Proc. NIPR Symp. Polar Meteorol. Glaciol., **11**, 51-66, 1997

A COMPENDIUM OF RECENT FRENCH CONTRIBUTION TO POLAR ICE CORE STUDIES

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Abstract: Over the last decade, researchers and drillers of Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE) were involved in four major international projects in Antarctica and Greenland. Vostok data (Antarctica) documented the links between major climate changes and the composition of atmospheric gaseous and particulate constituents. Then, for European glaciologists, Eurocore and GRIP represented an exceptional opportunity of working together in Greenland. A wealth of scientific results were amassed from shallow and deep ice cores collected from 1989 to 1992 at Summit for these projects. Finally, the strategy adopted successfully in Greenland is now being transferred to the Antarctic for Epica, the great glaciological research project to be developed by Europe during the next years. LGGE is particularly interested in the Dome Concordia drilling operation (the first phase of Epica).

A summary of French scientific activities related to these international projects is given.

1. Introduction

Terminated some ten years ago, the first phase of the analysis the Vostok ice core, confirmed strikingly that polar ice contains environmental information of great value for paleoclimatic studies. When ice drilling started 25 years ago at Vostok (Vostok is a Russian, formerly Soviet, scientific station located on the central East Antarctic Plateau, 78°28′S, 106°48′E, elevation 3490 m), it was already known from previous Greenland and Antarctic studies that isotope profiles from polar ice were proxy records of past temperature changes. In addition to this, Vostok research demonstrated convincingly that temperature and greenhouse gases concentrations changes are closely linked over a full glacial cycle (JOUZEL *et al.*, 1987; BARNOLA *et al.*, 1987; GENTHON *et al.*, 1987). Thereafter, the success of Vostok encouraged glaciologists to propose new ice coring initiatives on the Greenland and Antarctic ice caps in order to recover additional time series from other geographical areas.

Over the last decade, several important operations in both polar regions (Fig. 1) marked the development of ice core studies at LGGE, and more generally in France (LGGE is in charge of French polar ice core research, but samples are distributed to other groups over the country for specific measurements). It will be reported successively on:

1) the continuation of the collaborative ice-coring at Vostok and an amplification of the analytical programme on the samples,

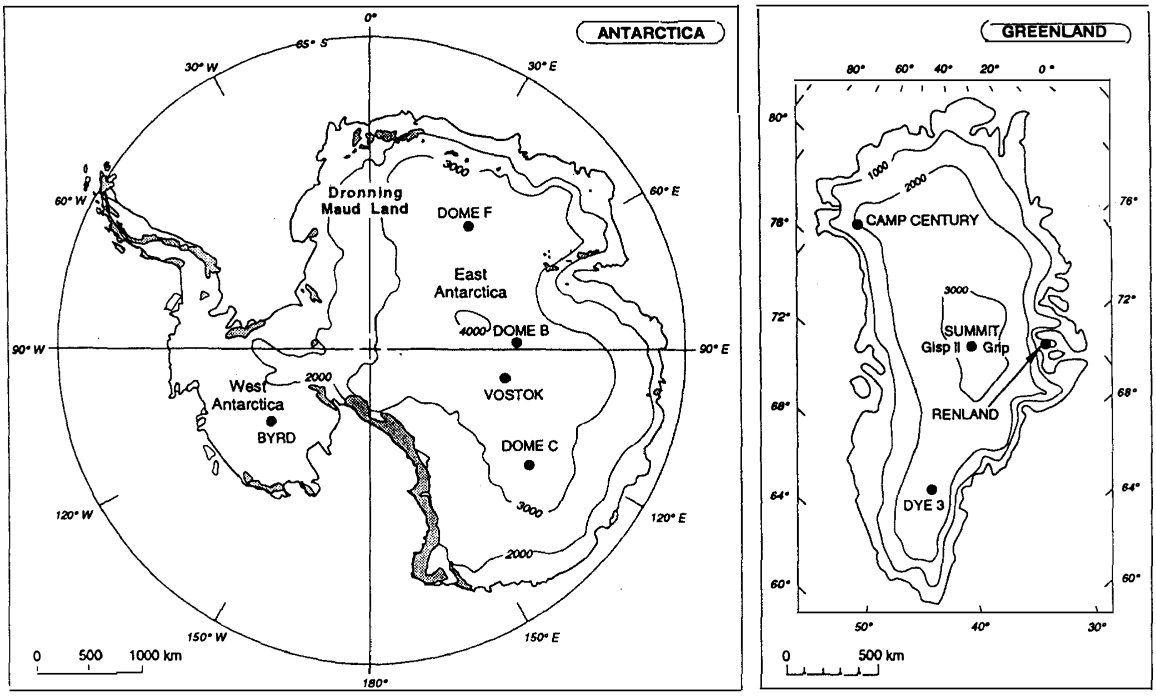

Fig. 1. Over the last decade, Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE) has been involved in several ice core studies in the Antarctic (Vostok) and Greenland (Eurocore and GRIP, Summit site). Other deep ice-coring sites are also indicated.

2) the creation of joint european activities at Summit, central Greenland, first with the aid of a CEC contract ("Eurocore") obtained between 3 european glaciological groups to study in detail the last millennium, then under the auspices of ESF (European Science Foundation) to continue the drilling operation to the ground with the participation of 8 European nations (GReenland Ice core Project, "GRIP").

