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Global Ice-core Research: Understanding and Applying Environmental Records of the Past

Glaciers Record Environmental Change

One way to study Earth's past environmental conditions is to look at ice cores recovered from glaciers. Every year a layer of snow accumulates on glaciers, like a page in a history book, and eventually turns to ice. Like reading the pages of a history book, analyzing the layers in a glacial ice core for specific chemical and physical components is a way of "reading" the environmental changes of the past. Information from ice cores collected from Greenland and Antarctica already has provided important historical clues toward a better understanding of modern global environmental changes (Dansgaard and Oeschger, 1989; Lorius and others, 1989).

Environmental changes are of major concern at low- or mid-latitude regions of our Earth simply because this is where 80 to 90 percent of the world's human population live. Ice cores collected from isolated polar regions are, at best, proxy indicators of low- and mid-latitude environmental changes. Because polar ice-core research is limiting in this sense, ice cores from low- and mid-latitude glaciers are being used to study past environmental changes in order to better understand and predict future environmental changes that may affect the populated regions of the world.

Figure 1. Locations of some low-and mid-latitude glaciers.

Low-and Mid-Latitude Glaciers Preserve Important Records of Environmental Change

Because of moderate temperatures, fewer glaciers exist in low- and mid-latitude regions of the world than in high-latitude or polar regions. Only a few mid-latitude glaciers preserve accurate records of environmental changes. A mid-latitude glacier must have certain characteristics to accurately preserve records in the ice:

- high altitude above sea level
- relatively simple ice-flow dynamics
- flat- to low-angle bedrock topography
- limited redistribution of snow from wind and avalanche
- minimal snowmelt during the summer season
- large ice thickness for maximum record length

Selected glaciers that meet these criteria (fig. 1) are:

- Upper Fremont Glacier, Wind River Mountain Range, Wyoming
- Inilchek Glacier, Tien Shan Mountains, Kyrghyzstan
- Nangpai Gosum Glacier, Himalayan Mountains, Nepal
- Quelccaya Ice Cap, Andes Mountain, Peru

Low- and Mid-Latitude Glaciers Also Preserve Records of Human Activities

In addition to recording naturally occurring past environmental information, some low- and mid-latitude glaciers also preserve a record of atmospheric input from human activities. Increased levels of many modern substances can be "read" in younger glacial ice (less than about 100 years old). These substances include pollutants from refrigerants, sulfate from acid rain, fallout from nuclear facilities and nuclear accidents around the world, and fallout from above-ground testing of nuclear weapons in the 1950s and 1960s.

Figure 2. Pack Goats carry scientific equipment to the Upper Fremont Glacier. Photo by D.L. Naftz, U.S. Geological Survey.

Detonation of nuclear devices by the United States and Great Britain over the Pacific Ocean in the mid-1900s created a significant quantity of radioactive particles, many of which were injected into the upper atmosphere. **Chlorine-36** (**^{36}Cl**) was one of the radioactive elements that was spread throughout the atmosphere and subsequently deposited around the globe by means of wet precipitation and dry deposition. During the weapons-testing era, a very small amount of ^{36}Cl became trapped each year in the glacial ice, thus compiling an atmospheric-based record of the past.

Tritium (**^{3}H**) is another radioactive element that was created in significant quantities during the era of nuclear-weapons testing. Like ^{36}Cl, it was injected into the upper atmosphere, fell to Earth in precipitation and dry deposition, and became trapped in glacial ice. It can be detected in the ice and provides additional evidence that glaciers can preserve an accurate record of past anthropogenic (human) input. Owing to its short half-life (12.26 years), weapons-tests ^{3}H soon will be indistinguishable from the naturally produced ^{3}H present in the ice. Chlorine-36, in contrast, with its long half-life of 301,000 years, will be available for documenting anthropogenic input to the environment for many years to come.

