The Vostok Venture: An Outcome of the Antarctic Treaty

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INTRODUCTION

Polar ice sheets and glaciers contain well-ordered archives of ancient ice that fell as snow, years to millions of years ago. With an ice blanket of more than 3 km thick and an annual precipitation rate comparable to that from hyperarid regions (equivalent to 2–5 cm water annually), the slow-moving East Antarctic plateau has considerable potential for providing a long-undisturbed ice sequence. Because of the remoteness of inland sites along with the harsh weather conditions, exploration and deployment of scientific traverses or deep ice core drilling operations require coordination of considerable logistic support, technical, and scientific skills.

Vostok station was settled at the time of the International Geophysical Year (IGY) by the Soviet Union and is a location 1,400 km from the coast at 3,488 m above sea level altitude, with an annual temperature of –55°C. Thanks to the Antarctic Treaty, which promoted the international collaboration, the study of a 2-km-deep ice core revealed the close link between temperature and atmospheric CO_2 over the last 150,000 years. This fact soon revealed the climate issues caused by increasing anthropogenic emissions of greenhouse gases.

The ice composition and impurities and the gases trapped in air bubbles provide a unique history of the past climate change and environmental and atmospheric composition. By reaching 3.4 km depth, the climate record was extended back 400,000 years, confirming the close climate–greenhouse gas relationship. This link is now further extended over 800,000 years.

At the base of the ice sheets the geothermal flux warms the ice, up to the melting point in some places. The water produced accumulates at the interface with the bedrock to form a lake. This is the case in the region of Vostok, where a giant lake lies under the station. Ice core drilling penetrated an ice massif of refrozen lake water at 3.6 km depth. The recovery of frozen lake samples opens new fields for research, especially for the search for life in this very extreme environment, which may help the search for life elsewhere.

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THE HISTORICAL CONTEXT

Vostok station was settled during the IGY on the East Antarctic plateau by the Soviet Antarctic Expedition and was opened on 16 December 1957 (Figure 1). For the image and prestige of this complex operation, the site needed to be located at a pole, and the geomagnetic South Pole was chosen. The geomagnetic South Pole is where the axis of a virtual magnetic dipole at the center of Earth, producing the major part of the observed Earth magnetic field, crosses the surface. This location was expected to be favorable for studying the ionosphere and the effects of magnetic storms. It is situated at 79°S, 105°E, and the place is known to be the coldest on Earth (–89.3°C in July 1983). Since its founding, the station, manned by approximately a dozen persons, has been operating almost continuously as an observatory for ionospheric studies, meteorology, magnetism, aerology, geophysics, glaciology, geodesy, etc. For supply and maintenance, over the last 50 years Vostok station has required the deployment of significant logistics (airplanes, ships, tractors, etc.) and personnel (e.g., Lukin et al., 2006). Since the mid-1960s, drilling has been conducted by dedicated and resourceful wintering teams (Vassilev et al., 2007) with the aim of geophysical studies (e.g., study of the ice sheet temperature in relation to ice sheet dynamics), glaciology, and, more recently, paleoclimatology as laboratory structures and techniques dedicated to ice core geochemistry evolved (e.g., water isotope mass spectrometry, gas and liquid chromatography, clean rooms, etc.).

Following IGY, the signature of the Antarctic Treaty alleviated administrative boundaries between nations, and despite the political context of the cold war, it gave scientists a structure for pursuing the IGY scientific endeavor. Scientists from Eastern and Western countries were able to travel abroad to meet regularly at annual colloquia. New ambitious exploration projects grew and became feasible through international collaborations. The bipartite Soviet-French collaboration began by the 1980s and then became a tripartite Soviet-U.S.-French venture (Figure 1), aiming to

FIGURE 1. Vostok Station and the 1990s tripartite collaboration for ice core studies. (top) Geomagnetic South Pole memorial and welcome signs. (bottom) Ice core "festival" and view of thin sections of glacier (small crystals) and lake ice (single large crystal) between crossed polarizers. The scale is in centimeters, and irregular thickness makes the color iridescence for the lake ice crystal (Photos ® Extra-Pol).

collaborate on the Vostok ice cores. This collaboration represents one of these emblematic projects that were set up independently from political considerations and that continued to exist despite the political context and difficulties.

