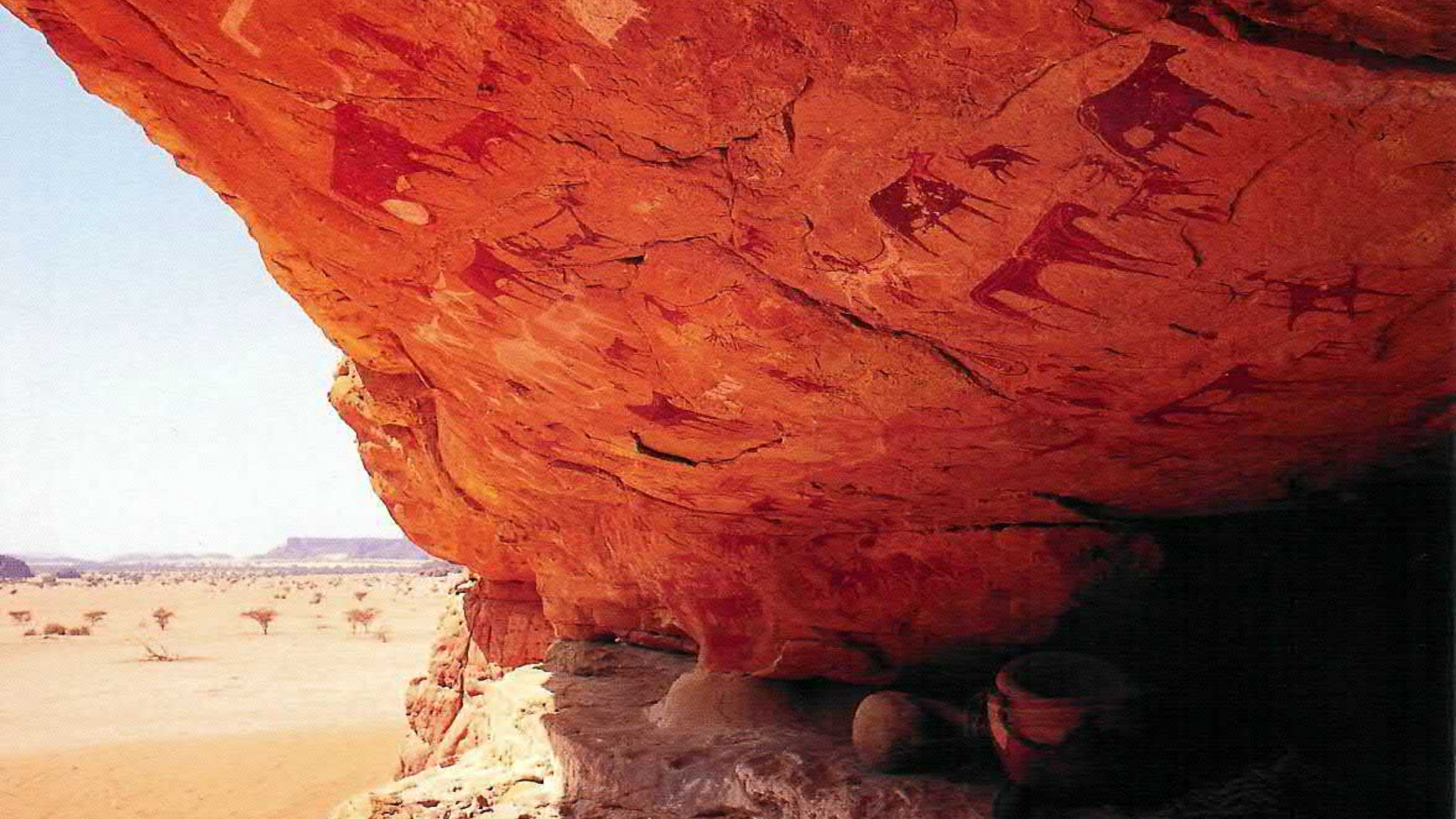
SFB 389
A2

(Kröpelin, Jesse, Keding et al. 2002)

Ennedi Plateau
NE Chad

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THIRD EDITION

PALEOCLIMATOLOGY

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RAYMOND S. BRADLEY

Front Cover Photograph

HOLOCENE ROCK ART FROM THE NORTHWESTERN FLANKS OF THE ENNEDI HIGHLANDS, EASTERN SAHARA, CHAD

The Ennedi highlands in the remote desert of Northeast Chad (17°22′N-21°09′E) have been called the "Garden Eden of the Sahara." The triangularly shaped sandstone plateau features spectacular cliffs and rock formations and is dissected by a labyrinth of canyons some of which include ecological niches with remnant crocodiles. Numerous rock shelters contain some of the best preserved painted rock art on Earth. An ideal sequence of superposed layers starts with engravings of archaic round-headed people roaming peacefully with herds of rhinos or giraffes, indicating a fully developed savanna landscape. They are overlain by imposing paintings of domestic cattle and detailed scenes of the village life of the later prehistoric pastoralist population. Subsequent layers include galloping horsemen which may be attributed to the Iron Age. Superposed layers show "flying" camels which were introduced only about 2000 years ago into an increasingly arid environment evidenced by plentiful snakes. The paintings hence vividly illustrate human adaption to the gradual desiccation of the "green" Sahara about 8000 years ago, to the planet's largest hyperarid desert. These changes are documented in a complete Holocene record of subannually varved deposits of proximate Lake Yoa, Ounianga Kebir.

Photograph courtesy by Stefan Kröpelin, University of Cologne.

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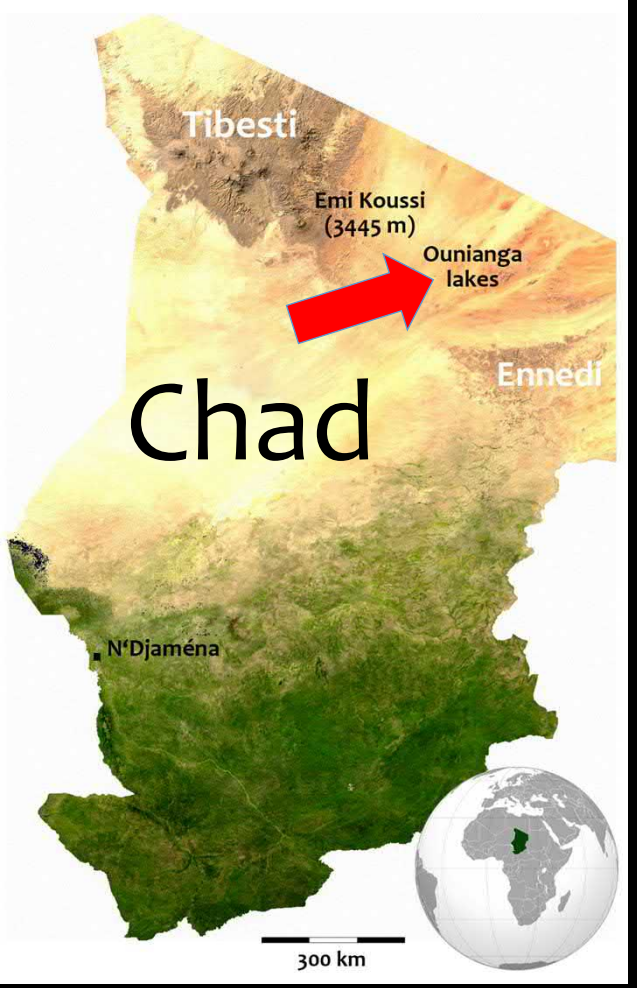
Ennedi, NE Chad, ca. 6000 -0 BCE

Lakes of Ounianga, N Chad



Lake Yoa, Ounianga Kebir

(Saudi Aramco World, May-June 2014)

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printemps 2009

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Jean-François Bach
Jean Dercourt

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la lettre de l'Académie des sciences n°25

