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Extending The Ice Core Record Beyond Half A Million Years

The EPICA Dome C 2001-02 science and drilling teams.
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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 its 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 a depth of 450.94 m, 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

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

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).

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 straight-forward; 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 1aboratories. A qualification in cold-temperature carpentry would be an excellent preparation for a season in the EPICA science shelter!

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

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 hot plate, and the melt from the inner, clean part of the core is sucked into a warm laboratory (+20°C), where it is analyzed for liquid electrical 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 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.

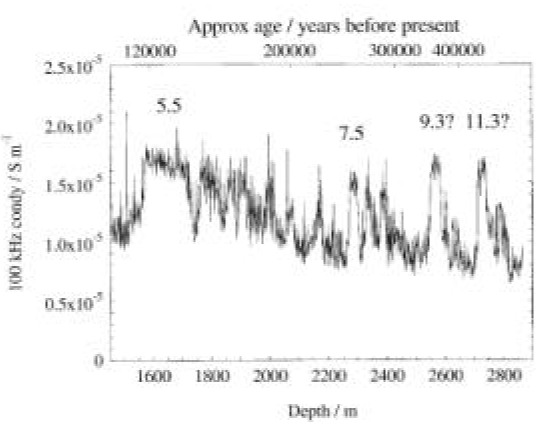

Fig. 3. Conductivity at 100kHz (as measured by DEP) of ice from the EPICA Dome C ice core. Only the lower half of the core is shown; the upper 1500 m contains the most recent glacial cycle. Data have been averaged to 1-m intervals. The ages at the top are estimates based on a glaciological flow model 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.

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.

Assuming that our tentative dating is con firmed by future data, then the ice at the cur rent 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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