THE 400,000-YEAR CLIMATE RECORD

At Vostok the ice thickness is 3,750 m, and the snow accumulation is only an equivalent of 2 cm annually. Such conditions offer a rare opportunity to obtain a long climatic record with relatively high time resolution. In the 1980s, ice core drilling reached 2,000 m depth. A first 150,000-year record of Antarctic temperature (Lorius et al., 1985; Jouzel et al., 1987) and CO_2 was published (Barnola et al., 1987). In January 1996, the drill reached 3,350 m depth. The climate record was extended back to 420,000 years (Petit et al., 1999). From the stable isotope composition of the ice, the gases trapped in air bubbles, the atmospheric dust particles, and the soluble chemicals, which are kept frozen, together provide a unique history of past changes of the climate, the atmospheric composition, and the environmental conditions over oceans and continents.

The climate record (Figure 2) displays a complete natural cycle of the temperature, which oscillates by about 12°C amplitude between the warm conditions of the present climate and the three previous interglacial periods (circa 120,000 BP, 220,000 BP, 330,000 BP, and 400,000

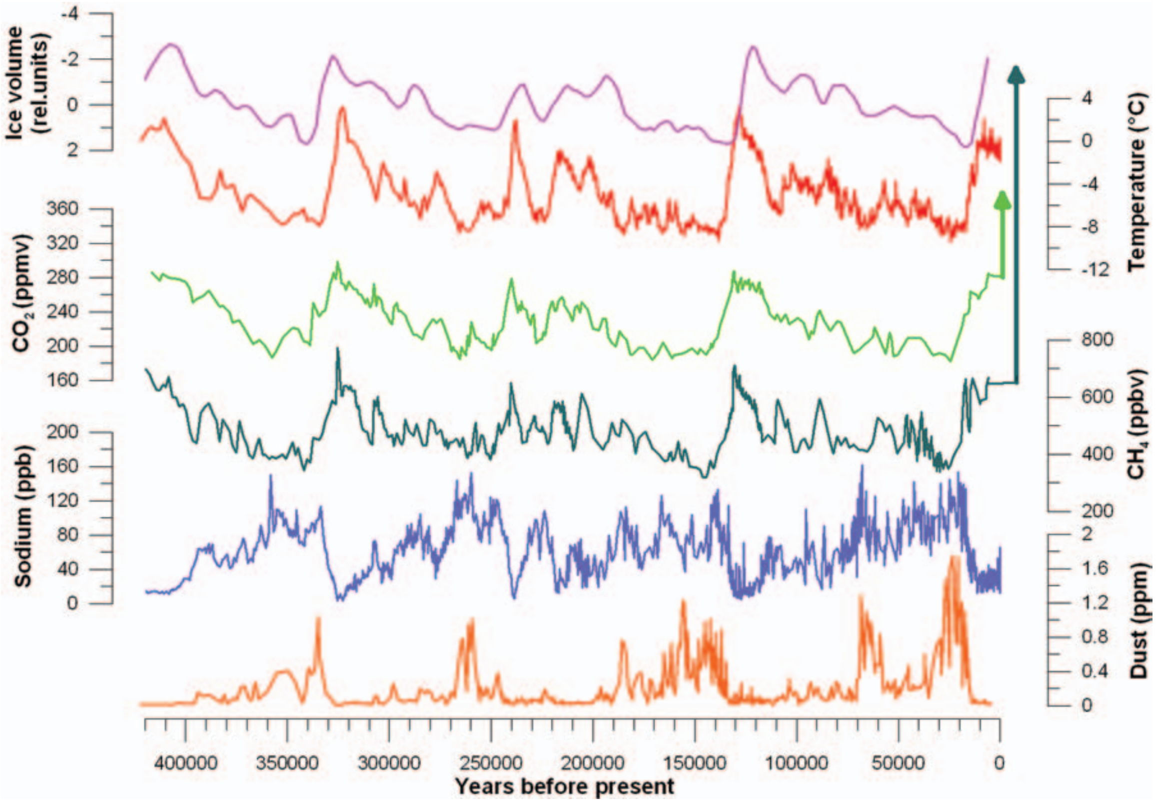

FIGURE 2. The climatic record over the last 400,000 years deduced from the first 3,310 m of the Vostok ice core (adapted from Petit et al., 1999). From top to bottom: Global ice volume (in relative units) as deduced from the marine sediment record; temperature (difference with the present surface temperature) deduced from the stable isotope composition of the ice; records of greenhouse gases CO_2 (ppmv: parts per million in volume) and CH_4 (ppbv: parts per billion in volume) as deduced from entrapped air bubbles; record of sodium concentration (ppb: parts per billion in mass), representative of sea spray aerosols; and record of dust concentration (ppm: parts per million in mass), representative of emissions from continental arid areas. Note that the recent increase up to the present levels for CO_2 (388 ppmv, http://co2now.org/) and CH_4 (~1800 ppbv, http://cdiac.ornl.gov/pns/current_ghg.html) are a consequence of anthropogenic activity since the 1850s.

BP), on the one hand, and the cold conditions of the glacial periods in between (e.g., between 80,000 BP and 20,000 BP to for the last glacial period), on the other. Most of this natural climate variability during glacial-interglacial changes occurs with periodicities corresponding to that of the precession, obliquity, and eccentricity of the Earth's orbit, with a larger concentration of variance in the 100,000-year band.