3) the elaboration and funding of EPICA (European Project for Ice Coring in Antarctica) for deep drilling and ice core analysis in central Antarctica up to the end of the century.

References given in this text are not exhaustive.

In addition to these major projects, LGGE has participated in various, generally co-operative activities, in the domain of ice core research in Greenland and Antarctica.

2. Vostok

Vostok drillings were initiated in 1970 by the Arctic and Antarctic Research Institute of Leningrad, USSR. First developed in France at the beginning of the 80ies as a Soviet-French collaborative research, the analysis of the 3G-Vostok core was continued afterwards in the frame of a Russian-US-French agreement. During the last decade, the progression of the Vostok ice coring has been very significant, but cahotic. Several successive boreholes had to be operated due to logistical or technical problems (Fig. 2). The 4G core, which began in 1984, was stopped in February 1990 at a depth of 2546 m due

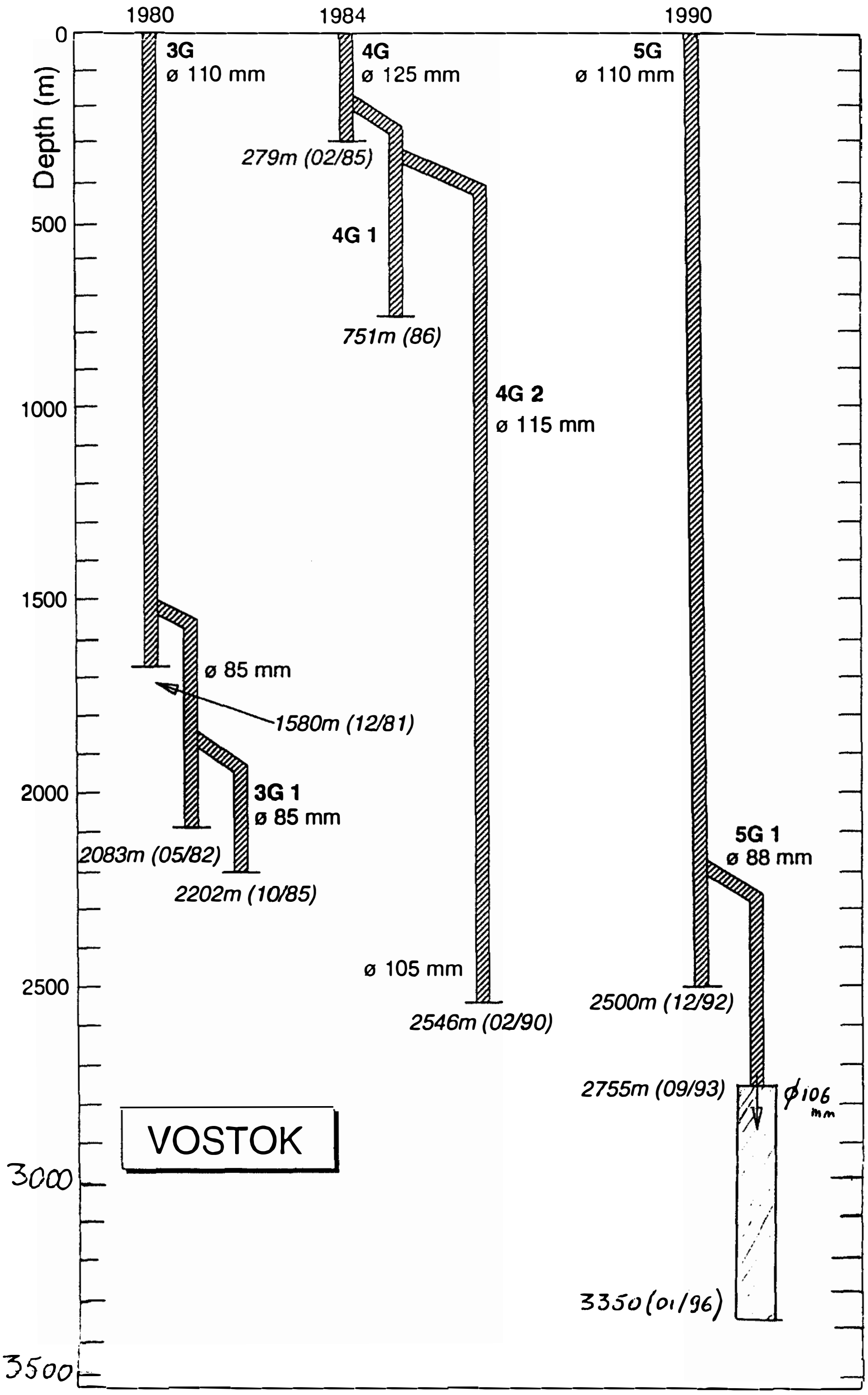

Fig. 2. Vostok drilling has been a long-term effort of Russian glaciologists. Several successive bore holes have been necessary before reaching the present depth of 3250 m.

to the loss of the drill and the cable. A new borehole (5G) began in 1990. After 2 years of drilling, the drill was lost at 2250 m depth, but fortunately coring activities could resume a few months later. 2755 m depth were reached in winter 1993, 3100 m in September 1995.

