Extending the ice core record beyond half a million years

Eric Wolff, Matthias Bigler, Emiliano Castellano, Jacqueline Fluckiger, Gerhard Krinner, Fabrice Lambert, Amaelle Landais, Angela Marinoni, Alessio Migliori, Mart Nyman, et al.

geogenic natural gas (F. Slemr, personal communication, 2002). Between the cities of Vyatka and Perm, as well as along the Tyumen–Omsk–Novosibirsk route, there are natural gas pipelines, and between Krasnoyarsk and Irkutsk, there are crude oil pipelines with the corresponding storage, condensate removal, and transport facilities that could be responsible for leaking CH_4 and light non-methane hydrocarbons. The frequency of air sampling for NMHC analysis is still not optimal and will be increased to support CH_4 source identification in future campaigns. In situ ethane measurements, in parallel to available CH_4, would also significantly benefit these studies.

Diurnal variations of ^{222}Rn, CO_2, and CH_4 concentrations due to micro-meteorological and boundary layer conditions, as well as their dependence on various soil sources and vegetation types, have been used to estimate the actual ecosystem fluxes of CO_2 and CH_4 from soils. The highest summer wetland release of CH_4 was ~70 ± 35 μmol m^{-2} h^{-1} for the West Siberian wetlands, and the lowest CH_4 efflux was ~3.2 ± 1.6 μmol m^{-2} h^{-1} for drier habitats of eastern Siberia [*Oberlander et al.*, 2002]. Conversely, while ambient CO levels of the West Siberian lowlands in summer were generally 110–135 ppbv or lower, very high CO concentrations, up to 1.5 ppmv, were registered east of Chita (~ 52°N; 113°E).

During the TROICA-5 experiment in June–July 1999, the most pronounced enhancements of CO were registered due to peat fires in Central Russia and due to extensive forest fires in the Russian Far East region. The peat burning plumes in the European part of Russia were intercepted over ca. 150 km, showing the highest CO mixing ratio observed during this campaign, i.e. 2467 ppbv. The CO concentration increase, reaching 1071 ppbv on the 1500-km section of the Russian Far East, was unique in extent reflecting severe wildfires. These fire events also caused a concomitant increase of CH_4, with high peaks exceeding 2 ppmv, and NO concentrations of ca. 2 ppbv. Back trajectory analysis confirmed the interception of fire plumes. Using ^{14}CO measurements, *Bergamaschi et al.* [1998] unambiguously showed, that in summer 1996, biomass burning caused an unusual increase in CO mixing ratios between Chita and Khabarovsk (Figure 2, TROICA-2, summer 1996). The nighttime O_3 concentrations increased up to 30 ppbv and higher were also registered on the Chita–Khabarovsk route, during eastbound and westbound parts of TROICA-2.

Similarly to TROICA-2, high nighttime O_3 values in eastern Siberia during TROICA-5 were observed in areas with tremendous CO concentration increases. This and back trajectory analysis indicate that TROICA-5 O_3-rich nocturnal events in the Russian Far East were most likely the result of extensive forest fires. Generally, ozone levels showed large diurnal variation between 0.4 ppbv at night and 65 ppbv in the daytime (TROICA-5, summer 1999) [*Oberlander et al.*, 2002]. Identifying the major regional sources of ozone precursors, such as VOCs, CO, and NO_x, will provide new insights into the degree and processes of photochemical O_3 formation in Russia, particularly the influence of Siberian forest fires on the regional and larger scale.

During the summer campaign in 2001 (TROICA-7), high levels of nocturnal O_3 of 45 ppbv and higher were observed in European Russia—near the western side of Ural Mountains—and in West Siberia, which originated from sources other than vegetation fires. The back trajectory analysis showed that air masses were transported from northwestern Russia where extensive oil and gas fields are situated. The photochemical O_3 production under VOC and NO_x-enriched conditions from oil/gas exploitation might have played a significant role, but a more systematic study is required.