Ice Core from the Upper Fremont Glacier, Wyoming, Helps Reconstruct Environmental Record

Of particular interest as a chronicle of past environmental changes at low- and mid-latitude regions of the world is the Upper Fremont Glacier in central North America (fig. 1). It is located in the Wind River Mountain Range of Wyoming at a latitude of N. 43°08 '. It is a relatively large mid-latitude glacier with a surface area between 2.5 and 3 square kilometers (km^2), an altitude of 4,100 meters (m) above sea level, and ice thickness greater than 150 m in the higher altitude sections. It is located nearly 40 kilometers (km) inside a designated wilderness area and is representative of precipitation falling in remote, high-altitude environments in the Western United States. Access to the glacier requires a rigorous two-day hike from the nearest road. Pack goats are sometimes used to transport scientific equipment (fig. 2). The Upper Fremont Glacier preserves an accurate record of past environmental changes at low- and mid-latitude regions of the world (Cecil and others, 1999, 1998; Cecil and Vogt, 1997; Naftz and others, 1996, 1993; Naftz, 1993; Schuster and others, 2000).

During 1991, a continuous 160-m long ice core was obtained from the Upper Fremont Glacier by using a solar-powered thermal drill (Naftz and Miller, 1992). Chemical age-dating techniques were used to establish and refine the chronology of the ice core for interpretation and reconstruction of the environmental record. Tritium concentrations exceeding 300 TU at a depth of about 29 m below the surface of the glacier corresponded to snowfall deposited in 1963 during the peak of ^{3}H production

What is Chlorine-36?

Chlorine-36 (**^{36}Cl**) is a radioactive form of chlorine that occurs naturally in small quantities in the environment. It is produced in the Earth's atmosphere when cosmic rays strike particles that are in the upper atmosphere.

Each atom of ^{36}Cl contains a nucleus (the centermost part of an atom) that is composed of 17 protons and 19 neutrons for a total of 36 particles. (Protons and neutrons are atomic particles that make up all atoms.) Atoms of ^{36}Cl are unstable (radioactive) and eventually decay to argon, an inert noble gas. The half-life of ^{36}Cl (the time it takes for half of a sample of ^{36}Cl to decay away) is 301,000 years. This long half-life makes it ideal as an environmental tracer.

What is Tritium?

Tritium (**^{3}H**) is a radioactive form of hydrogen and is found naturally in the environment in harmless quantities. Each atom of ^{3}H contains 3 particles in the nucleus, 1 proton and 2 neutrons. Tritium atoms are unstable and have a half-life of 12.26 years. Tritium atoms eventually decay to stable helium.

Tritium has been used for decades in short-term environmental studies, but it decays relatively quickly and cannot be used in long-term studies. A common unit of measurement for tritium is the tritium unit (TU). One TU = 1 tritium atom in 1,000,000,000,000,000,000 stable hydrogen atoms.

by weapons testing (Carter and Moghissi, 1977) (fig. 3). Radioactive carbon-14 (^{14}C) age dating of a **grasshopper leg** entrapped 152 m below the surface of the glacier (fig. 3) indicated that ice near the bottom of the core formed from snow deposited between 1716 and 1820 (Naftz and others, 1996). Using the age-to-depth relations developed from the ^{3}H and ^{14}C data, it was established that approximately 250 years of record are preserved at this site.

How Do Insects End Up in Glacial Ice?

The Wind River Mountain Range of Wyoming is aptly named, because the wind plays an important role in all that occurs. The wind continually blows debris, like pollen and dust, onto the glaciers. The wind also blows a variety of insects, including grasshoppers, dragonflies, and moths onto the glacial surface. In time, snow buries the insects. Later, when the snow changes to ice, the insects become entombed in the glacier.

Dozens of insects were found in the ice cores that were collected from the glacier. Most of the insects were wholly preserved when they were melted out of the shallower sections of the ice. An entomologist identified a grasshopper leg that was found 152 m below the surface of the glacier as from a species that is now extinct.