Lac Yoa,
Ounianga Kebir,
Tchad

Dossier

Les déserts d'Afrique et d'Arabie

SOMMAIRE

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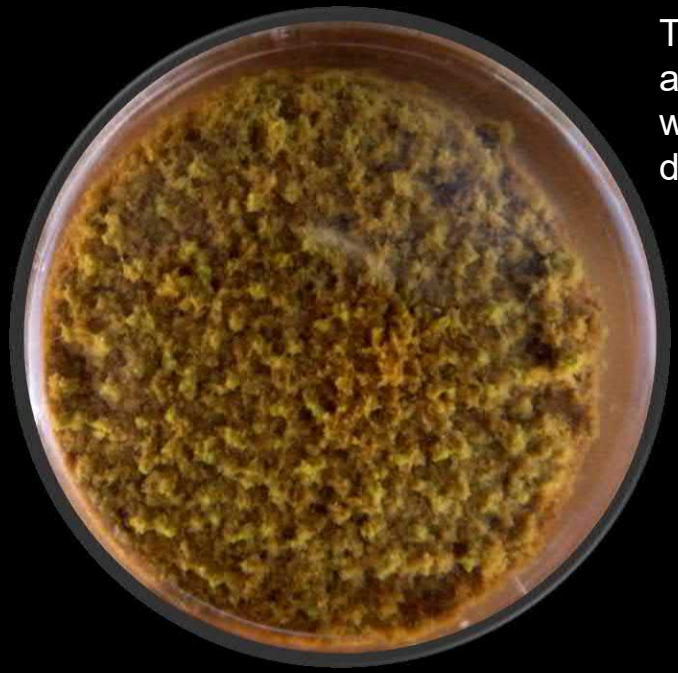
Location of test coring
Jan. 1999

7/2009

Lake Yoa, Ounianga Kebir
NE Chad (19° N - 20.5° E)



Top layer at 26 m water depth

OUNIANGA FIELD WORK

Test coring (1 m core):
Jan-Feb 1999 (6 weeks)

Transfer, repair:
Jan-Feb 2003 (6 weeks)
April 2003 (2 weeks)

2nd coring (4 m core):
Nov-Dec 2003 (7 weeks)

3rd coring (8 m core):
Oct-Nov 2004 (5 weeks)

4th coring (16 m core):
Feb-Mar 2010 (5 weeks)

Surveys, sampling:
Oct 2011 (2 weeks)
Mar 2013 (1 week)

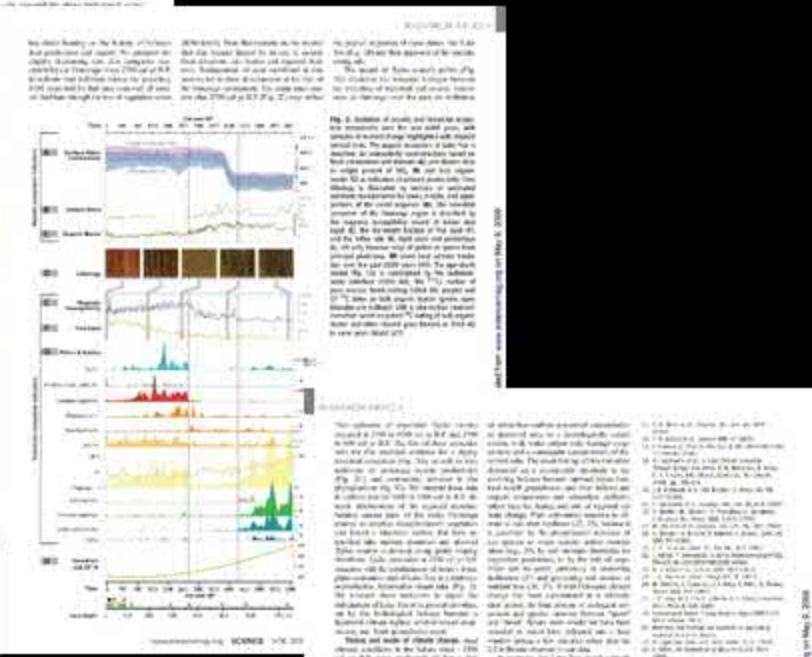
Stays in N'Djaména:
1999 - 2016 (16 weeks)

(total: 52 weeks)

Lakes of Ounianga


RESEARCH ARTICLE

Climate-Driven Ecosystem Succession in the Sahara: The Past 6000 Years



COVER

Lake Boku at the Ounianga oasis in remote northeastern Chad, one of the few remaining bodies of water in the almost rainless Sahara. Still sustained by fossil groundwater dating from the humid past, it is doomed because of encroaching dunes. See page 765.

Photo: S. Kröpelin

5/2008

The New York Times

In Lake, Signs of Slow Shift From Savannah to Sahara

By KENNETH CHANG

Six thousand years ago, northern Africa was a place of trees, grasslands, lakes and people. Today, it is the Sahara — a desolate area larger than Australia.

Lake Yoa, in northeastern Chad, has remained a lake through the millennia and is still a lake today, surrounded by hot desert. Although little rain falls, Lake Yoa's water is replenished from an underground aquifer.

By analyzing thousands of layers of sediment in a core, which is a column of sediment drilled from the lake bottom, a team of scientists has reconstructed the region's climate as the savannah changed to the Sahara.

In Friday's issue of the journal Science, the researchers, led by Stefan Kröpelin, a geologist with the Institute of Prehistoric Archaeology at the University of Cologne in Germany, report that the climate transition occurred gradually. In particular, the changing types of pollen that fell on the water and drifted to the bottom tell a story of how the terrain shifted from trees to shrubs to grasses to sand — "where today you don't find a single piece of grass," Dr. Kröpelin said.

The findings run counter to a prevailing view that the change happened abruptly, within a few centuries, about 5,500 years ago, marking the end of the "African Humid Period" when monsoon rains poured down on the region. That view arises from ocean sediment cores drilled off the coast, to the west of Mauritania. In 2000, analysis of the cores by researchers led by Peter B. deMenocal of Columbia University's Lamont-Doherty Earth Observatory showed a sudden rise in the dust blown off Africa at that time.

Dr. Kröpelin did not dispute the ocean core data but said it had been "overinterpreted."

Data about what was happening on land is sparse, because blowing sands do not preserve a clear geological record the way lake sediments do. But at Lake Yoa, ancient water from underground aquifers that filled during the humid period, which began 14,800 years ago, is still flowing into the 80-foot-deep lake. It is enough to offset the six meters of water lost to evaporation every year, Dr. Kröpelin said. Only a few millimeters of rain fall a year.

Dr. Kröpelin said he hoped to return to Lake Yoa next year to drill a core that could trace the climate history back 12,000 years.

Dr. deMenocal praised Dr. Kröpelin's research. "I think it's a very good body of work," he said. "It's really the only thing of its kind from the arid interior." But he said he wondered whether the pollen might have come mostly from the area immediately by the lake and not the larger Sahara.

Jonathan A. Holmes, director of the Environmental Change Research Center at University College London, said both sets of research had been carefully done, and the challenge would be to put together a more complex history of the area's climate.

"I don't think either record is somehow wrong," said Dr. Holmes, who wrote a commentary accompanying the article in Science. "I think what they are representing are slightly different things."

Dr. Holmes said one possibility was that the offshore dust might reflect a drop in water levels around Lake Chad, revealing more dust-producing soil.

However fast the drying occurred, it pushed people out of north-central Africa, Dr. deMenocal said, and that climatically forced migration might have led to the rise of the pharaohs and Egyptian civilization.

Scientists drilled a column of sediment from the bottom of Lake Yoa, in northeastern Chad, to study the history of the Sahara.

LE FIGARO

Le lac Yoa, situé au nord-est du Tchad, subit une forte évaporation équivalente à 6 mètres de hauteur par an. Alimenté par les eaux fossiles de l'aquifère nubien, il ne s'est pourtant jamais asséché. Stefan Kröpelin

Comment le Sahara est devenu un désert

CLIMAT
L'histoire récente de la désertification du Sahara vient d'être reconstituée grâce à des sédiments déposés au fond d'un lac tchadien. Le processus s'est étalé sur plusieurs milliers d'années.

Yves Miserey

Frankfurter Allgemeine
ZEITUNG FÜR DEUTSCHLAND

Paläoklimatologie

forschung
Das Magazin der Deutschen Forschungsgemeinschaft

3/2008 ▶ Seen in der Sahara ▶ Der Komponist mit der Januskopf ▶ Signale aus Dahlem ▶ Grenzen überwinden Freiräume schaffen ▶ Zürcher Zuteilung ▶ Am seidenen Faden der Reproduktion

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Natural Sciences

Im Klimaarchiv: Die Sahara wurde langsam zur Wüste

Selbst erhebliche Veränderungen des Klimas können sich abrupt ereignen. So hat sich herausgestellt, dass das Klima am Ende der letzten Eiszeit regelrecht flatterte. Dabei kam es zu Sprüngen der Jahresdurchschnittstemperaturen von mehr als zehn Grad in nur wenigen Jahrzehnten. In ähnlicher Weise wurde bisher angenommen, dass Nordafrika in nur wenigen Jahrhunderten von einem grünen Garten Eden zur Sahara versteppte. Nach gründlichen paläoklimatischen Untersuchungen in Tschad stellt eine internationale Forschergruppe diese Annahme jetzt in Frage. Die Forscher behaupten vielmehr, der Übergang von einer relativ feuchten, mit vielen Pflanzen bewachsenen Landschaft zur Wüste habe sich recht langsam – im Laufe von mehr als zwei Jahrtausenden – vollzogen.