Summary

Using the detailed set of data in Figure 2, we have shown that the TROICA train-based measurements provide invaluable information for climate-related studies of European and Asian Russia. It covers the continental ecosystems area of almost 100° in longitude (37.7–135.0°E) in latitudinal belt of 48.5–58.5°N—an area most sensitive to climate change. With relatively low investment and operational cost requirements, continuous in-situ measurements of O_3, N_2O, NO_x, CO, CO_2, CH_4, ^{222}Rn, halocarbons and other trace gases were obtained without significant contamination from the train. Using the Trans-Siberian railway to survey the atmospheric boundary layer over vast distances of Russia plays a significant role in air pollution studies and helps provide information on emissions, which in the future could be used for regional and global models.

Authors

Eva A. Oberlander, Carl A. M. Brenninkmeijer, Paul J. Crutzen, Jos Lelieveld, and *Nikolai F. Elansky*
For additional information, contact Eva Oberlander, Air Chemistry Department, Max Planck Institute, P.O. Box 3060, D-55020, Germany; E-mail: eao@mpch-mainz.mpg.de

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Extending The Ice Core Record Beyond Half A Million Years

PAGES 509, 517

Ice cores have been a crucial source of information about past changes in the climate and atmosphere. The Vostok ice core from Antarctica has provided key global change data sets extending 400,000 years in the past [*Petit et al.*, 1999], while Japanese scientists drilling at Dome Fuji have obtained records extending to 330,000 years. Now, a new core being drilled by a consortium of European laboratories has surpassed these ages, and looks like extending the ice core record several hundred thousand years into the past.

Ice cores are unique: of all the paleo-records, they have the most direct linkage with the atmosphere. At some sites, the time resolution is sufficient to study extremely fast climate changes; and they have information about many forcing factors for climate (including greenhouse gas concentrations) displayed in the same cores as the resulting climate changes.

Ice cores have already played a central role in informing the debate about global change, providing the only direct evidence of historical changes in greenhouse gas concentrations, the clearest evidence of past linkage between greenhouse gases and climate, and the first indication that very rapid climate changes (linked to changes in thermohaline circulation) occurred in recent Earth history.

Both European and U.S. ice core scientists scored major successes with the completion of cores to bedrock in central Greenland in the early 1990s (the Greenland Ice Core Project (GRIP), and the Greenland Ice Sheet Project Two (GISP2)) [*Hammer et al.*, 1997]. To follow this up, the next challenge was to produce a series of equally definitive records from Antarctica. The European team turned their eyes to central Antarctica, and formed the European Project for Ice Coring in Antarctica (EPICA). This is a consortium of laboratories from 10 European nations, under the auspices of the European Science Foundation (ESF), and funded by the European Union (EU) and national organizations.

EPICA aims to drill two cores to bedrock, one at Concordia Station, Dome C (75°06′S, 123°24′E), the other at Kohnen Station in Dronning Maud Land (DML) (75°00′S, 00°04′E). The Dome C drilling aims to retrieve a record covering a time period that is as long as possible, while the DML drilling aims to retrieve a high-resolution record of one complete glacial-interglacial cycle at a site facing the Atlantic Ocean.

The DML drilling made a successful start during the 2001–2002 austral summer, completing the drill installation, and penetrating to 450.94 m depth, which means the core has reached early Holocene ice. At Dome C, this was a major year of drilling, with the drill reaching 2864 m below the surface, just 400 m above the estimated depth of bedrock. This article describes the work at Dome C during the past season.

Constructing Antarctica's Third Inland Permanent Station

Dome C is a remarkable location, over 1000 km from the coastal stations that supply it, with a mean annual temperature of below -50°C and an annual snowfall of just 3 cm water equivalent per year. The arriving visitor is struck first by the thin air (at an altitude of 3233 m above sea level); and then, by the temperature, which only rarely rises above -20°C at midsummer; and finally, by the generally light winds and clear weather—a corollary to the low snowfall rate.