Oxygen-18 Record from the Upper Fremont Glacier Ice Core Indicates Rapid Climate Change During the Mid-1800s

A record of air temperature changes also is preserved in glacial ice and can be reconstructed by analyzing the ice samples for relative ratios of oxygen-18 (^{18}O) to oxygen-16 (^{16}O) (both are stable forms of oxygen). The oxygen ratio in the sample is compared to a standard global oxygen ratio maintained by the International Atomic Energy Agency in Vienna, Austria. The resultant value can be positive or negative with respect to this standard and is given in units of "permil," which means parts per thousand. For example, the average value for the entire Upper Fremont Glacier ice core was -18.90 permil (represented by the red line in fig. 4). This means that, on

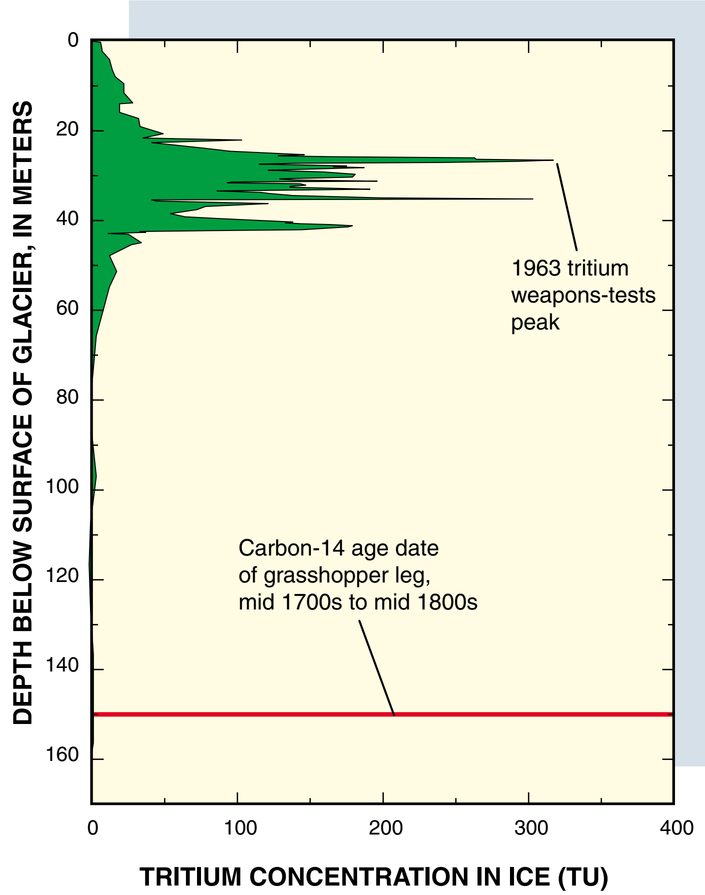

Figure 3. Tritium concentration in ice from the Upper Fremont Glacier in tritium units (TU). The 1963 tritium weapons-tests peak and a grasshopper leg found 152 meters below the surface of the glacier were preserved in the ice.