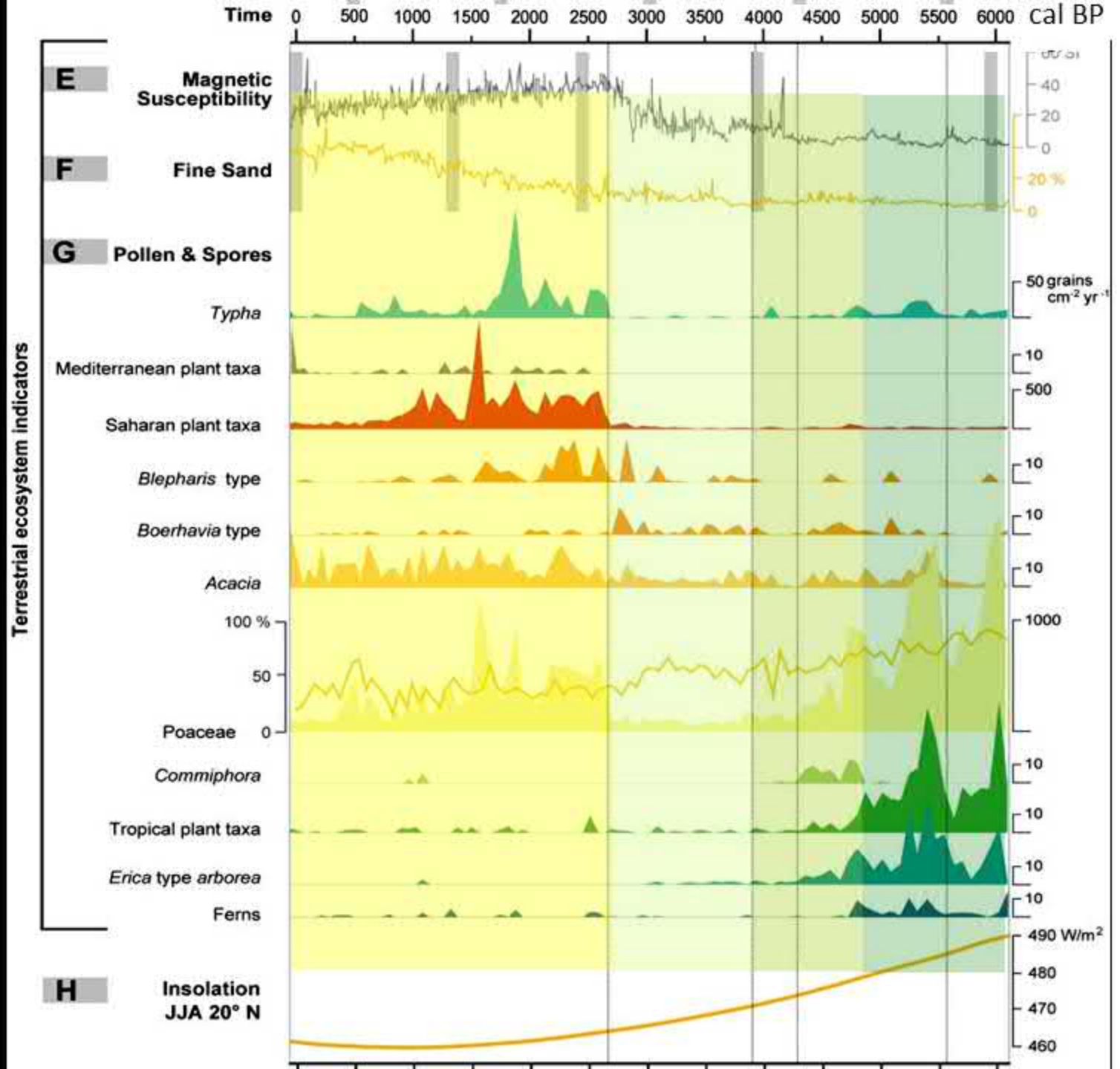
Die Sahara ist eine junge Wüste. Bis vor etwa 6000 Jahren fielen beispielsweise in Tschad noch etwa 25 Zentimeter Niederschlag im Jahr. Heute bleibt dort der Regen oft jahrelang aus, und im langfristigen Mittel liegen die Niederschlagswerte unter fünf Zentimetern pro Jahr. Bisher hatten die Forscher vermutet, der Übergang von einem feuchten, vom Monsun geprägten Klima zu den äußerst ariden Zuständen einer Wüste habe recht schnell stattgefunden. Man stützte sich dabei auf die Untersuchung von Meeressedimenten aus dem Atlantik vor der Westküste Afrikas. In den meisten der geschichteten Sedimentproben taucht nämlich Wüstenstaub in großen Mengen relativ plötzlich vor etwa 5500 Jahren auf. Weil ältere Schichten so gut wie keinen Staub enthalten, glaubten die Forscher, die Sahara sei in kurzer Zeit ausgedörrt.

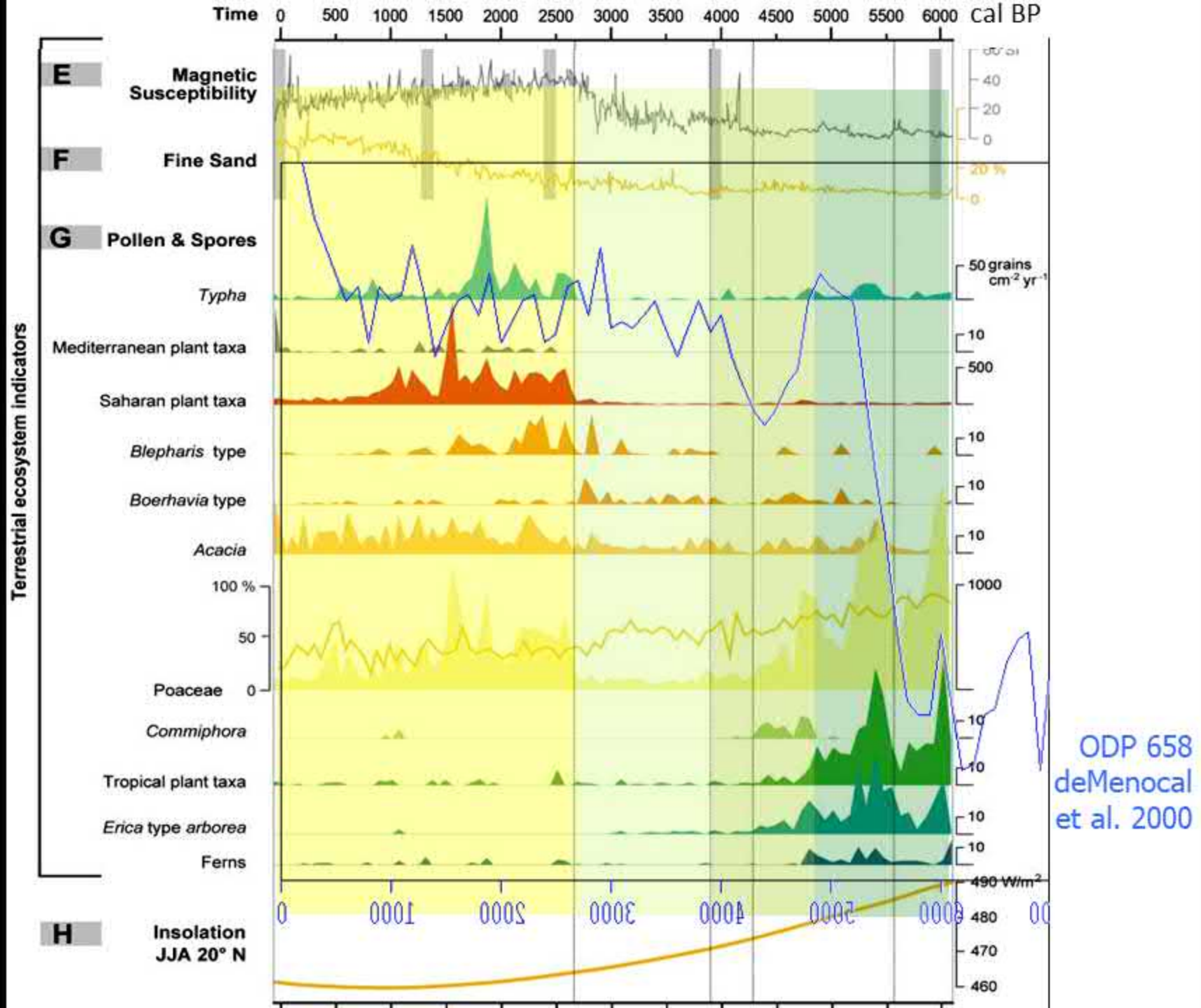
Neben den Meeresablagerungen gelten Sedimente in Binnenseen als wichtige Archive für Informationen über das Klima der Vorzeit. In der Sahara gibt es aber wegen der trockenen Bedingungen nur wenige Binnengewässer, die mehrere tausend Jahre ununterbrochen Wasser führten. Einer internationalen Forschergruppe unter Leitung von Stefan Kröpelin von der Universität Köln ist es nun gelungen, ein lückenloses Klimaarchiv der vergangenen 6000 Jahre im Yoa-See im Ounianga-Becken von Tschad zu erbohren. Der See hat derzeit eine Oberfläche von etwa 4,3 Quadratkilometern und ist mit maximal 26 Metern relativ flach. Weil es keinen Abfluss gibt, ist das Wasser im Yoa-See versalzen.