The summer camp at Dome C (Figure 1) is a collection of buildings housing up to 50 people for 10–12 weeks each summer. It forms a surprisingly cozy "international village," supplied by Twin Otter aircraft originating from the Italian Terra Nova Bay coastal station, and by tractor trains that make three round trips each year. The latter carry heavy equipment from the French Dumont d'Urville station, 1100 km away. Some of the summer personnel are engaged in constructing a new year-round station, Concordia, that will be operated by French and Italian Antarctic organizations as only the third inland Antarctic permanent station (after the U.S. Amundsen-Scott station at South Pole, and the Russian Vostok station).

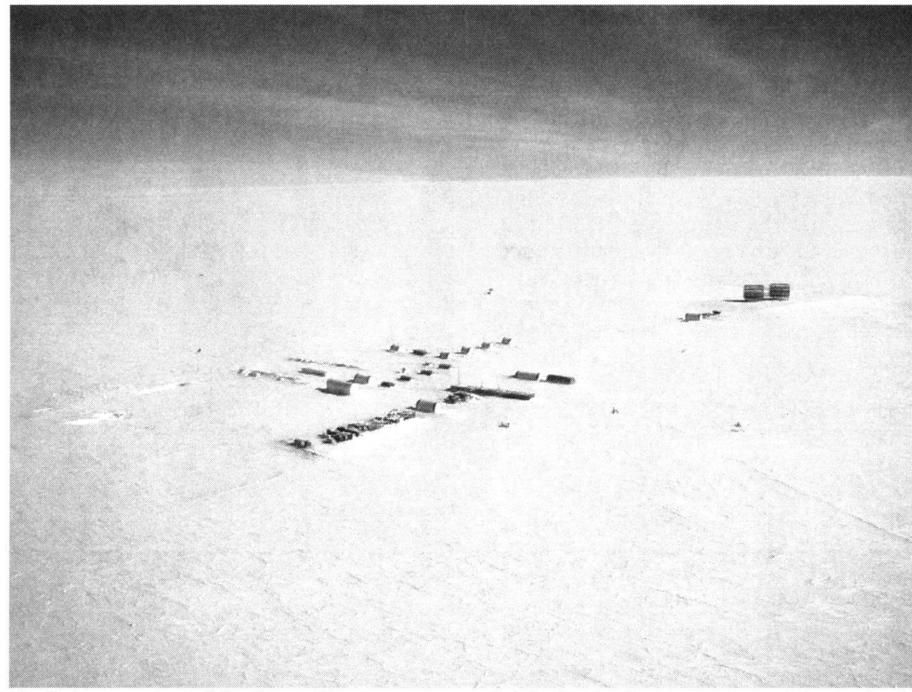

Fig. 1. An overview of the Dome C summer camp. Original color image appears at the back of this volume.

EPICA activities are located in a large drilling tent, and two laboratories. During 2001–2002, 8 drillers and 14 scientists, of seven different nationalities, occupied these facilities. A first EPICA drilling at Dome C had foundered when the drill became stuck at 788 m in 1999, but the team at the site in summer 2000–2001 had successfully drilled to a depth of 1458.19 m. As the science team that year was limited to 3 people, only preliminary measurements were made on the ice, which was left on site. There was therefore a considerable buffer of ice awaiting the 2001–2002 science team when they arrived.

Mechanics of Ice Core Drilling

The EPICA electro-mechanical ice drill is a system that has evolved from a family of equipment used in Greenland and Antarctica over 20 years or more. It produces 98-mm-diameter cores, generally in unbroken lengths of just over 3 m for each run. A typical cycle takes 90 minutes. Most of the time is spent lowering the drill down the hole to the drilling depth, and raising it again. In the middle are the tense few minutes when the drill is cutting new core, and the drillers are monitoring the cutting parameters supplied by the electronics package to ensure that the drill is cutting in a normal manner. The hole is kept open by balancing the pressure of the flowing ice by filling it with a suitable drill fluid.