Finally, before closing for 1996 winter, the "world record" was won in January 1996 with 3350 m [3523 m in January 1997]. Preliminary analyses (water stable isotopes) and measurements (ECM) on these very last cores indicate that the Vostok ice record is now covering four full glacial and interglacial stages climatic stages, *i.e.* about 410000 years. It is estimated that 350 m of ice are still to be drilled before reaching the ground, but the lake detected under the ice sheet at this location could complicate the completion of the ice coring effort.

Ice samples are analysed not only at LGGE but also near Paris at LMCE (Laboratory for Climate and Environment Modeling, Nuclear Research Center Saclay) and CSNSM (Center of Nuclear Spectrometry and Mass Spectrometry, University of Orsay). From 160000 years studied and published in 1987, the records were extended in 1993 back to 220000 years (JOUZEL *et al.*, 1993, 1996), which represents two full ice ages and even the end

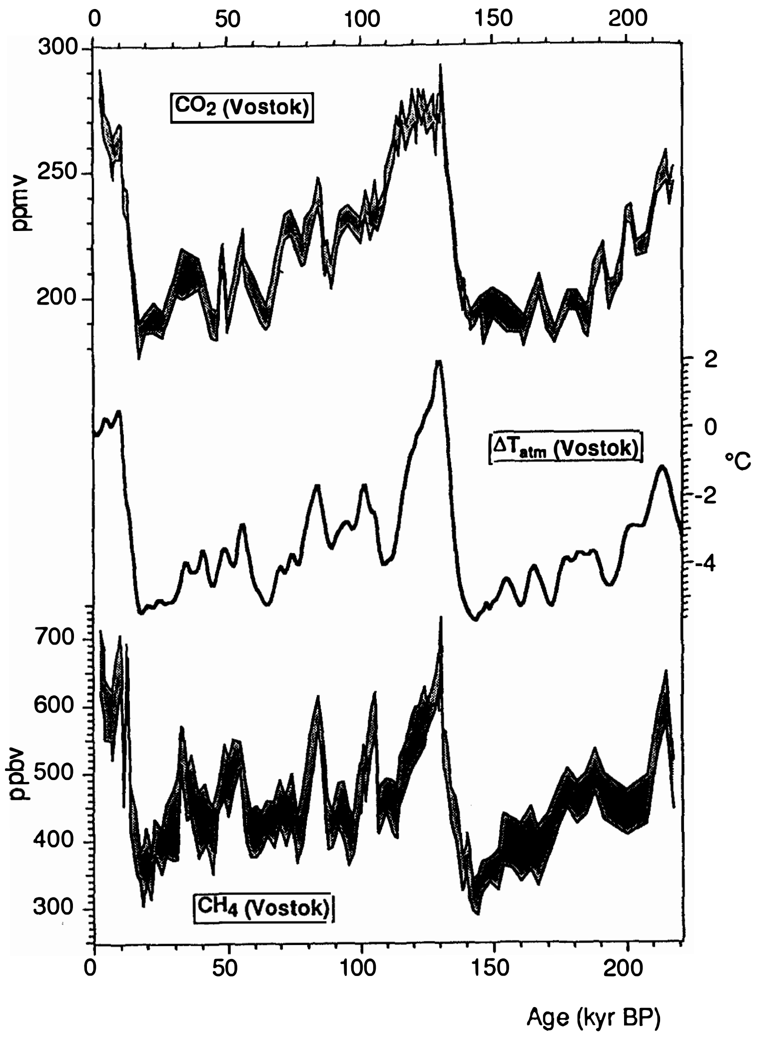

Fig. 3. Methane and carbon dioxide concentrations are low during glacial periods. This is one of the most significant observations obtained from the study of the Vostok core over the last 220000 years. Methane concentrations mimic particularly well temperature changes (from JOUZEL et al., 1993).

of the preceding interglacial. The chronology correlates well with oceanic records. The conclusions of 1987 are roughly confirmed by the new data set, *i.e.* lower greenhouse gases concentrations (BARNOLA *et al.*, 1991; RAYNAUD *et al.*, 1993) (Fig. 3) and higher dust deposition (PETIT *et al.*, 1990) in cold climatic conditions. However, the penultimate glacial period (PGP), lasting from about 140 to 200 kyr B.P., appears to have been more uniformly cold than the last last glacial maximum (LGM). The dust record shows that, like LGM, PGP was characterized by more dust produced from desert areas and transported to Antarctica. CO_2 concentrations are low from 140 to 190 kyr B.P., with values similar to the ones observed for the second part of LGM. Also similar, or even sometimes slightly lower than during the LGM, the lowest methane concentrations are observed only for the last stage of PGP. In collaboration with a japanese group, gas clathrate formation have been investigated in relation with crystal size (UCHIDA *et al.*, 1994). Ion concentrations, in particular those concerning the major global cycles of S and N, have also been determined and related with long-term changes of the atmospheric environment (LEGRAND *et al.*, 1988, 1991, 1992a). Two marked peaks of ^{10}Be concentrations (35 and 60 kyr BP) have been found. They were interpreted as reflecting changes in global production of this radionuclide and not being due to snow accumulation changes (RAISBECK *et al.*, 1987).