Wie die Forscher in der Zeitschrift „Science" (Bd. 320, S. 765) schreiben, ist das Wasser nicht immer salzig gewesen. Früher war der See noch erheblich größer und enthielt auch weit mehr Wasser als heute. Es gab einen Abfluss, was dazu führte, dass die Salzkonzentration nicht ständig durch Verdunstung wachsen konnte. Vor etwa 4300 Jahren nahm der Niederschlag dann allmählich ab, so dass sich im Wasser Salz anreicherte. Ebenso begannen sich in dieser Zeit die in den Seesedimenten abgelagerten Pollentypen deutlich zu verändern. Anstelle von Pflanzen, die unter verhältnismäßig feuchten Bedingungen gediehen, tauchten immer mehr Pollen von Pflanzen auf, die Dürren gut tolerierten. Schließlich sank der Pollengehalt der Sedimente auf extrem geringe Werte, was darauf schließen lässt, dass die Umgebung des Sees zu einer weitgehend pflanzenlosen Wüste geworden war. Nach Meinung der Forschergruppe vollzog sich dieser Übergang zur Trockenzone und die damit verbundene Versteppung aber recht langsam. Wahrscheinlich hat es mehr als 2000 Jahre gedauert, bis die Pflanzen in der Gegend um den Yoa-See verschwanden und sich der hyperaride Zustand der heutigen Sahara etablieren konnte. (hra)

5/2008

Kröpelin et al. 2008
Science 320: 765-768





Kröpelin et al. 2008
Science 320: 765-768

SEDIMENTOLOGY
the journal of the International Association of Sedimentologists

Sedimentology (2013) **60**, 911–934 doi: 10.1111/j.1365-3091.2012.01370.x

Varved sediments of Lake Yoa (Ounianga Kebir, Chad) reveal progressive drying of the Sahara during the last 6100 years

PIERRE FRANCUS*,†, HANS VON SUCHODOLETZ‡,§, MICHAEL DIETZE§, REIK V. DONNER¶, FRÉDÉRIC BOUCHARD*, ANN-JULIE ROY**, MAUREEN FAGOT††, DIRK VERSCHUREN††,[1] and STEFAN KRÖPELIN‡‡,[1]

*Institut National de
9A9, Canada (E-mail:
†GEOTOP Research C
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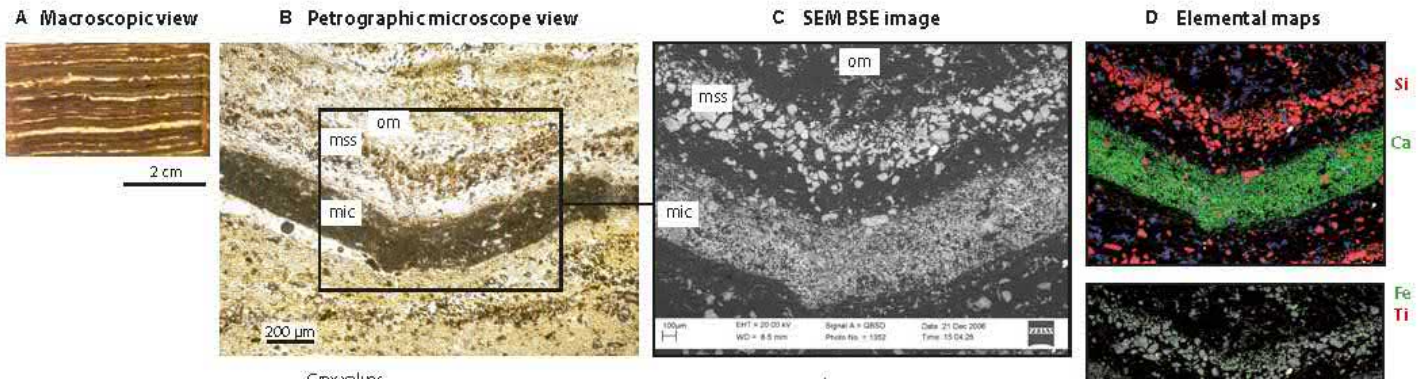
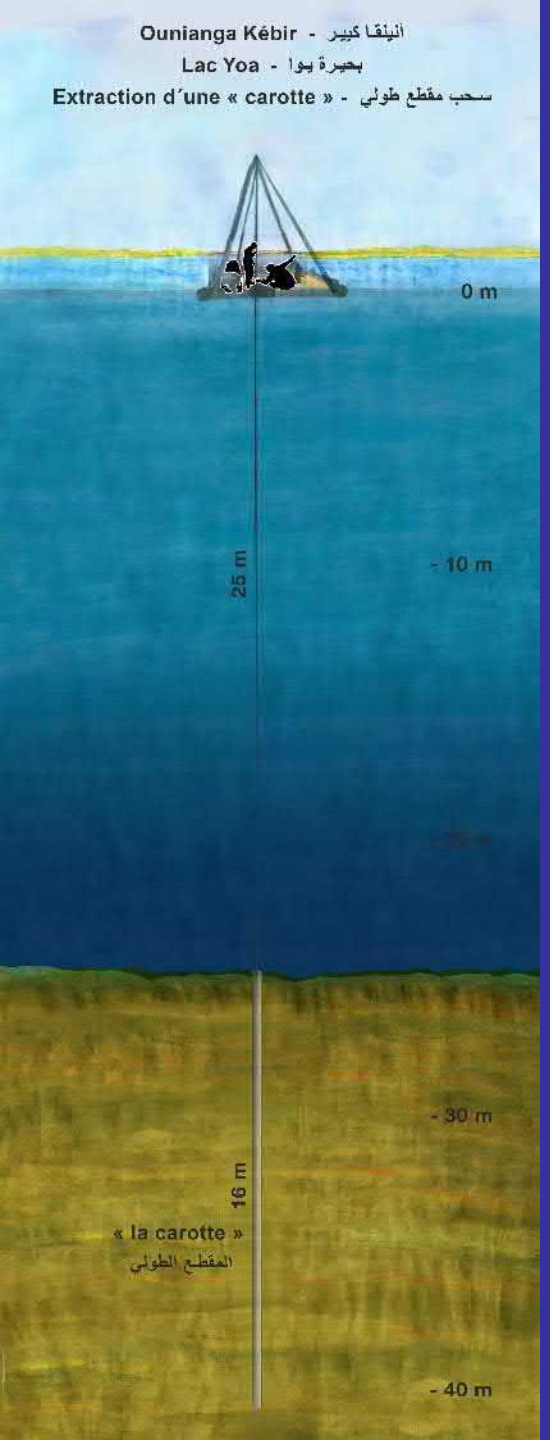
††Limnology Unit, De
‡‡Institute of Prehistc



.. "Detailed microscopic investigation revealed the sedimentary processes responsible for the formation of the fine laminations, identified the season during which they were formed, and their annually rhythmic nature. High-resolution XRF core scanning allowed distinction of each individual lamination over the entire record, opening new perspectives for the study of finely laminated sediment sequences." ..