The drilling team worked round the clock in shifts for most of the season (Figure 2), and by the end, they had reached way beyond their target for the season, to 2864.19 m (as measured by the core processors). That means that there is less than 400 m left to reach bedrock. The remaining drilling is unlikely to be straightforward; the ice near the surface has a temperature close to the mean annual temperature of Dome C air, but warms as it approaches the bed toward temperatures uncomfortably close to the pressure melting temperature. Drilling next season will therefore have to be carried out with great care, and new designs of cutting head to cope with the warm ice are currently being tested.

Once the new length of ice has been retrieved, it is cleaned of fluid, and added to the buffer of core awaiting attention from the team of core processing scientists. The well-insulated, 40-m-long science shelter is maintained at a temperature of -20°C: this is an excellent temperature for maintaining the cores, but a challenging environment for the scientists! Once the core has been physically measured and marked, its electrical properties are measured in the dielectric profiler (DEP). It then passes through a series of bandsaws that dissect the cross-section into pieces for different measurements and laboratories. A qualification in cold-temperature carpentry would be an excellent preparation for a season in the EPICA science shelter!

Analyzing the Cores

A first sliver of ice is cut into samples that are mounted on glass slides so that thin sections can be made and photographed in a second, smaller shelter. This reveals the changes in crystal size and orientation. A second part of the core is sliced into 11-cm lengths that are packed for analysis of oxygen isotopes and deuterium of the ice; this is the proxy used by ice core scientists to estimate the past temperature. A further piece is used for chemical analysis of the ice in the field (described below). Another electrical conductivity measurement (ECM) is made on the cut core, and the remaining parts are sectioned for return to Europe for analysis of gases (such as CO_2), dust, mechanical properties, and a host of other measurements. Finally, at least a quarter of every core is carefully packed in plastic bags in boxes that are stored in a snow cave at Dome C—the one place where the cold temperatures ensure that our archive will be safe from freezer failures!

The chemical analysis of the ice is partly carried out in the field. A square section strip of ice is mounted on a hotplate, and the melt from the inner, clean part of the core is sucked into a warm laboratory (+20°C), where it is analysed for liquid conductivity, dust content, hydrogen peroxide, formaldehyde, and a wide range of inorganic ions (sodium, calcium, ammonium, nitrate, chloride, sulfate) in a continuous flow analysis system [*Röthlisberger et al.*, 2000], and a fast ion-chromatography system [*Udisti et al.*, 2000].

The scientific team also exceeded all expectations, processing the core from 770 m to 2200 m depth. The data and samples from this processing are now distributed in many laboratories around Europe.

The deepest ice drilled last season remains in the core buffer at Dome C, and will be processed during the austral summer 2002–2003. On this part of the core, only the DEP measurement was made in the field (Figure 3). Although DEP conductivity responds to a variety of ions [*Wolff et al.*, 1997] under the conditions at Dome C, it is essentially measuring the acidity of the ice. In Antarctica, this does not vary in a simple way with climate, so it is difficult from the DEP data alone to assign climatic periods to the ice, and therefore, to estimate the age of the ice. However, the signal from marine isotope stage (MIS) 5E is seen very clearly at around 1570–1730 m depth. The shape of this signal is very similar to that seen in the same period in the ECM record from the Vostok core [*Petit et al.*, 1997], and the depth is close to that predicted from the glaciological age model used to date the upper sections of the ice.

It then appears as if each glacial cycle is characterized by a generally upward trending ramp through the glacial period (with a lot of structure superimposed), culminating in a high (acidic), square-shaped, interglacial episode. If this is true, then we can assign the previous interglacials as indicated in Figure 3.