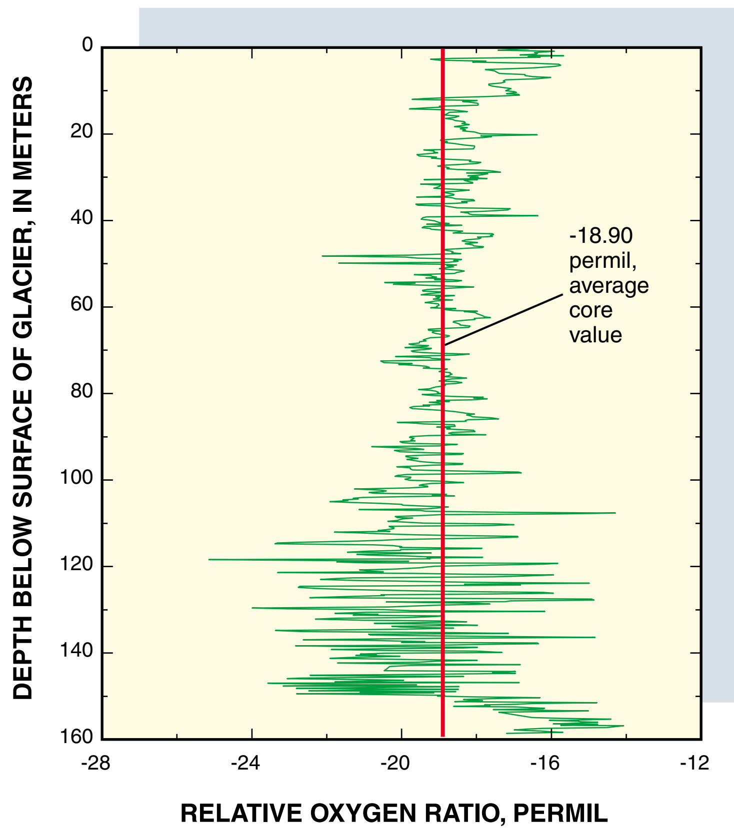

Figure 4. Oxygen ratios in ice from the Upper Fremont Glacier. The red line represents the average value through the entire core.

average, the ice-core samples contained 18.90 parts per thousand less ^{18}O than the standard. Any value more negative than -18.90 indicates less ^{18}O relative to the average value of the core, and any value less negative than -18.90 indicates more ^{18}O relative to the average core value.

The 160-m ice core was divided into 760 equally spaced sections and analyzed for oxygen ratios (fig. 4). Between the depths of 102 to 150 m in the ice core, the oxygen ratios shifted abruptly to an average value of -19.85 permil, 0.95 permil more negative than the average core value of -18.90. This section of the core contained fewer ^{18}O atoms relative to the average value. Age-to-depth relations developed from the ^{3}H and ^{14}C data showed that this section also corresponded to the approximate time interval from the mid-1700s to mid-1800s anno domini (A.D.). This period of time is referred to as the Little Ice Age (LIA).

The core interval from 102 to 150 m (fig. 4) was marked with drastic oscillations (swings) in the relative oxygen ratios. The oscillations probably were due to less melting during the many cool summers of the LIA and lower temperatures during the colder winters of the LIA (Naftz and others, 1996).

When the LIA ended, the summers and winters became warmer. Oxygen ratios in shallower ice from the Upper Fremont Glacier (102 m below the surface and up) abruptly shifted to much smaller oscillations and also shifted to less negative values (meaning the ^{18}O content was more like the standard with which it was compared). The transition from the LIA was abrupt, probably fewer than 10 years. This indicates a sudden termination of the LIA in the alpine regions of the Wind River Range, Wyoming (Schuster and others, 2000).

An ice core in the Southern Hemisphere collected from the Quelccaya Ice Cap in the Andes Mountains (fig. 1) also was analyzed for relative oxygen ratios (Thompson, 1992). Ice that corresponded to snowfall from 1600 to 1800 A.D. showed a -0.7 permil shift in the relative oxygen ratios, compared with the -0.95 permil shift in ice from the Upper Fremont Glacier that was deposited as snow before the LIA ended. Thus, the changes in the relative oxygen ratios in these two glaciers indicate a distinct shift toward less negative values at the termination of the LIA. The linkage between the data from these two ice cores further indicates that an accurate global environmental record is preserved in ice from the mid-latitude Upper Fremont Glacier in the Northern Hemisphere.