Lake Yoa, Ounianga Kebir (March 2010)



Lake Yoa long core Co1240

- Continuous subannually varved 10,500-year continental record
- Exceptional thickness of Holocene varved sequence (16 m)
- Evidence of all natural and anthropogenic events
- Most detailed chronology of climate change on the African continent

AGU FALL MEETING
San Francisco | 12–16 December 2016

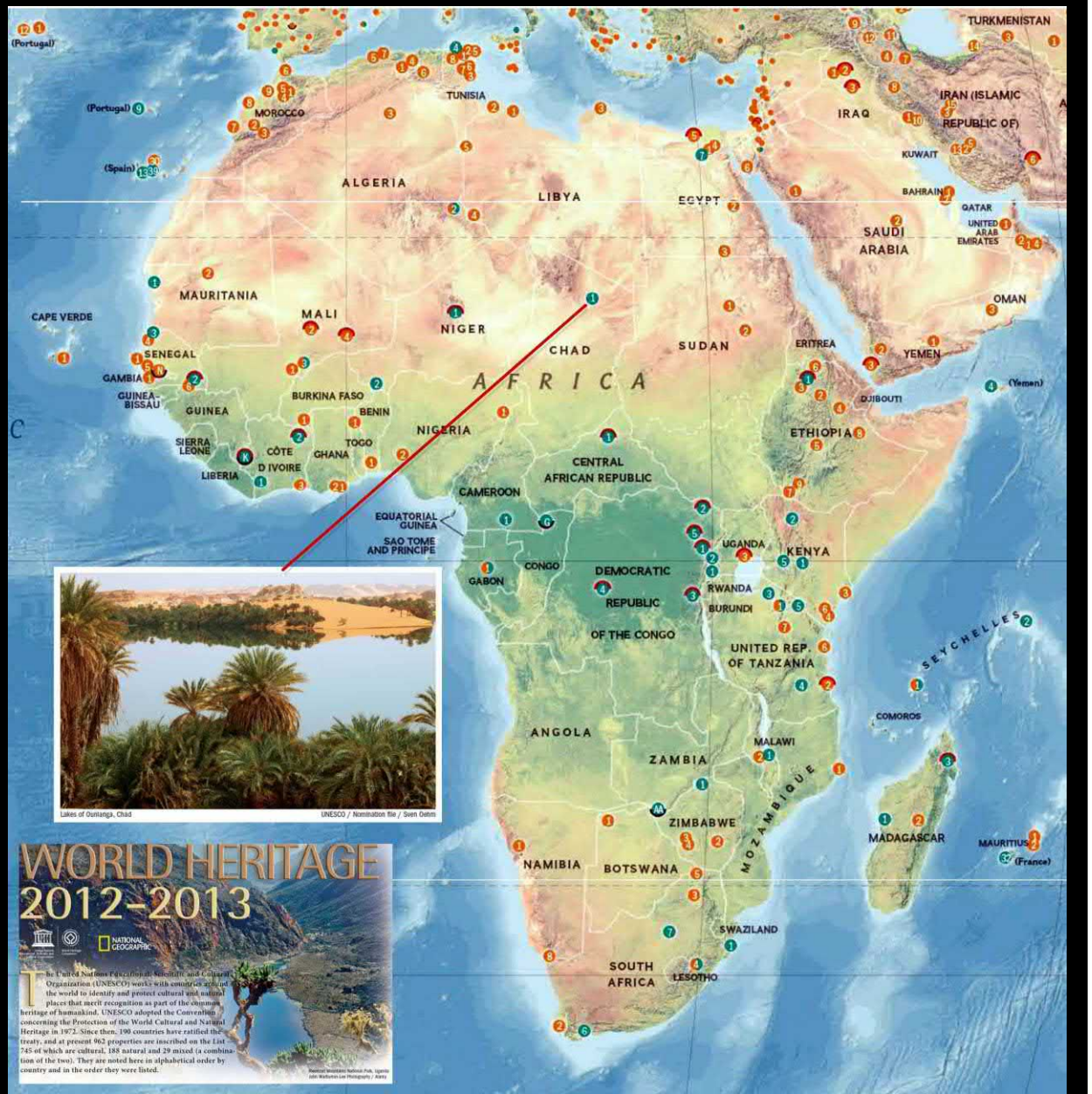
PP41D-08: Lake Yoa (Northern Chad): A Seasonal Footprint of 10,500 Years of Climate Change in the Sahara

Thursday, 15 December 2016
09:45 - 10:00
Moscone West - 2010

We present Africa's most complete Holocene climate record in a long awaited breakthrough that few would have expected in one of the driest and most remote parts of the Sahara, the planet's major hot desert. A 16 m thick continuous sequence of seasonally laminated (varved) deposits at the bottom of a now fully groundwater-supported oasis lake at Ounianga Kebir in northern Chad extends our earlier 6,000 year record published in 2008 back to the onset of postglacial humid conditions 10,500 years ago in unrivalled detail. Main results indicate a rather slow regreening in northern Africa after ~100,000 years of apparently continuous late Pleistocene aridity; precisely define the severe environmental impact of global climate events such as the 8,200 BP North Atlantic cooling even in hypercontinental positions far away from the oceans; and corroborate the gradual termination of the last "Green Sahara" period over millennia. Lake Yoa's varve count-controlled age model also shows the high error potential of the existing ^{14}C chronology from bulk carbonate-dated paleolacustrine archives elsewhere in the Sahara and provides a basis for its correction. The new terrestrial multiproxy data set discloses agreements and discrepancies to marine and ice core data, and numeric climate models. As a natural analogue, it helps to foresee how North Africa's climate and environments might evolve due to anthropogenic global warming.

Lakes of Ounianga
Chad's first UNESCO World Heritage Site

Ernennung 6.7.2012
36COM St. Petersburg



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DATE D'INSCRIPTION
6 Juillet 2012

LE DIRECTEUR GÉNÉRAL DE L'UNESCO

8/2006

Climate-Controlled Holocene Occupation in the Sahara: Motor of Africa's Evolution

Rudolph Kuper and Stefan Kröpelin*

Radiocarbon data from 150 archaeological excavations in the now hyper-arid Eastern Sahara of Egypt, Sudan, Libya, and Chad reveal close links between climatic variations and prehistoric occupation during the past 12,000 years. Synoptic multiple-indicator views for major time slices demonstrate the transition from initial settlement after the sudden onset of humid conditions at 8500 B.C.E. to the exodus resulting from gradual desiccation since 5300 B.C.E. Southward shifting of the desert margin helped trigger the emergence of pharaonic civilization along the Nile, influenced the spread of pastoralism throughout the continent, and affects sub-Saharan Africa to the present day.

During the past decade, it has become increasingly clear that climate signals extracted from polar ice caps and ocean floor sediments cannot be directly translated into climate and environmental fluctuations on tropical and subtropical continental regions habitable by humans. Contrary to the concept of the Holocene as a climatically stable period (*1*), all geological and archaeological evidence from the hypercontinental Eastern Sahara indicates marked climatic and environmental changes over the past 12,000 years that often do not reflect climate anomalies recorded in high-latitude archives (*2*). The Eastern Sahara covers >2,000,000 km^2 and includes the Western Desert of Egypt, Northwest Sudan, and the adjacent parts of Libya and Chad, which together are about the size of western Europe. Today, it is the largest hyper-arid warm desert on Earth, with virtually no rainfall (<2 mm/year) in its center and maximum precipitation of 30 mm/year at its peripheries against potential evaporation rates of up to >6000 mm/year (*3*).

As a consequence of the extreme aridity and scarceness of wells, the Eastern Sahara—outside the Nile valley and groundwater-supported oases in the Egyptian "New Valley," Fayum, and Siwa—has been completely void of permanent human settlement in recent millennia. For this reason, it is a unique natural laboratory for the reconstruction of the links between changing climate and environments, and human occupation and adaptation, with prehistoric humans as sensitive indicators of past climate and living conditions. Their mere presence there, documented in countless archaeological remains and occupation sites, or their absence, serves as unfailing evidence for shifting climatic zones, as well as the development of Neolithic achievements, interregional contacts, and innovative strategies that have modeled the sociocultural evolution on the African continent to the present day.

Understanding the spatial and temporal variations of past rainfall requires integration of geological, archaeological, archaeobotanical, and archaeozoological field data into regional chronologies at several time slices and distinct latitudinal zones. A vast region, stretching 1800 km from latitudes 15°N to 31°N and 1300 km between longitudes 22°E and 34°E, can hardly be treated as a single entity. Such a multi-indicator and supraregional approach prevents overstressing of local stratigraphies that may not necessarily reflect conditions in the same geographical latitude (*4*) and avoids the ambiguity of condensing geological and biological evidence from several millennia into a single age loosely defined as "Holocene optimum" (*5*, *6*).