The first analyses for deuterium (G. Dreyfus and J. Jouzel, personal communication, 2002) of the ice to 2200 m depth (which can be matched to Vostok core data) confirm our assessment to that depth. Glaciological models (F. Parennin, personal communication, 2002) for the age-depth relationship, in which the date for MIS 5E is fixed, also support our assignments, and will not allow any other reasonable solution. The ages implied by these models are shown on the top of Figure 3.

Fig. 2. The EPICA Dome C drilling team shows off the core from 2000-m depth. Original color image appears at the back of this volume.

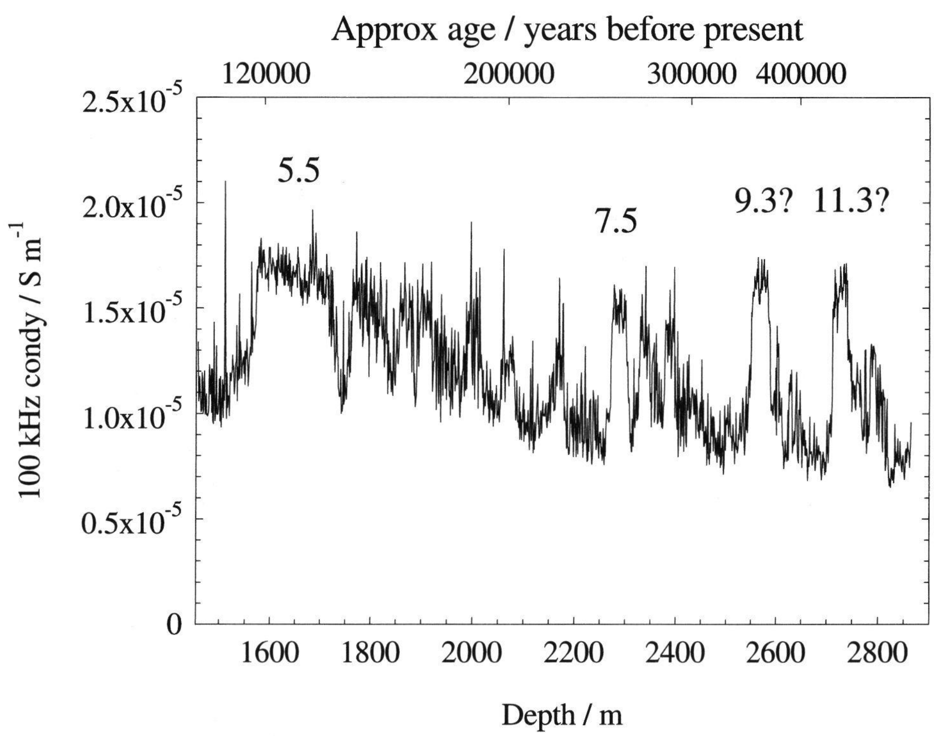

Fig. 3. Conductivity at 100 kHz (as measured by DEP) of ice from the EPICA Dome C ice core. Only the lower half of the core is shown; the upper 1500 m contains the most recent glacial cycle. Data have been averaged to 1-m intervals. The ages at the top are estimates based on a glaciological flow model as discussed in the article; the ice thins with depth, so that the time scale is increasingly compressed toward the base of the ice sheet.

Assuming that our tentative dating is confirmed by future data, then the ice at the current drill depth (2864 m) is 530,000 years old. The useable Vostok record extends to the middle of MIS 11 (below that, the meteoric ice containing a climatic record gives way to refrozen ice from the underlying lake [*Jouzel et al.*, 1999]). The EPICA Dome C core is therefore already the oldest sequence of ice brought to the surface, and should include a detailed record for all of the important stage 11.

But there is still 400 m of ice to drill. If the models are correct, and if the chronological record is undisturbed nearer to the bed, then we can expect to reach ice 800,000 years old 200 m above the bed. At this age, we will have passed through the Brunhes-Matuyama magnetic reversal, and the dominant 100,000-year astronomical cycles will yield to 41,000-year cycles. An ice core record through this transition should yield insight into the response of the carbon cycle to the shorter periods and the causes of the change.