3. Eurocore

The Eurocore project was conceived and first discussed at an atmospheric chemist meeting organized in Ringberg, Bavaria, in November 1985. Officially accepted and funded by CEC Brussels and Swiss authorities in January 1988, it permitted to re-activate European ice core drilling activities in Greenland.

The studies developed in the framework of Eurocore and Eurocore-Follow Up concern the 10% shallowest meters (the recovered "Eurocore" is 306 m long) of the Greenland ice cap at Summit (72°58′N, 37°64′W; elevation: 3200 m a.s.l.). They can therefore be considered as pre-GRIP operations (see below). However, Eurocore was clearly an atmospheric chemistry-oriented project whereas the objectives of GRIP were rather paleoclimatic.

The overall objective of Eurocore was to help decision-makers to estimate more accurately the consequences of atmospheric pollution on the global environment and climate.

The following topics were more specifically addressed in this project:

1- the atmospheric chemistry changes and the composition of the pre-industrial atmosphere from approximately 800 A. D. to present,
2- the determination of the natural sources of atmospheric impurities, their transport ways, and deposition mechanisms on the snow,
3- the changes in composition, concentrations and seasonal deposition patterns of chemical species caused by anthropogenic activities since 1840 A. D.,
4- the improvement of the central Greenland ice record of climate changes over the millennium by detailed isotope studies,
5- the interplay between climate and atmospheric chemistry, in combination with other paleoclimate records.

Initially proposed for 4 years (1988-91), the project lasted finally longer due to the simultaneous involvement of European glaciologists in GRIP. In addition to LGGE, the main institutions in charge of Eurocore were the Geophysical Institute of the Copenhagen University and the Physikalisches Institut of the Bern University. A few other European laboratories participated in the analytical phase of the ice samples for specific measurements.

A new strategy of ice core study was defined by the partners: it was decided to develop novel and specific analytical methods (*e.g.* for H_2O_2, NH_4. . .) to be used in a scientific trench (Fig. 4) and to run an ion chromatograph in a warm laboratory for major ion analyses in the field (LEGRAND *et al.*, 1993). It was expected to obtain (partly by field measurements, partly in home laboratories) the ion budget of the soluble impurities, putting special emphasis on gas-derived compounds like HNO_3, H_2SO_4 and carboxylic acids.

The 306 m ice core and several hundred meter cores were recovered in July 1989.

Eurocore Follow-Up was proposed two years later, mainly to foster the determination of new environmental parameters from ice cores. This complementary research was composed of four individual projects: the determination of S and N isotope ratios on sulfate and nitrate ions, respectively; the determination of particulate and soluble carbon and the speciation of organo-lead pollution.

Most of the initial objectives of Eurocore have been fulfilled, in some cases more completely than expected. At LGGE and in French laboratories, the emphasis was put on the following topics: water stable isotopes and deuterium excess for climate research, major ion chemistry, cycles of carboxylic and fluoride anions, pollution by heavy metals (lead, copper, zinc, cadmium, BOUTRON *et al.*, 1992, Fig. 5), lead isotope composition (with Australian collaboration, ROSMAN *et al.*, 1993), organolead compounds (with Belgian collaboration, LOBINSKI *et al.*, 1993), reconstruction of greenhouse gas (CO_2, CH_4) and CO concentrations (HAAN *et al.*, 1996) and determination of total organic carbon (CACHIER, 1995).

Fig. 4. Eurocore scientific trench at Summit (July 1989).

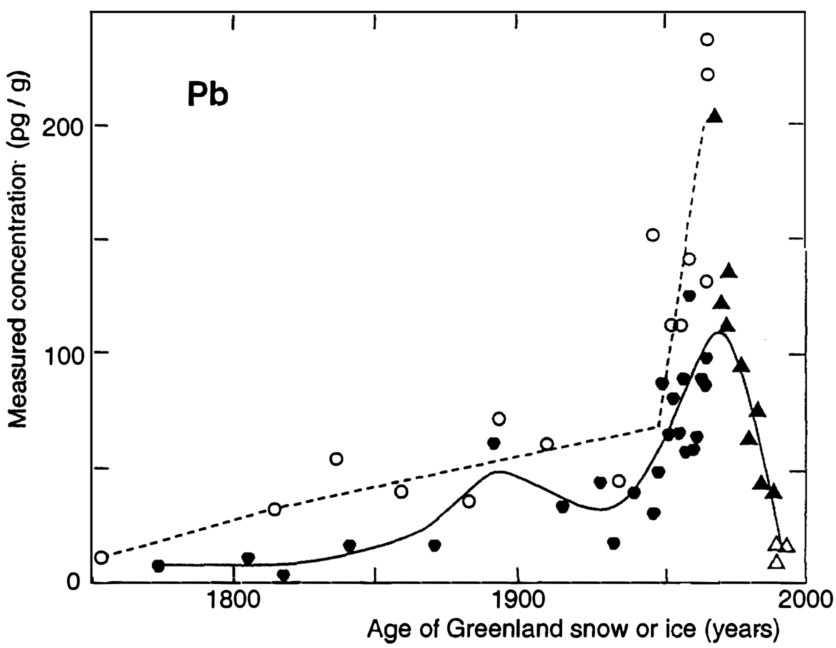

Fig. 5. *Changes in lead concentrations at Summit (central Greenland) over the last two centuries. Full triangles are Eurocore data (*Boutron *et al., 1992).*