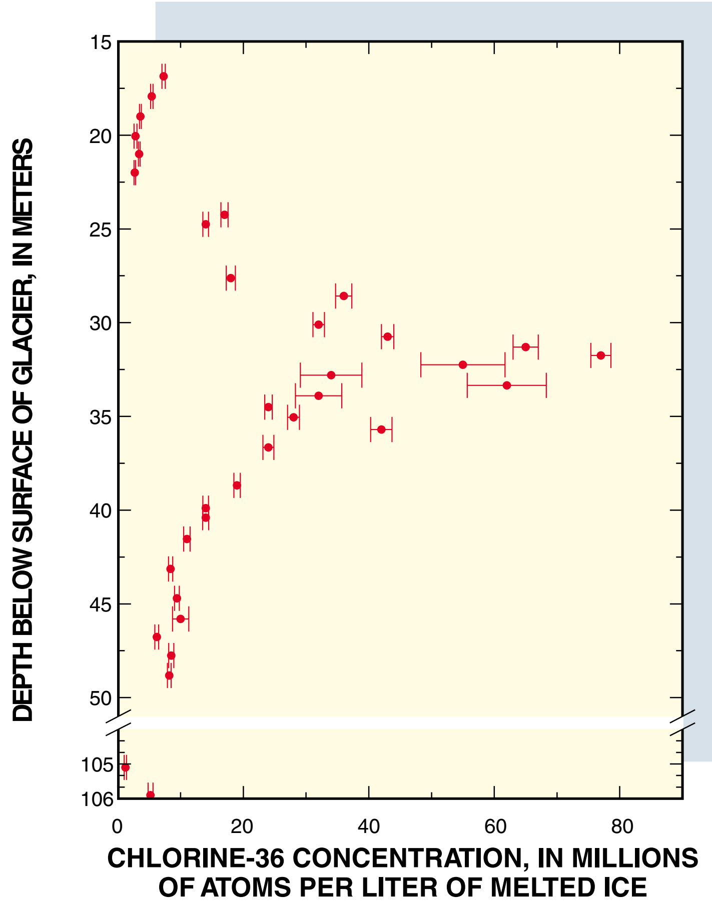

Figure 5. Chlorine-36 concentration in melted ice samples from the Upper Fremont Glacier.

Accelerator Mass Spectrometry is an Important Tool for Environmental Research

Nuclear-weapons testing in the 1950s and 1960s created significant concentrations of ^{36}Cl. However, only minute amounts actually became trapped in glacial ice. In fact, the quantity of ^{36}Cl in the ice is so incredibly small that conventional scientific methods of detecting it cannot be used. In recent years, a modern analytical technique called accelerator mass spectrometry was developed that allows as little as a few ^{36}Cl atoms to be detected in 1,000,000,000,000,000 stable chlorine atoms (Elmore and Phillips, 1987).

Chlorine-36 Results from the Upper Fremont Glacier Ice Core Indicate Deposition from Weapons Testing

Chlorine-36 concentrations in melted ice-core samples collected from the Upper Fremont Glacier are shown in figure 5. The results are plotted as sample depth below the surface of the glacier, in meters, in relation to ^{36}Cl concentration, in millions of atoms per liter of melted ice core. The sample that contained the largest concentration of ^{36}Cl was extracted from the glacier at 32 m below the surface and corresponded to ice that was deposited as snow in 1958 during the peak of ^{36}Cl production by weapons testing. Ice samples collected deeper in the glacier (about 100 m of depth) contained much smaller concentrations of ^{36}Cl, as did samples collected from shallower depths (about 20 m of depth).

The presence of the peak ^{36}Cl concentration in the ice is another clear indication that environmental records are preserved in the Upper Fremont Glacier ice.

Ice-Core Results Can Be Applied to Ground-Water Studies

Once the concentration of ^{36}Cl in low- or mid-latitude glacial ice is determined, the results can be applied to ground-water studies at nuclear facilities such as the U.S. Department of Energy's Idaho National

Engineering and Environmental Laboratory (INEEL) in Idaho (fig. 1). Because the INEEL is at nearly the same latitude as the Upper Fremont Glacier (N. 43° to 44°), similar amounts of ^{36}Cl probably were deposited in the mountains around the INEEL as were incorporated into the ice of the Upper Fremont Glacier. The precipitation that fell in the mountains around the INEEL during the weapons-testing era is currently traveling in ground water under the INEEL and has mixed with contaminated ground water already present. It is desirable to determine how much of the contamination in the ground water is due to natural production, how much is due to nuclear-weapons input, and how much is due to nuclear-waste disposal practices at the INEEL. The detection of weapons-produced ^{36}Cl in glacial ice directly aids such studies.