This month, a new team of 17 drillers and scientists will set out for Dome C, via Christchurch (New Zealand) and Terra Nova Bay. They will drill as close to the bedrock as they feel is safe with the current drill head and the warmer temperatures, and will process the ice already drilled and the new material from this season. Meanwhile, the analyses from the existing ice will be continued in Europe, and we should see the first record of greenhouse gases, climate and atmospheric chemistry from stages 11 and 12 emerging in the next 18 months.

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Authors

The EPICA Dome C 2001-02 science and drilling teams.
For additional information, contact Eric Wolff, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, England; E-mail: ewwo@bas.ac.uk

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PLUME Investigates South Pacific Superswell

PAGES 511, 514

The French Ministère de la Recherche is funding a multidisciplinary project, the Polynesian Lithosphere and Upper Mantle Experiment (PLUME), to image the upper mantle structures beneath French Polynesia. This region of the southwestern Pacific, which is far from any plate boundary, comprises oceanic lithosphere with ages varying between 30 and 100 Ma, as well as two major fracture zones. The area is characterized by a "swarm" of volcanic island chains—the Society Islands, the Austral Islands, and the Marquesas—that may represent "hot spot" tracks [*Duncan and McDougall*, 1976]. The individual hot spots are superimposed on the large South Pacific Superswell [*McNutt*, 1998]. The region is also characterized by a large-scale, low-velocity anomaly in the lower-most mantle [*Su et al.*, 1994] and anomalous converted phases from the 660-km discontinuity [*Vinnik et al.*, 1997].

These observations have been interpreted as evidence of a lower-mantle "super-plume" that is at least partially blocked in the transition zone, and crowned by several small-scale "upper mantle" plumes that give rise to the hot spot tracks observed on the surface. Such an image is in rather good agreement with large-scale mantle plumes observed in recent analogic [*Davaille*, 1999] and numerical [*Brunet and Yuen*, 2000] models of mantle convection.

Thus, French Polynesia is a unique area to study active mantle plumes. The experiment will combine seismological, bathymetric, and gravimetric observations; petrophysical and geochemical investigations of mantle xenoliths brought to the surface by the hot spot volcanism; and multi-scale numerical models. Researchers will study the interaction between plume and lithosphere, probe the interaction between mantle plumes and the large-scale mantle flow, image the geometry of plumes in the upper mantle and their eventual connection with the South Pacific super-plume, and quantify the mass transfers through the transition zone.

The PLUME seismic network is composed of 10 broadband stations deployed in French Polynesia for a period of 2 years. The first were deployed in October 2001 (Figure 1). The region under study covers an area equivalent to the one being studied in Europe, with a relatively short spacing of a few hundreds of kilometers between the temporary stations. The deployment of the PLUME network has been designed to supplement the permanent Incorporated Research Institutions for Seismology (IRIS), Geoscope, and Commissariat à l'Energie Atomique (CEA) stations available in the region, providing more homogeneous instrument coverage of the entire area.

The design of the experiment should primarily benefit surface-wave tomographic studies. Except in its southern-most part, the Pacific plate is surrounded by subduction zones that provide an excellent azimuthal distribution of deep events with well-excited overtones (Figure 2). In Australia, regional waveform analysis applied in a similar context has produced a surface wave tomographic model with a lateral resolution of a few hundred kilometers for both the lateral variations in shear wave velocities and the azimuthal anisotropy [*Debayle and Kennett*, 2000]. We expect a similar lateral resolution in the whole upper mantle beneath this region from the large number of higher modes provided by the subduction zone earthquakes and the dense ray crossing beneath the PLUME network. This study should significantly improve upon previous regional and global tomographic imaging in the southern Pacific. Researchers also hope to characterize the large-scale mantle flow from surface wave anisotropy to locate possible plumes in the upper mantle, and to address the question of their lateral extent and their possible connection with a deeper, larger-scale structure in the transition zone or lower mantle.