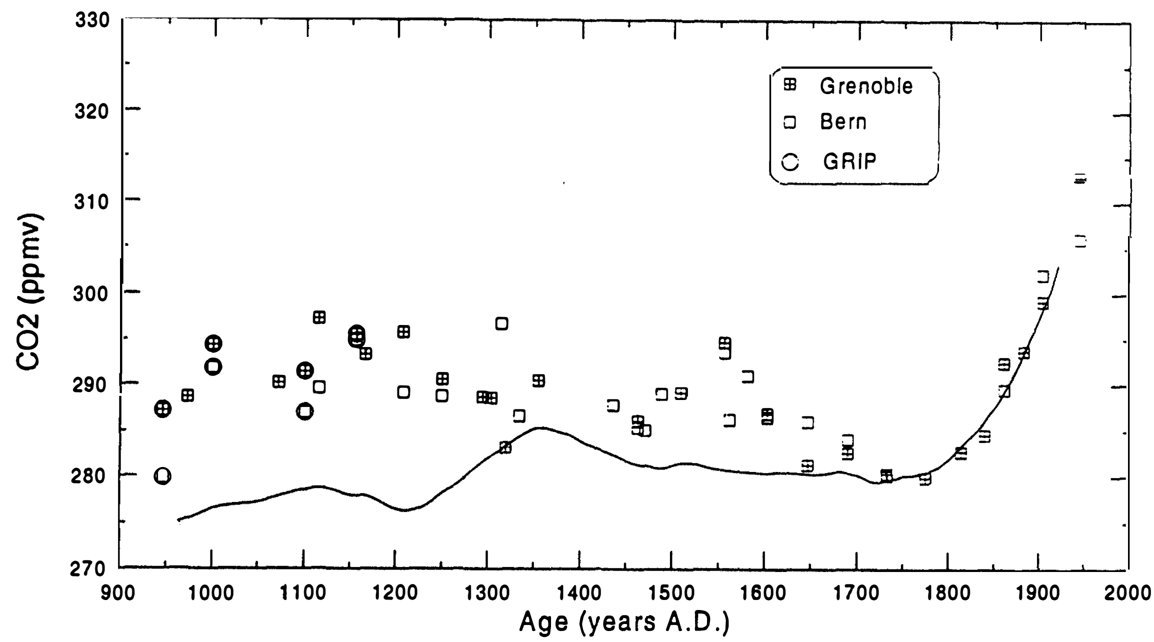

Fig. 6. *Reconstruction of carbon dioxide concentrations over the last millennium from Eurocore (squares), GRIP (circles), and Antarctic (continuous line) data (from* Barnola *et al., 1995).*

Eurocore contributed to several technical and scientific advances and experiments, such as:

— Development of analytical methods especially applicable for continuous measurements on ice cores (FUHRER *et al*., 1993; SIGG *et al*., 1994),

- Study of some physico-chemical processes like: the air/snow transfer function of atmospheric impurities (SILVENTE and LEGRAND, 1995), the occlusion of trace gases at the firn to ice transition (SCHWANDER *et al*., 1993), and the redistribution of acid gases in the firn layers (DE ANGELIS and LEGRAND, 1995; FREYER *et al*., 1996),
- Detection of new environmental trace species (*e.g*. fluoride ion and carboxylic acids, DE ANGELIS and LEGRAND, 1994),
- Identification of the source of natural or anthropogenic atmospheric compounds (LEGRAND *et al*., 1992b; ROSMAN *et al*., 1993; LEGRAND *et al*., 1997)
- Pointing-out of pre-industrial fluctuations for the greenhouse gas concentrations over the last millennium (BLUNIER *et al*., 1993) and of a CO_2 interhemispheric gradient (BARNOLA *et al*., 1995, see Fig. 6).

4. GRIP

LGGE was strongly involved in GRIP, a European research programme which developed from 1989 to 1994 at Summit, central Greenland. Most European glaciological groups participated in this multinational effort, with the objective of recovering a broad spectrum of informations on past environmental changes of global concern in the field of climate and atmospheric environment (STAUFFER, 1993).

The field camp was installed in July 1989 (in parallel with the Eurocore operation) and during the early 1990 summer season. Most of the logistical equipment which served for Eurocore was re-used. The Eurocore subsurface laboratory was extended up to 30 m long. Three summer seasons were necessary to reach the ground, on July 12, 1992, at 3029 m below the surface of the snow (Fig. 7), with the aid of the danish-swiss electromechanical drill "ISTUK". The core diameter was 10 cm and the typical core length recovered in one run was about 2.5 m.

LGGE glaciologists and French scientists participated in GRIP in many ways. Our drillers joined the international team in charge of operating "ISTUK". French scientists were more specifically involved in water stable isotope, long-lived cosmic radioisotope, major ion chemistry, heavy metals and greenhouse gas measurements. They also participated actively in the paleoatmospheric modelling effort based on obtained data. Due to the very important amount of samples to be analysed for multiple parameters, the investigation based on GRIP sampling is still continuing in 1996.