The "sawtooth" pattern of the Vostok temperature record roughly mimics the sea level changes deduced from marine sediment studies. The CO_2 concentrations deduced from analyses of the air bubbles also oscillate between high values of about 280 parts per million in volume (ppmv) for the preindustrial times (prior to circa AD 1850) and the warm interglacial periods and lower values of about 190 ppmv for the glacial periods. Indeed, the CO_2 record mimics the temperature record over the four climatic cycles, and the record in Petit et al. (1999) extended the one published 12 years before (Barnola et al., 1987) by three more climatic cycles. In the late 1980s, a set of three papers dedicated to Vostok ice core published by *Nature* magazine (Jouzel et al., 1987; Barnola et al., 1987; Genthon et al., 1987) made a large impact and generated much interest, with someone calling it a "big bang" for the scientific community. The link between the climate and the carbon cycle was clearly established, and polar ice became the indisputable complementary archive to marine sediments. More importantly, ice core records provided a natural record of climate and atmospheric changes from which the sensitivity of the surface temperature to variations of the global atmospheric composition could be deduced (Lorius et al., 1990). Looking ahead, the question of the potential impact of the rising CO_2 concentration (388 ppmv today) due to anthropogenic activities on the climate was clearly opened. The close linkage between climate and CO_2 throughout the four climatic cycles is now extended over 800,000 years with the ice core at Dome C by the European Project for Ice Coring in Antarctica (EPICA) (EPICA Community Members, 2004; Luthi et al., 2008) and supports the role of the greenhouse gases as amplifiers of initial orbital forcing.

OTHER ENVIRONMENTAL INFORMATION AND BRIDGING WITH GREENLAND RECORDS

In addition to the past temperature and atmospheric composition, other climatic indicators extracted from the ice core depicted complementary features of environmental changes (De Angelis et al., 1987; Legrand et al., 1988; Petit et al., 1990, 1999). The much higher concentration (factor of ~50) of atmospheric dust particles during full glacial periods than during interglacials (Figure 2) observed over the last 800,000 years (Wolff et al., 2006; Lambert et al., 2008) is interpreted as indicating more-extensive deserts and arid areas due to the deep cold climate and the very dry atmosphere. The reduced hydrological cycle caused the continental aridity, and the lower atmospheric cleansing induced a more-efficient aerosol transport to polar regions. This transport efficiency may also explain the higher input (factor of 5) observed for sea spray aerosols (sodium, Figure 2), although the role of sea ice extent and higher winds remains to be determined (Wolff et al., 2006; Petit and Delmonte, 2009).