Upper mantle flow beneath each seismic station will be probed using body waves and particularly, the splitting of teleseismic shear waves. Seismic anisotropy in the upper mantle results from intrinsic elastic anisotropy of rock-forming minerals—particularly olivine in the upper mantle—and from their preferred orientations, which developed in response to tectonic flow. Measurement of teleseismic shear wave splitting induced by seismic anisotropy can be used to probe frozen or active mantle deformation with a lateral resolution of a few tens of kilometers, and to characterize its relationship with absolute or relative plate motion. From anisotropy inferred from body and surface wave, we should be able to detect the presence of several anisotropic layers in the upper mantle that could give insight into lithosphere-asthenosphere interactions and plate motion changes.

Figure 3 is an example of an event recorded at some of the recently deployed PLUME stations. The event occurred on 31 March 2002 in Taiwan and generated SKS and SKKS phases clearly visible on the radial components, but with no energy on the transverse components. This coherent "null" splitting measurement obtained throughout French Polynesia suggests a homogeneous structure beneath the whole area, either isotropic, or with a fast anisotropic direction within the upper mantle oriented close from the event back azimuth. Interestingly, this direction is close to the absolute plate motion vector. This could explain why an anisotropy induced by the plate drag could not be seen by a Taiwan event. Other splitting measurements with different back azimuths are needed to determine the presence and

Fig. 1. An overview of the Dome C summer camp.

Page 509

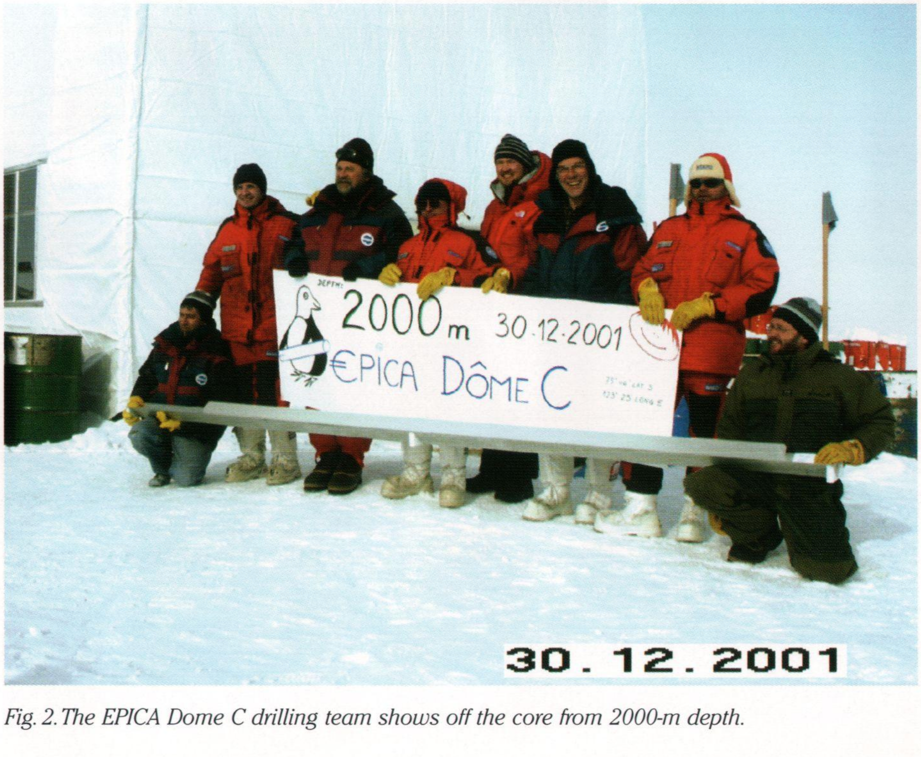

Fig. 2. The EPICA Dome C drilling team shows off the core from 2000-m depth.

Page 517