First of all, isotope measurements confirmed that climate of the Northern Hemisphere is generally unstable (DANSGAARD *et al*., 1993; GRIP Project Members, 1993). Rapid variations are observed for glacial ages and climatic transitions (JOHNSEN *et al*., 1992). For instance, 22 interstadials were found over the last glacial period (DANSGAARD *et al*., 1993). More surprisingly, drastic climate variations were also observed for part of the last interglacial (called "Eemian", 140–110 kyr B.P., a relatively warm period, often suggested as an analog to our present climate after a greenhouse warming). However, this pure climatic interpretation of the variations in interglacial climatic conditions was made questionable a few months later by the publication of the results obtained in GISP2, the American equivalent programme developed 30 km from GRIP site and terminated one year after GRIP. Both data sets are in excellent agreement up to 2700–2750 m depth, but the

Fig. 7. *The very last GRIP ice core is recovered on July 12, 1992. Note the dark color of the ice, due to its high content in rock powder.*

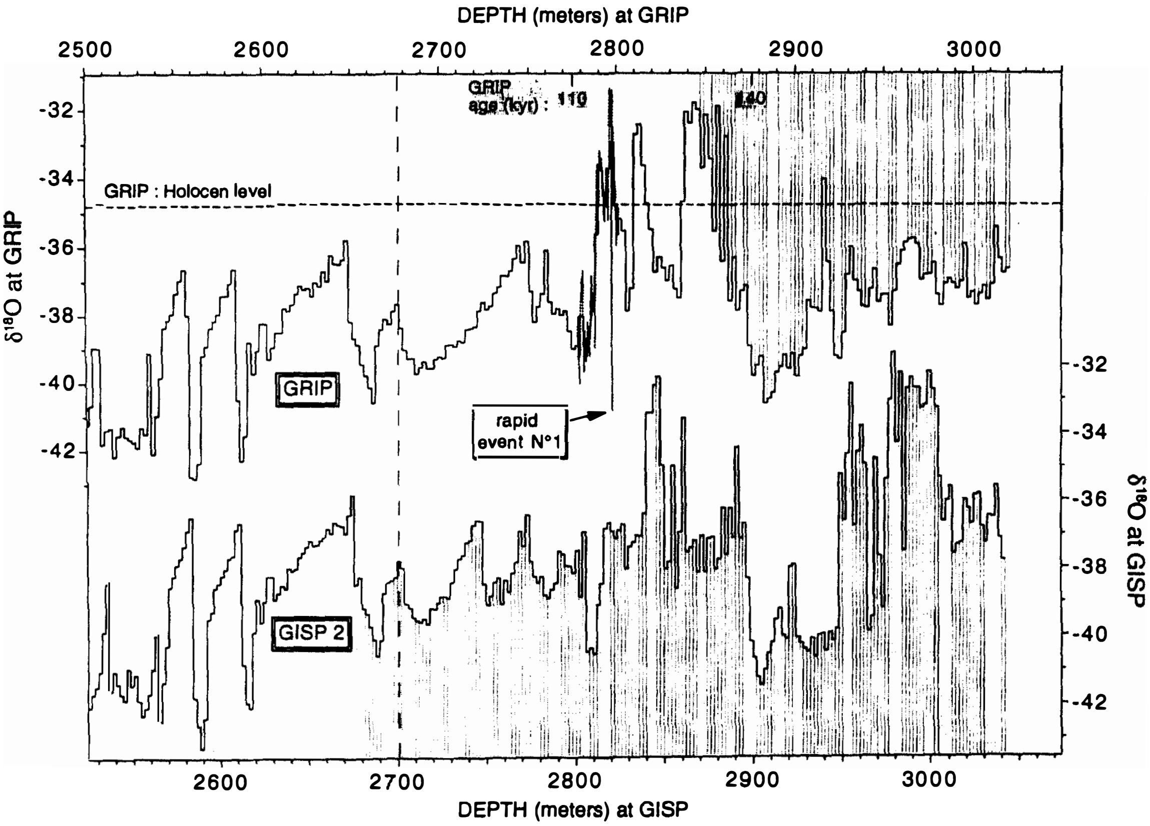

Fig. 8. *Isotope record of the deepest part of the GRIP core. Below 2700 m depth, differences are observed between the GRIP and GISP 2 records, suggesting disturbances in the layering of the ice (from* JOUZEL *et al., 1994).*

bottom 10% of the isotope records differs markedly (TAYLOR *et al.*, 1993; GROOTES *et al.*, 1993; JOUZEL *et al.*, 1994) (Fig. 8). It is probable that the differences between the records result from flow deformation occuring in ice layers located in the last hundred meters close to the bedrock (JOHNSEN *et al.*, 1995).