The methane (CH_4) was also extracted and measured from the air bubbles. Methane is produced mostly by the biological activity of soils and wetlands and therefore is sensitive to the temperature, and at first order it follows the temperature (Figure 2). Indeed, methane is sensitive to temperature over the continents in the Northern Hemisphere (Chappellaz et al., 1993) and has a higher variability spectrum. On the other hand, methane atmospheric concentration changes at a global scale and represents a useful stratigraphic marker as a proxy of the Northern Hemisphere temperature, which is preserved within Antarctic ice. This has been used for matching the high-resolution EPICA Droning Maud Land ice core to the Greenland record over the last 100,000 years. During the last glacial period, the high-amplitude wiggles of the temperature (so-called Dansgaard-Oeschger events) recorded in the Greenland ice core result from changes in the meridional ocean circulation and the switch of advection of heat from the tropics, sometimes coincident with the northern ice cap discharge of armadas of icebergs. The comparison between Greenland and Antarctic ice core records revealed companion events in Antarctica (EPICA Community Members, 2006). The Greenland sudden warming is out of phase by a few hundred years with a warm phase occurring in Antarctica, and the amplitude of Greenland warming appears to be proportional to the duration of the preceding Antarctic warm phase (Figure 3). Such a seesaw phenomenon suggests heat storage in the Southern Ocean and its distribution to the north through the Atlantic Ocean, a phenomenon reflecting millennial-scale temperature variability that persisted during the glacial periods of the past eight glacial cycles. (Loulergue et al., 2008).

Reconstructions of past environments are now recognized as important information for climatic and environmental studies. They allow assessing the degree of natural variability and place current observed changes in