Onset of humid conditions. During the Alleröd interstadial (about 11,900 to 10,800 B.C.E.), when Northwest Europe witnessed temporarily waning ice sheets, and the following Younger Dryas, the final cold phase of the Pleistocene, the Eastern Sahara was still void of any aquatic environments and as hyper-arid as it was during the Last Glacial Maximum at 20,000 B.C.E. The first signal of a changing climate occurred in the early Preboreal with the establishment of postglacial conditions in the mid-latitudes, supported by evidence of a sudden appearance of carbonate lake formations in the Sudanese Sahara and of siliceous mud deposits in the Egyptian Sahara.

Radiocarbon dates of the base levels of these paleolakes and playa-type rain pools reveal the almost contemporaneous onset of pluvial conditions between latitudes 16°N and 24°N at about 8500 B.C.E., indicating an abrupt northward shift of the tropical rainfall belts over as much as 800 km within just several generations (*7*, *8*). This decisive climate change can be attributed to tropical summer rains owing to a major extension of the paleomonsoon system, whereas the contribution of Mediterranean winter rain systems north of 24°N remains vague. As a result, notable improved environmental conditions spread over the entire Eastern Sahara (*7*–*15*), with semihumid climates in its southern part and semi-arid conditions in its center.

Time transgressive drying of the Eastern Sahara. The chronology of radiocarbon dates from early and mid-Holocene occupation sites along a north-south transect through the Eastern Sahara provides a spatial and temporal synthesis of the directional trend in shifting human population (Fig. 1 and fig. S1). It was compiled from almost 500 radiometric results from about 150 excavations at non-oasis sites, supplemented by condensed chronologies for Nabta and Kiseiba (*4*) the Egyptian oases (*16*, *17*), and the Nile valley (*18*). The general array of radiocarbon dates, with older dates in the north and the bulk of younger dates in the south, clearly indicates (i) a movement of prehistoric populations toward the present-day Sahelian zone; (ii) a dearth of early Holocene data from the Nile valley at a time when human presence in the Eastern Sahara is well documented; and (iii) a sharp break of settlement in the Egyptian Sahara at about 5300 B.C.E. (except for some ecologically favored refuges such as the Gilf Kebir Plateau), the time when Neolithic and predynastic farming communities began flourishing in the Nile valley.

Phases of human occupation. Cumulative curves of the archaeological chronological data (Fig. 2) indicate four distinct occupation phases: (i) the Reoccupation phase (8500 to 7000 B.C.E. starting with surprisingly early settlement in the Egyptian Sahara; (ii) the subsequent Formation phase (7000 to 5300 B.C.E.), ending abruptly in all areas without permanent water; (iii) the Regionalization phase (5300 to 3500 B.C.E.), featuring retreat to highland refuges with continuing rain and temporary lakes; and (iv) the Marginalization phase (3500 to 1500 B.C.E.), with only transient human activities in the Egyptian Sahara and prehistoric occupation restricted to Northern Sudan.

Here, we discuss these major occupation phases in the context of their assumed environmental settings. We provide the climatic background in synoptic zones, limited by best estimate isohyets (lines of equal annual precipitation) on the basis of geological, archaeozoological, and archaeobotanical data (*7*, *9*–*12*, *19*). Correlation between the proposed pluviometric pattern and the archaeological evidence produces a coherent scenario for environmental, sociocultural, and economic change in the Eastern Sahara since the terminal Pleistocene.

At that time, the Saharan desert extended about 400 km farther south than it does today, covering more than one-third of the African continent (Fig. 3A and fig. S2A). Prehistoric sites along the Nile are overrepresented at Lake Nubia (because of the archaeological rescue missions related to the

Collaborative Research Center 389 (ACACIA), University of Cologne, Institute of Prehistoric Archaeology, Africa Research Unit, Jennerstraße 8, 50823 Köln, Germany.

*To whom correspondence should be addressed. E-mail: s.kroe@uni-koeln.de

Aswan high dam) but contrast clearly with the complete lack of evidence from the desert. During the terminal Pleistocene "Wild Nile" stage at about 12,000 B.C.E (*20*), living conditions along the river became harsh and caused conflicts for land and food, as indicated, for example, by the late Paleolithic Nubian cemetery of Jebel Sahaba, in which many of the buried individuals died a violent death (*21*).

Early Holocene reoccupation (8500 to 7000 B.C.E.). With the rapid arrival of monsoon rains at 8500 B.C.E., savannah-like environments turned the Eastern Sahara into a habitable region, and prehistoric humans soon settled there (Fig. 3D and fig. S2D). Groups from the south, already adapted to savannah ecology, extended their traditional way of life following the northward shifting rains, whereas Nile dwellers may have left the inhospitable valley. The epipaleolithic tool kit, as well as archaeozoological evidence from Nabta and Kiseiba, defines them as hunter-gatherers possibly already practicing some animal husbandry (*4*). While this pastro-foraging economy needs further confirmation, "wavy line" decorated pottery, the first ceramics in the Old World—is a key African achievement of the ninth millennium B.C.E. (*22*).

Epipaleolithic camp sites in the Regenfeld area dated to 8000 to 7000 B.C.E. demonstrate quick migration of populations over several hundreds of kilometers into the central Great Sand Sea, where they encountered satisfactory living conditions in what is today the Libyan Desert's most barren part (*23*). Rakita had termed the late Pleistocene dunes into pasture that provided wild grains for the hunter-gatherers and browsing for their game. Most notable is the almost complete lack of settlements in the Egyptian Nile valley, with the exception of El Kab (*24*). The dearth of archaeological sites along the Nile and in the Wadi Howar region reflects conditions too marshy and hazardous for settlement. During the early Holocene humid optimum, hunters and gatherers obviously preferred the less wooded grassland farther north to the regularly flooded and densely wooded environments of the southern Sahara.

Mid-Holocene formation (7000 to 5300 B.C.E.). After 7000 B.C.E., human settlement became well established throughout the Eastern Sahara by way of economical and technological adaptations to regionally different ecological requirements (*25*) (Fig. 3C and fig. S2C). On the Egyptian Abu Muhariq Plateau, bifacial technology obviously rooted in the Levant caused a complete change in the lithic tool kit that can be traced into the later predynastic cultures of the Nile valley (*26*). Impression-decorated pottery of Sudan tradition, on the other hand, is represented as far north as the Egyptian oases and the Great Sand Sea (*27*). The most important achievement of this phase is the introduction of domestic livestock. Sheep and goats, for which an early record also exists in Egypt's Eastern Desert (*28*), must have been introduced from their wild progenitors in western Asia (*29*), whereas cattle appear to have been domesticated locally. Livestock keeping, well documented at Nabta Playa (*6*), for example, became an essential component of a multi-resource pastoral economy that marks the beginning of African pastoral societies. Depending on local factors, their economic base differed substantially. In the western Abu Ballas area (Mudpans site 85-56), for example, rich faunal material from about 6400 B.C.E. did not reveal any evidence of domestic livestock (*30*), whereas in the eastern Great Gilf (Isatsous site 96/2) cattle are well documented, together with a new type of undecorated late Neolithic pottery (*25*).

The radiocarbon dates do not indicate any rupture in regional climatic development between 7000 and 5300 B.C.E. The disparity in ceramics and lithic artifacts at Djara and Mudpans at 6000 B.C.E. suggests a break, between two phases ("A" and "B"), which coincides with the arrival of sheep and goats (*26*). Some cultural changes may consequently have occurred beyond climate control.

According to the deficiency of occupation sites, regular monsoonal rains have ceased to reach the Egyptian Sahara not later than 5300 B.C.E. At Djara and on the Abu Muhariq Plateau there is a substantial decline in radiocarbon dates (*23*). Another abrupt end of occupation is observed in the central Great Sand Sea, whereas the few younger dates from Abu Minqar may be linked to local springs and transhumance from the oases depression (*27*). A comparable pattern of semi-nomadic occupation underlies the evidence for cattle at Eastern 96/2, when living conditions in the more distant parts of the Abu Ballas region had already deteriorated. With the end of the Formation phase at 5300 B.C.E., multi-resource pastoralism appears to have become the vital human subsistence strategy in the Egyptian Sahara while at the same time the first farming communities developed in the Fayum.