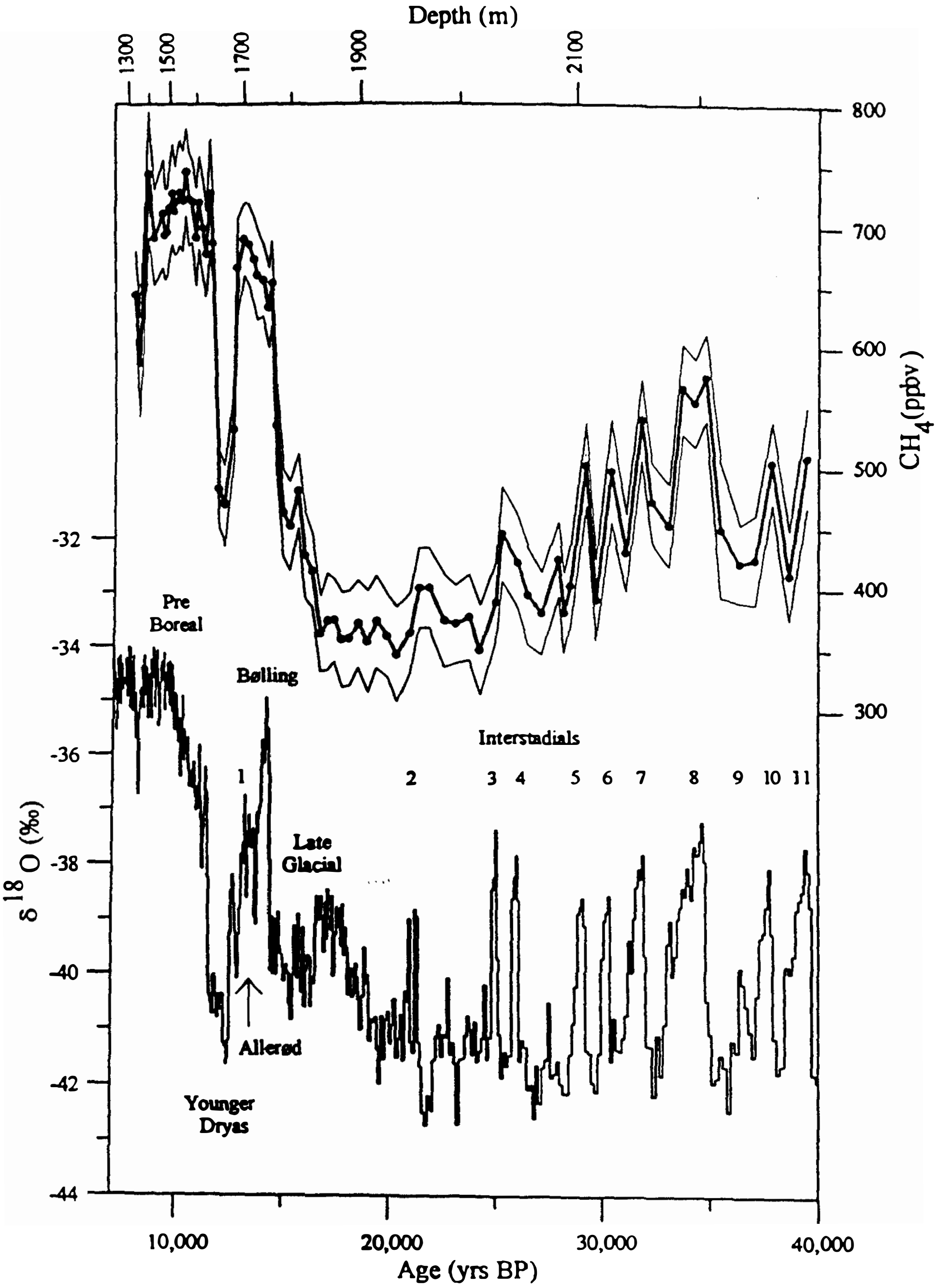

Fig. 9. Variations of methane concentrations in the GRIP core for the time period 10–40 kyr B.P., compared to isotope temperature profile. Note that variations of both parameters look very similar. Rapid climatic events are well marked for methane (from CHAPPELLAZ *et al., 1993).*

GRIP and Vostok time scales correlate satisfactorily over about the last 100000 years. The agreement is less convincing for the preceding climatic periods due the glaciological disturbances earlier mentioned. All the difficulties on the deepest part of the GRIP core does not make us forget the wealth of paleoenvironmental information gathered from the upper hundreds of meters of high quality ice records.

In addition to pure climatic phenomena, GRIP results revealed the importance of continental biological processes for global atmospheric composition whereas in Antarctica the influence of the surrounding oceans is very significant. Measurements shown that emissions from boreal forest fires and vegetation play a major role in atmospheric chemistry (LEGRAND *et al*., 1992b, 1995). Continuous measurements of ammonium along the core revealed long-term changes of ammonia emissions from soil and vegetation in the Northern Hemisphere (FUHRER *et al*., 1996). Temperature changes are therefore not only identified by water isotope composition, but also by the environmental changes which follow climatic variations. The concentration of such a compound like methane, which depends mainly on soil humidity (BLUNIER *et al*., 1995), mimics astonishingly temperature variations (CHAPPELLAZ *et al*., 1993, Fig. 9). The concentrations of formic and acetic acids seem to be closely linked with the extent of vegetation at mid to high northern latitudes (LEGRAND and DE ANGELIS, 1995).

Regarding marine biogenic activity, sulfate and methanesulfonate (MSA) measurements are not in agreement with Antarctic data. In particular, high MSA values are not observed in glacial conditions (LEGRAND *et al*., 1997). Marine biogenic activity is responsible for the relatively high sulfate content of Antarctic precipitation whereas, in the North, this influence is much less sensible. On the other hand, volcanic sulfate is probably a more important contribution in Greenland than in the Antarctic. Eruptions of global concern have been detected by electro conductometric measurements carried out in the Summit scientific trench along the Eurocore and GRIP cores (CLAUSEN *et al*., 1995). The various components of ice electroconductivity have been assessed (MOORE *et al*., 1994).