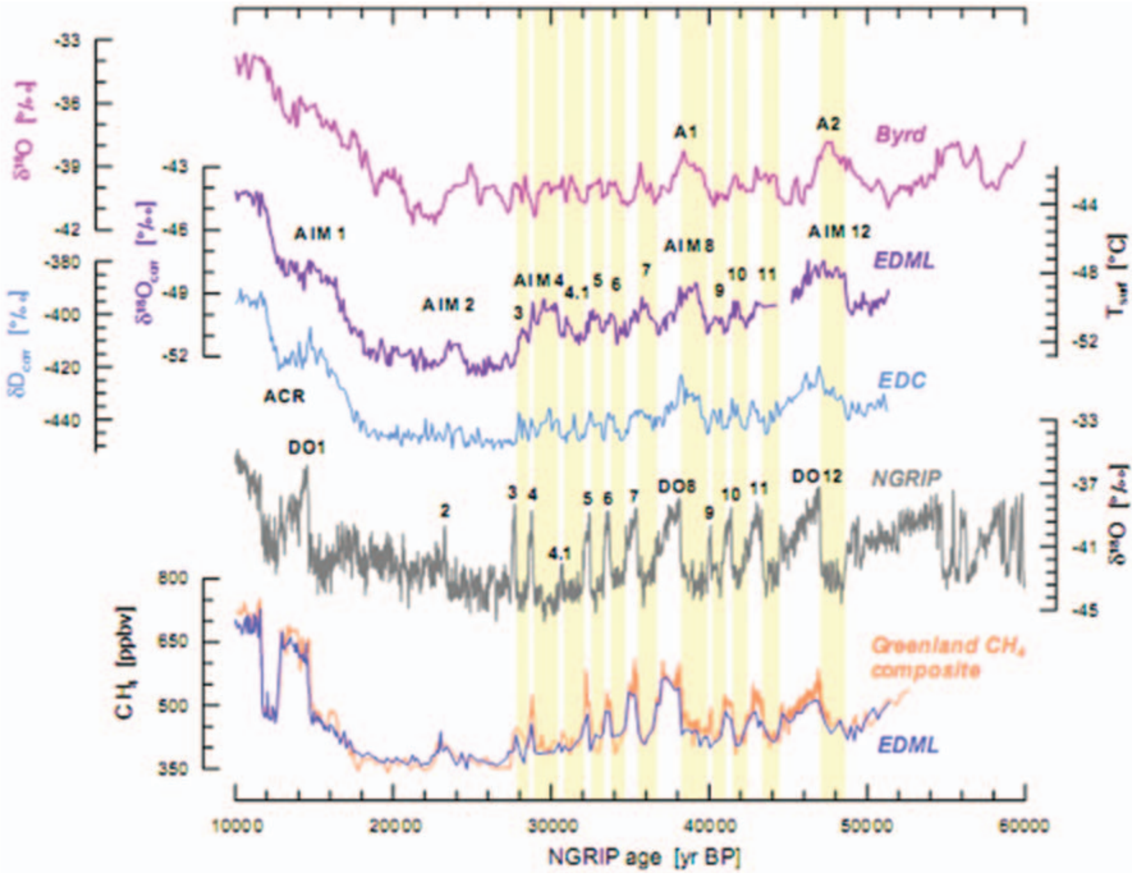

FIGURE 3. North-south connections: one-to-one Greenland and Antarctic climate variability during the last glacial period (adapted from EPICA Community Members, 2006). Stable isotope variations (100-year averages) in the EDML (Epica Dronning Maud Land), EDC (Epica Dome C), and Byrd ice core are compared with the NGRIP (North Greenland Ice Project) δ^{18}O record from northern Greenland. Temperature estimates for EDML are shown on the right axis. The EDML, EDC, and Byrd have been CH_4 synchronized with NGRIP. Yellow bars indicate the Greenland stadial (cold) periods related to respective Antarctic temperature increases.

a broader perspective (Jansen et al., 2007). They help us to understand causes and mechanisms of the changes and contribute to validating models by comparison of output with empirical data. The last few hundred thousand years are an appropriate context in which we can learn how the Earth system works.

SURPRISES FROM THE DEEP ICE

In January 1998, the tripartite Russian-French-U.S. collaboration got new highlights from deep drilling by reaching 3,623 m depth, which was the deepest ice core ever recovered (3,667 m was then reached in 2008). The drilling stopped 130 m above Lake Vostok, a deep subglacial water body discovered and mapped earlier from satellite observations (Ridley et al., 1993). The lake extends below the ice sheet over an area of 15,000 km^2, similar to Lake Ontario today. With water depth up to 1,200 m, its total volume represents 5,000 km^3, suggesting it has been present a very long time (Kapitsa et al., 1996; Siegert et al., 2001).

The recovery of ice refrozen from lake water (accretion ice) at the bottom of the ice core opens an unexpected window to this unknown environment. The accretion ice formed by large ice crystals (Figure 4) as the result of a very slow freezing process represents the best analogue for lake water composition and biological content. The high pressure, the low temperature, the absence of solar energy, the nutriment supply from the very clean overlaying ice, and the isolation from our environment for thousands