Additional Research Activities on the Upper Fremont Glacier Are Currently (1997-2001) Underway

Research activities at the Upper Fremont Glacier study site were renewed in 1997 by means of a cooperative agreement between the U.S. Department of Energy and the U.S. Geological Survey. Initial field activities included the installation of an automated weather station and a snow-depth sensor in September 1997. In 1998, two additional continuous ice cores, in lengths of 50 and 162 m, were collected from the glacier (fig. 6). Sixty meters of this deeper core were processed between October 1998 and June 1999 in preparation for chemical and isotopic analyses. Carbon-14 age dating of grasshopper parts found in the 162-m core is being performed at the University of Waterloo, Canada.

Figure 6. Section of ice core collected from the Upper Fremont Glacier, 1998. Photo by P.F. Schuster, U.S. Geological Survey.

Other Glaciers Add to Our Understanding of the Past

Inilchek Glacier, Kyrghyzstan

Another mid-latitude glacier that is of interest and is being studied with researchers from the University of California at Santa Barbara is the Inilchek Glacier (fig. 1). It is located in the Tien Shan Mountains and covers parts of three countries: Northern China, Southern Kazakhstan, and Eastern Kyrghyzstan. Altitudes exceed 6,000 m on many parts of the remote, 65-km-long glacier (fig. 7). Its depth of as much as 300 m could represent 1,000 to 5,000 years of accumulation. The altitude is sufficient that minimal or no melting occurs, which means that the environmental record contained within an extracted ice core should be intact (Aizen and others, 1997).

In August 1998, a reconnaissance team traveled to the Inilchek Glacier and collected a shallow 22-m ice core. The core was transported (still frozen) to the University of New Hampshire where analyses of the ice are underway. Funding has been received to return to the Inilchek Glacier to retrieve two more ice cores. One core would span the period during which nuclear weapons-testing occurred. The other core would span the entire depth of the glacier and could be used to reconstruct an environmental and climatic record of the last 1,000 to 5,000 years.

Figure 7. The Inilchek Glacier in Kyrghyzstan, surrounded by towering peaks. Photo by V.B. Aizen, University of California, Santa Barbara

Nangpai Gosum Glacier, Nepal

One additional glacier of interest is the Nangpai Gosum Glacier in Nepal (fig. 1). This glacier is located about 25 km west-northwest of Mt. Everest at an altitude of 5,700 m. Researchers from the University of New Hampshire and Woods Hole Oceanographic Institute collected a 37-m ice core from the glacier in 1998 (fig. 8). Analysis of the ice core showed a distinctive rise and fall of ^{36}Cl concentrations resulting from anthropogenic input, just as in the Upper Fremont Glacier ice core. The core was also analyzed for cesium-137, another

Figure 8. Moonrise over Mt. Everest. The Nangpai Gosum Glacier, Nepal. Photo by K. Kreutz, Woods Hole Oceanographic Institute.

byproduct of nuclear-weapons testing. Once again, the isotopic signal showed a rise and fall caused by anthropogenic influences. Information obtained from this glacier will add significantly to our understanding of global environmental changes archived in low- and mid-latitude glaciers.

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Sources of Additional Information

The following publications contain additional information about paleoenvironmental data, the interpretation of ice-core records, and the glaciers where our research is being conducted.

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Thompson, L.G., 1992, Ice core evidence from Peru and China, in Bradley, R.S., and Jones, P.D., eds., Climate Since A.D. 1500: New York, Routledge, p. 517–548.

Additional information about these glacial research programs also can be obtained from the World Wide Web at the following sites:

http://idaho.usgs.gov/projects/icecore/index.html

http://www.icess.ucsb.edu/~aizen/aizen.html

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