Huge amounts of alkaline dust are transported in the glacial atmosphere and deposited in Greenland. This input changes markedly the chemical and physical properties of the ice corresponding to cold periods. During climate transitions, it may have also an indirect impact on the concentration of carbon dioxide in the air bubbles of the ice (DELMAS, 1993).

The analysis of the upper part of the GRIP ice core demonstrated that mining activities during Greek and Roman times have had also a marked influence on the atmospheric cycle of lead (HONG *et al*., 1994) and copper (HONG *et al*., 1996).

Detailed ^{10}Be measurements along the GRIP core (YIOU *et al*., 1997) shown that concentration changes of this radionuclide are primarily linked to snow accumulation changes. However, a solar and geomagnetic modulation is also detected, as also possibly primary cosmic ray variations. The most recent (about 38000 B.P.) of the two peaks found in the Vostok core is well recorded in GRIP.

The analysis of the chemical composition of the gases entrapped in basal ice has revealed unexpected phenomena which are presently not fully understood (SOUCHEZ *et al*., 1995a, b).

Finally, thorough ice physics studies on the GRIP core have been carried out in the field and in the laboratory by three European groups working in collaboration. In particular, the data obtained from this core offered a unique opportunity to test polycrystal models (CASTELNAU *et al.*, 1996).

5. North GRIP (NGRIP)

In the lower 300 m, we made mention that the results of GISP2 and GRIP ice cores do not agree totally. Flow effects are suspected. NGRIP operation was decided to better document that period of time, before 100 kyr BP, where the dating of the ice layers is seriously questionned. Drilling started in 1996 at a site located some 300 km NNW from Summit, under the leadership of Denmark and Germany and with the participation 7 additional nations (incl. France). It is expected that at this site the interested time period is situated farther from the ground and therefore less disturbed than at Summit.

6. EPICA

After several years of successful common efforts in central Greenland, European glaciological laboratories decided to work in central Antarctica, with the objectives of reconstructing high resolution histories of past changes in climate, ice cover and atmospheric composition and circulation, for a time period spanning several glacial-interglacial cycles. This project (LORIUS and JOUZEL, 1996) named EPICA (European Research Programme in the Antarctic) will be a major contribution to the international effort aimed at understanding climate change, in accordance with the recommendations of WCRP, Past Global Changes (PAGES) of IGBP and Scientific Committee for Antarctic Research (SCAR).

Specific scientific topics of global concern will be addressed: the link between atmospheric chemistry and climate, the rôle of Antarctica on the climate changes recently found in Greenland ice cores, the development and testing of ice sheet and atmospheric circulation models.

This research will complement previous information obtained from Greenland ice cores and it is expected to answer to open questions like:
— are the rapid warming events seen in Greenland in the last ice age global ?
— what about the stability of the Holocene climate ? Is it typical of interglacial periods ?
— are global climate changes triggered by Greenland or Antarctic phenomena ?

Two regions have been selected for deep drilling:

Dome Concordia ("Dome C", 75°07′S, 120°20′E, Fig. 1) has been chosen as the first ice coring site. Due to favorable glaciological conditions, the climatic record is expected to be undisturbed over the last 500000 years (about 3300 m of ice). Long term climatic changes and potential forcing factors (greenhouse gases, aerosols, solar activity, volcanic events) will be studied. France and Italy are more specially involved in the Dome Concordia project.

The second site will be located in Dronning Maud Land, where higher accumulation rates will allow more detailed temporal resolution of the records.

These two sites, situated in two very different geographical sectors of the Antarctic continent, are submitted to different climatic and environmental regimes. Together with American (West Antarctica) and Japanese (Dome Fuji) projects, European research will contribute significantly to the coverage of the Antarctic ice sheet.

The first phase of EPICA is presently being started at Dome Concordia. The deep-drill has been developed and constructed at LGGE in conjunction with the North GRIP project in Northern Greenland and the drilling operation is anticipated to begin at the end of 1996 for a duration of 3 summer seasons. In the meantime, the detailed geophysical reconnaissance and preliminary shallow drilling in Dronning Maud Land will be performed, in order to select the optimal drilling site of the second phase of EPICA, planned for the turn of the century.

7. Conclusion

In about ten years, ice core studies in both polar regions have documented not only past climate changes but also the modifications of the global environment which are generally the consequences of (but which may also significantly contribute to) climatic variations. LGGE has participated actively in the international effort, in particular in the framework of CEC (Commission of the European Community) environmental research programme. More ice core work is still needed in Antarctica. Each of the various geographical areas of this vast continent deserve specific projects. This will be the task of the international glaciological community. Several nations (United States, Russia, Japan, Europe. . .) have already defined their programmes. Europe has selected two sites for Epica. France will be strongly involved in the Dome Concordia ice coring, which will complement the paleoclimatic information currently discovered from the Vostok core.

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(Received December 2, 1996; Revised manuscript accepted May 16, 1997)