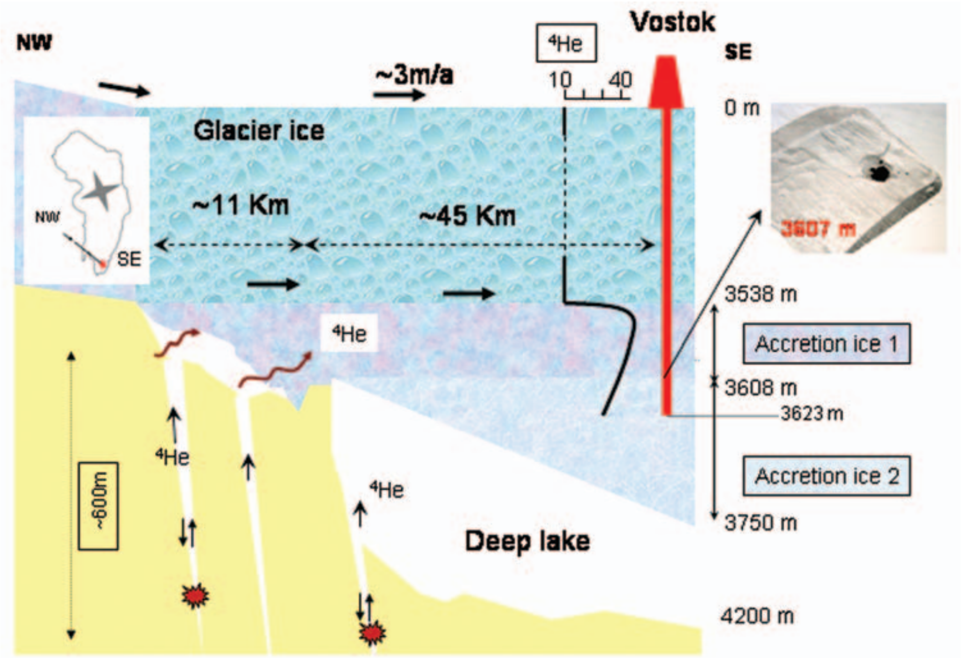

FIGURE 4. Sketch of the glacier and lake basement along the Vostok ice flow line (adapted from Bulat et al., 2004). On the 3,623 m Vostok ice core, the accreted ice interval from 3,538 to 3,608 m depth (accretion ice 1) contains visible sediment inclusions (insert on the right). Deeper ice and likely that down to the glacier-water interface (accretion ice 2) are clean. A glacier flows at about 3 m per year from the northwest to southeast (insert on the left). A rise in relief is located at about 11 km, enfolding a shallow-depth embayment where sediments could be trapped into accreted ice. Then the glacier floats over a ~600 m deep lake. The rock basement is characterized by escarpments where deep faults allow water to seep in depth and to circulate. Fault activity (explosion symbols) may fuel hydrothermal circulation and activate ^{4}He degassing from the rocks. Also represented is a sketch of down-core ^{4}He concentration (Jean Baptiste et al., 2001) showing a constant value for glacier ice and the change, by a factor of 3, at the glacier-accretion ice boundary. In accretion ice a ^{4}He maximum concentration suggests contribution from a shallow-depth area upstream from Vostok (adapted from Bulat et al., 2004).

(maybe millions) of years make the subglacial lakes one of the most extreme environments on Earth and a probable limit for life.

Ongoing studies of Lake Vostok accretion ice core show that because of the low biomass, the forward contamination of samples is a substantial problem and the main cause of diverse chemical and biological results (Priscu et al., 1999; Karl et al., 1999; Christner et al., 2001; Bulat et al., 2004), the drilling fluid coming in contact with the ice being one source of contamination (Alekhina et al., 2007). From repeated independent investigations, the accretion ice is now found to be essentially carbon- and germ-free, indicating that the water body (at least the upper layer) beneath the ice sheet should support only a highly sparse life, if any. In recent studies, a phylotype representing the extant thermophilic facultative chemolithoautotrophic bacterium *Hydrogenophilus thermoluteolus* gave a reliable molecular biology signature and is the single print of life found to date in the Lake Vostok ice horizons (Bulat et al., 2004; Lavire et al., 2006). Such thermophilic organisms are unlikely to thrive in the open lake, where the temperature is a little above zero and the high concentration of dissolved oxygen is expected to be a significant constraint for any bacterial life. Rather, they live at great depths in "hot" basement faults filled with sediments that may have been colonized soon after their formation and possibly before the onset of the Antarctic glaciation around 30 MYA. According to a scenario built from the available geophysical and geochemical information, some niches have been suggested within deep faults or sediments close to fault mouths where chemolithoautotrophic microorganisms are likely to be protected and fed by hydrothermal fluids. The way they are integrated into the accretion ice, likely boosted by sporadic local or distant seisms, would be the result of the contact between the mouth of bedrock faults with the base of the glacier upstream from Vostok (Bulat et al., 2004). The helium concentration (^{4}He), which is found in excess in the accretion ice, supports the suggestion of a modest but persistent tectonic activity, although the absence of ^{3}He rules out the presence of hydrothermal vents like the black smokers observed in deep oceans that are associated with magma ascending into crustal fractures (Jean Baptiste et al., 2001).