Mid-Holocene regionalization (5300 to 3500 B.C.E.). The retreat from desiccating regions into ecological niches such as the Gilf Kebir and the beginning exodus to the Sudanese plains, where rainfall and surface water were still sufficient (Fig. 3D and fig. S2D), fostered more regionally diverse sociocultural adaptations. The few dates from the western fringes of the Great Sand Sea, the Abu Ballas area, and the Abu Muhariq Plateau reflect only sporadic occupation, whereas the eastern Abu Minqar and Abu Ballas areas lie within the range of transhumance from the Tarafia and Dakhla oases. Certain ceramic traditions that originated in the Gilf Kebir later occurred in the Laqiya region of Northern Sudan (*27*), where progressive southward movement is reflected, for example, by the distribution of distinct grinding implements (*30*). The previously ubiquitous "wavy line" pottery is replaced by more local pottery styles. Of particular importance is the rise of specialized cattle pastoralism (*4*, *31*), which later became a basic way of life throughout sub-Saharan Africa. This Saharan path to a productive economy was a specific African variant of a crucial change in human evolution, contrasting with the traditional Near East model of Neolithization. In place of the transition from nomadic hunter-gatherers to sedentary, pottery-producing farmers and livestock keepers, evidence suggests that largely sedentary and pottery-producing hunters, fishers, and gatherers became nomadic cattle herders. Cereal farming does not seem to have been a constituent of this Saharan "Neolithic revolution," given that the mid-Holocene savannah still provided sufficient wild-growing grains, fruits, and tubers.

Paradoxically, in certain landscapes the decreasing trend in annual precipitation may have been associated with an increase in the vegetation cover because of a change in seasonality. Geoarchaeological evidence from the Gilf Kebir suggests that the intense daytime summer monsoon rains of the early Holocene pluvial resulted in less grass growth than the quantitatively lesser winter rains of the terminal humid phase, which presumably fell at night (*32*). These favorable circumstances may have maintained the rich culture of cattle keepers depicted in the rock art of the Jebel Uweinat and Gilf Kebir.

The large-scale exodus from the Egyptian Sahara coincides with the rise of sedentary life along the Nile. The first Neolithic communities in Fayum and Merimde, starting around 5000 B.C.E. with already fully developed cultivation of wheat and barley, are clearly rooted in Near East traditions. At the same time, essential social and cognitive aspects can be traced back to Saharan cattle herders and their spiritual heritage. Neolithic settlements of the Badari culture in the Nile valley recall African livestock enclosures and suggest a rather mobile existence (*33*). The practice of cattle burials is a presumably religious custom that has been recorded in the Egyptian Sahara from the fifth millennium B.C.E. (*4*). Saharan traditions of cattle pastoralism have thus become an essential component of Neolithic life in the Nile valley.

Late Holocene marginalization (3500 to 1500 B.C.E.). After 3500 B.C.E., rains ceased even in ecological niches such as the Gilf Kebir, and permanent occupation was restricted to southern areas such as Laqiya (*34*) and Wadi Howar in Northern Sudan (fig. S2L). For the pharaonic empire, well established after 3000 B.C.E., the Western Desert obviously played a marginal role. Generally considered a "country of evil and death," it was thought to bar the Egyptian Nile valley from the Sudanese Sahara, where cattle herders still practiced their Neolithic lifestyle. Sporadic finds of Egyptian pottery near Laqiya (*27*) support rare historical reports about desert journeys during the sixth Dynasty that were considered as daring advances into the unknown.

Recent discoveries, however, shed new light on pharaonic activities in the Egyptian Sahara. Besides an elaborate desert station of King Khufu, the builder of the great pyramid, 30 outposts between Dakhla and the Gilf Kebir indicate the first trans-Saharan trail into the interior continent (*35*–*37*). At first related to Ain Asil, Ancient Egypt's westernmost town in Dakhla (*38*), and then throughout dynastic times, these desert stations indicate watch-posts concerned with prospecting or trading, or the prevention of smuggling, of African goods to the Nile valley. Because the camel was introduced to Africa only during the first millennium B.C.E., any long-distance travel through waterless desert had to rely on donkeys. Their water needs required extraordinary logistical skills and geographical knowledge—an example of how early societies coped with the challenges of hyper-arid environments.

Conclusions. Whereas earlier studies have dealt with the response of discrete cultures to climate changes in distant regions during different periods (*39*, *40*), we present here a consistent model of how past climate changes, over a coherent region of subcontinental scale, have affected human societies throughout the Holocene. Contrary to inferences from offshore marine sediment records and numeric modeling (*41*, *42*), the only supraregional climate signal in the geological and archaeological archives of the

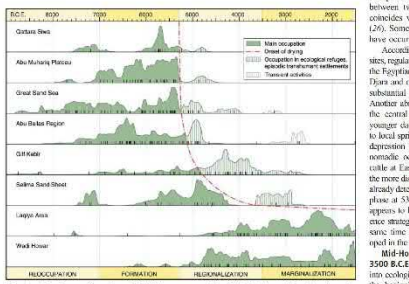

Fig. 2. Major stages of early and mid-Holocene occupation in the Eastern Sahara based on the cumulative curves of calibrated radiocarbon dates from 150 archaeological excavations. Regions are arranged from north to south. The Reoccupation phase (8500 to 7000 B.C.E.) is characterized by early settlements in the northern regions at the beginning of the Holocene humid optimum. Major occupation continues during the Formation phase (7000 to 5300 B.C.E.) until the onset of arid conditions in the Egyptian Sahara. The Regionalization phase (5300 to 3500 B.C.E.) is characterized by the retreat of populations to ecological refuges such as the Gilf Kebir plateau, seasonal or episodic transhumance, and a marked migration into the Sudanese Sahara. During the Marginalization phase (3500 to 1500 B.C.E.), Southwest Egypt receives only passing visits while prehistoric occupation in Northern Sudan persists until the end of humid conditions at 1500 B.C.E.

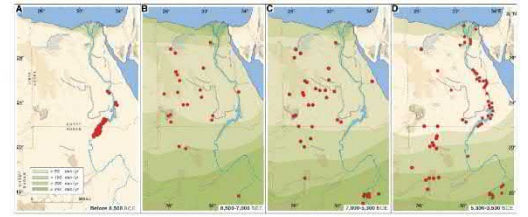

Fig. 3. Climate-controlled occupation in the Eastern Sahara during the main phases of the Holocene. Red dots indicate major occupation areas; white dots indicate isolated settlements in ecological refuges and episodic transhumance. Rainfall zones are delimited by best estimate isohyets on the basis of geological, archaeozoological, and archaeobotanical data. (**A**) During the Last Glacial Maximum and the terminal Pleistocene (20,000 to 8500 B.C.E.) the Saharan desert was void of any settlement outside of the Nile valley and extended about 400 km farther south than it does today. (**B**) With the abrupt arrival of monsoon rains at 8500 B.C.E., the hyper-arid desert was replaced by savannah-like environments and swiftly inhabited by prehistoric settlers. During the early Holocene humid optimum, the southern Sahara and the Nile valley apparently were too moist and hazardous for appreciable human occupation. (**C**) After 7000 B.C.E., human settlement became well established all over the Eastern Sahara, fostering the development of cattle pastoralism. (**D**) Retreating monsoonal rains caused the onset of dereliction of the Egyptian Sahara at 5300 B.C.E. Prehistoric populations were forced to the Nile valley or ecological refuges and forced to exodus into the Sudanese Sahara where rainfall and surface water were still sufficient. The return of full desert conditions all over Egypt at about 3500 B.C.E. coincided with the initial stages of pharaonic civilization in the Nile valley.

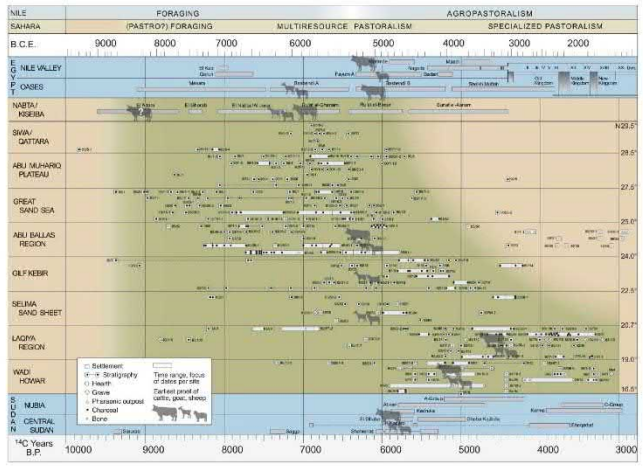

Fig. 1. Radiocarbon dates from early and mid-Holocene occupation sites in the Eastern Sahara. The graph is arranged from north to south and based on almost 500 radiometric results from our excavations of non-oasis prehistoric sites, with condensed chronologies for the Egyptian sites of Jebel Nabta and Bir Kiseiba (*4*), and the Egyptian and Sudanese Nile valley and oases (*16*–*18*). The data show the clear trend of southward shifting occupation driven by the retreat of monsoon rainfall, and the contrasting economies in the Nile valley and the Sahara. Green shading marks humid conditions; symbols of domesticated cattle demonstrate the spread of pastoralism. See fig. S2 for details and site locations. Years B.P., years before present; Dyn., dynasty.