At the bottom of Lake Vostok a deep biosphere within a "biotectonic environment" is likely, which represents an interesting alternative scenario for primary production consistent with the extreme environment of the lake. Finally, the multidisciplinary approach that has been developed for searching for life in the Lake Vostok ice leads to some guiding principles that could be applicable for searching life in other extreme environments or for the study of extraterrestrial samples (Petit et al., 2005).

TALES FROM THE FIELD AND HIGHLIGHTS FROM THE VOSTOK VENTURE

Drilling operations are never simple, and at Vostok drillers overcame many technical issues (Vassilev et al., 2007), and unexpected events are the rule of the exploration. As an example, at the time (during the 1990s) of the dramatic and economical changes that occurred in connection with the collapse of the Soviet Union, Vostok station endured a critical epoch and had to close for winter. The tripartite Soviet then Russian-U.S.-French collaboration (1989–1998) remained in effect, however. This collaboration allowed several issues regarding providing more technical help and logistic support to be solved. In 1995, the situation improved, and drilling operations were soon resumed. The ice core reached 3,109 m depth, establishing a new world record.

The long-lasting Vostok venture is one of the fortunate outcomes from the Antarctic Treaty. The climate record and the relationship with CO_2 in the past as revealed by the deep ice core soon became a reference curve. This salient result also highlighted the potential of the ice cores for climate studies and promoted other projects (e.g., EPICA and Dome Fuji) for obtaining longer climate records (EPICA Community Members, 2004; Watanabe et al., 2003). At time of the IGY more than 50 years ago, by choosing the south geomagnetic pole for the settlement of Vostok station, nobody envisaged the presence of a huge subglacial lake there. Even more, once the subglacial body was known, no one expected an ice massif of frozen lake water at the drilling spot. As a result, a unique window to a subglacial environment has been offered.

Under the influence of anthropogenic activities, recent climate change creates a real concern about the future of human societies on our planet The present-day atmospheric CO_2 concentration and its rapid increase are likely to be unprecedented over the history of the past 800,000 years (Luthi et al., 2008). Climate scientists are trying to provide realistic assessments of how our climate will change in the future (Jansen et al., 2007). International collaboration helped to decipher the dynamics of the climate and pacing of the ice ages. The Vostok CO_2-climate correlation was and is still greatly impacting the ongoing research on the carbon cycle and its evolution in relation to climate changes. In this sense, the Vostok record has been one of the "iconic records" used throughout the various Intergovernmental Panel on Climate Change (IPCC) assessments dealing with the fate of the anthropogenic CO_2.

The discovery of more than 200 subglacial lakes in Antarctica generates a great deal of scientific and public discussion and speculation about the origin, nature, and fate of the subglacial lakes. For example, the numerous lakes raise questions on their possible contribution to the ice sheet dynamics as well as on the stability and evolution of the ice caps (Wingham et al., 2006). Also, the discovery of imprints of water on Mars and icy Europa, a Jovian satellite, is promoting the ever-asked question of extraterrestrial life. In this context the subglacial Antarctic lakes buried under more than 3,000 m of ice, representing an extreme environment and a limit for potential life, were soon taken as a possible analogue of the hydrosphere of such icy environments. Finally, the subglacial lakes attracted technological experiments that led to projects for robotic exploration promoted within Scientific Committee on Antarctic Research (SCAR) committees, and Vostok, its ice core, and its giant subglacial lake are still being studied is a tribute to the Antarctic Treaty.

ACKNOWLEDGMENTS

This work is dedicated to the memory of colleagues from the Vostok community who have passed away. Acknowledged with gratitude are researchers, engineers, technicians, administrative personnel, and field participants from Institutes, Universities, and Academies from Russia, USA, and France. Field operations were supported by Russian Antarctic Expeditions (RAE), US National Science Foundation (NSF), and the French Polar Institute (IPEV).

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