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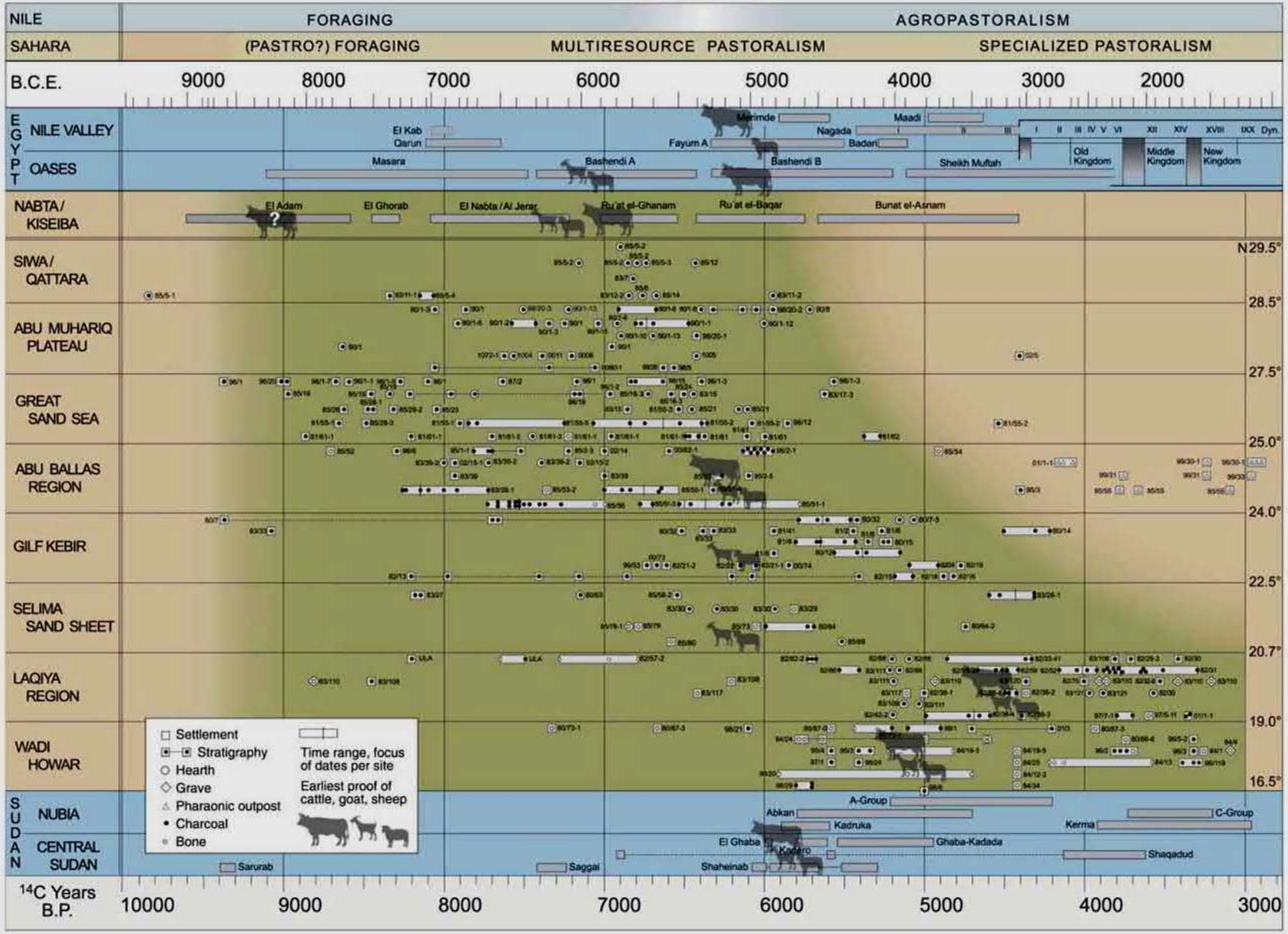

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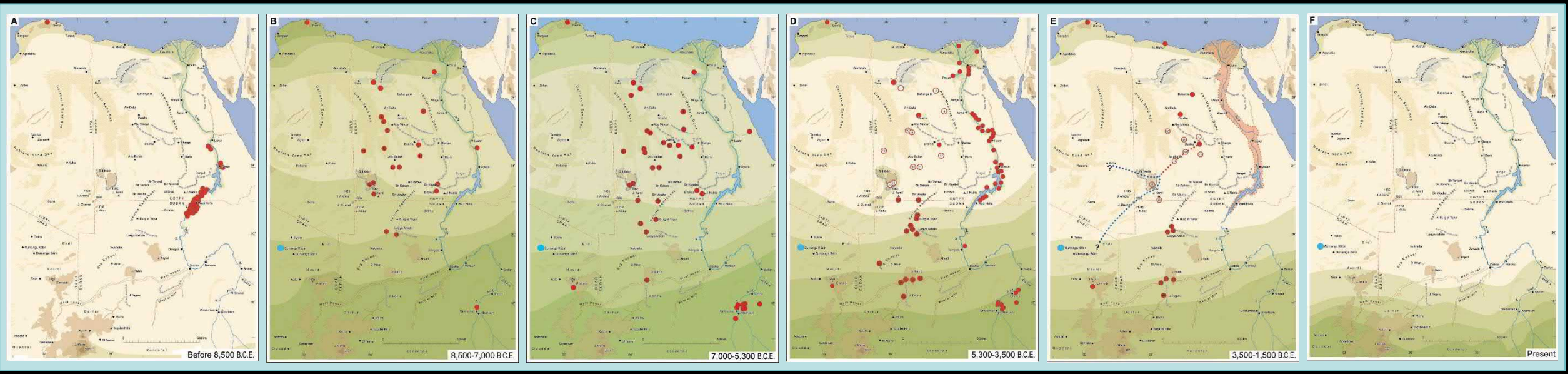
A
Before 8,500 B.C.E.
B
8,500-7,000 B.C.E.
C
7,000-5,300 B.C.E.
D
5,300-3,500 B.C.E.
E
3,500-1,500 B.C.E.
F
Present
> 50 mm/yr
> 150 mm/yr
> 300 mm/yr
> 450 mm/yr
Occupation in ecological refuges, episodic transhumant settlements
Pharaonic state
Pharaonic trail
Possible continuation

Climate change and prehistoric occupation in the Eastern Sahara

- From ~ 8,500 BCE increasing monsoon rainfall pushed the former desert margin some 800 km north to beyond the Tropic of Cancer creating semi-arid conditions in the north (Egypt, Libya) and semi-humid conditions in the south (Chad, Sudan)
- Transformation of the late Pleistocene desert into diverse savannah environments with wide-spread lakes and wadis resulted in rapid dissemination of wild fauna and diversely swift reoccupation by hunters and gatherers from the south
- Relatively stable favourable environments prevailed over ~ 3,200 years
- From ~ 5,300 B.C.E. gradual southward retreat of the monsoons causing environmental deterioration and shifting occupation
- Mobility was the key to survival and drove prehistoric societies from semi-sedentary foraging to a multi-resource economy
- The desiccation of the Sahara (co)triggered the emergence of Egyptian and Sudanese civilization in the Nile valley, influenced the spread of pastoralism throughout the continent and was a motor of Africa's evolution

The “African Humid Period” in the (Eastern) Sahara

- Extent – Timing – Causes?
- “Abrupt onset at 14,800” vs Rather slow onset from ~11,000 – 10,000
- “Abrupt termination at 5500” vs Gradual southward retreat of monsoon rains from ~ 7300 - 2700
- Validity of marine sources for continental African paleoclimatology?
- Validity of numeric climate models?

(dates cal BP)

Und nach der Expedition zur Kaffeepause …