USGS RESEARCH ON THREE MID-LATITUDE GLACIERS

Jaromy R. Green[1], L. DeWayne Cecil[1], David L. Naftz[2], and Paul F. Schuster[3]

ABSTRACT

Low- and mid-latitude regions of the earth are home to 80 to 90 percent of the world's population. Because of this, the U.S. Geological Survey (USGS) is conducting a research program to study the geochemistry of precipitation, snow, ice, and runoff samples from mid-latitude glaciers in Kyrghyzstan, Nepal, and the United States. Areas of research, such as ground-water studies, reconstructing paleoclimate records, describing anthropogenic input of chemicals to the environment, and modeling global climate change, are important to the well being of the worlds' population and can be supplemented by the collection and chemical analysis of snow and ice cores. Nearly all the constituents that compose snow and ice-core samples contribute vital information, whether it be the microbial communities that flourish in snow, radionuclides present in various amounts in all the samples, or location-specific deposits of mercury and nitrate. This work is hastened by the fact that mid-latitude glaciers, and the information preserved in them, are rapidly disappearing as a result of global warming. Research collaboration for this project includes 12 national and 7 international universities, and 4 government agencies. Funding is provided by the National Science Foundation, the U.S. Department of Energy, and the USGS.

INTRODUCTION

The majority of the world's population (80 to 90 percent) lives in low- or mid-latitude regions. Mid-latitude alpine regions of the Earth support some glaciers but many of these glaciers suffer from thawing, refreezing, and associated meltwater percolation. Recently, however, it has been shown that some mid-latitude glaciers in the Northern Hemisphere accurately preserve isotopic and chemical records, thus providing information about climatic and environmental changes (Cecil and Vogt, 1997; Naftz and others, 1996). In addition to recording naturally occurring past environmental changes, mid-latitude glaciers may also preserve a record of atmospheric input from human activities. Increased levels of many modern substances are preserved in younger glacial ice (less than about 100 years old). These substances include pollutants from refrigerants, sulfate from acid rain, isotopic fallout from nuclear facilities and nuclear accidents around the world, and fallout from above-ground testing of nuclear weapons in the 1950s and 1960s.

Mid-latitude glaciers must have certain characteristics to preserve records in ice-core samples. These include relatively simple ice-flow dynamics, flat- to low-angle bedrock topography, limited redistribution of snow from wind and avalanche, minimal amounts of snowmelt during the summer season, and large ice thickness for maximum record length. A critical aspect of determining whether a glacier has some of these characteristics is analysis of snow samples. Snow samples can provide information about lateral variability of constituents across the surface of the glacier from processes such as wind, temperature, and altitude gradients. Many glaciers from around the world have been investigated for these characteristics.

The U.S. Geological Survey (USGS) is conducting this multi-disciplinary research in collaboration with 12 national and 7 international universities, and 4 government agencies. Funding is provided by the National Science Foundation, the U.S. Department of Energy, and the USGS.

METHODS

Ice and meltwater samples can be analyzed for isotopes using various laboratory methods. After melting ice in a controlled environment to minimize contamination with ambient air, the resultant water can be prepared for analyses. Chlorine-36 (^{36}Cl) and cesium-137 (^{137}Cs) are analyzed by accelerator mass spectrometry (Elmore and Phillips, 1987). Tritium (^{3}H) can be analyzed using direct liquid-scintillation, proportional-gas counting, or electrolytic enrichment (Ostlund and Werner, 1962; Thatcher and others, 1977). Samples for sulfur-35 (^{35}S) analysis are collected in the field by passing approximately 20 liters (L) of water through an ion exchange column. The column is then returned to the laboratory where the sulfate is eluted and precipitated as barium sulfate. The ^{35}S concentration is then determined by liquid-scintillation counting. Carbon-14 (^{14}C) analysis is performed by

[1] U.S. Geological Survey, 900 N. Skyline Drive Suite C, Idaho Falls, Idaho 83402; phone = (208) 528-2625; fax = (208) 528-2605
[2] U.S. Geological Survey, 2329 Orton Circle, Salt Lake City, Utah 84119; phone= (801) 908-5053
[3] U.S. Geological Survey, 3215 Marine Street Suite E-127, Boulder, Colorado, 80303-1066; phone = (303) 541-3052

accelerator mass spectrometry (Currie and others, 1985). Electrical-conductivity measurements (ECMs) are performed by drawing a pair of electrodes along the entire length of an ice core at a constant velocity (Schuster and others, 2000). Concentrations of chloride, nitrate, and sulfate are determined by ion exchange chromatography (Fishman and Friedman, 1989). Concentrations of sodium, magnesium, and calcium can be determined by inductively-coupled plasma emission spectroscopy (Garbarino and Taylor, 1979); however, recent advances in ion exchange chromatography equipment have permitted the analyses of these constituents, along with ammonium and potassium, at low concentrations. Values for delta oxygen-18 ($\delta^{18}O$) are determined using a gas- or solid-source mass spectrometer (Kendall and Caldwell, 1998). For microbiological analyses, total numbers of microbial cells and organic matter were determined by acridine orange direct count microscopy.

STUDY SITES

Upper Fremont Glacier

The Upper Fremont Glacier (UFG) (figure 1) is located in the Wind River Mountain Range of Wyoming, USA, at a latitude of 43°08′. It is a relatively large mid-latitude glacier with a surface area between 2.5 and 3 square kilometers (km), 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 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 as well as the use of pack goats to transport scientific equipment. Ice cores were collected from the glacier in 1991 and 1998. The UFG preserves an accurate record of past environmental changes at mid-latitude regions of the north-central Rocky Mountains (Cecil and others, 1999, 1998; Cecil and Vogt, 1997; Naftz and others, 1996, 1993; Naftz, 1993; Schuster and others, 2000).

Nangpai Gosum Glacier

Researchers from the University of New Hampshire and Woods Hole Oceanographic Institute are studying the Nangpai Gosum Glacier, located 25 km west northwest of Mt. Everest in the Himalayan Mountains of Nepal (figure 1). It occurs at a latitude 28°02′ and has an elevation of 5,700 m above sea level at the ice-core drilling site. In 1998, a 37-m ice core was collected from the glacier and transported to the University of New Hampshire.

Inilchek Glacier

The Inilchek Glacier is being studied by researchers from the University of California at Santa Barbara (figure 1). The glacier, located in the Tien Shan Mountains, 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. Its maximum 300-m depth could represent 1,000 to 5,000 years of accumulation. The altitude is

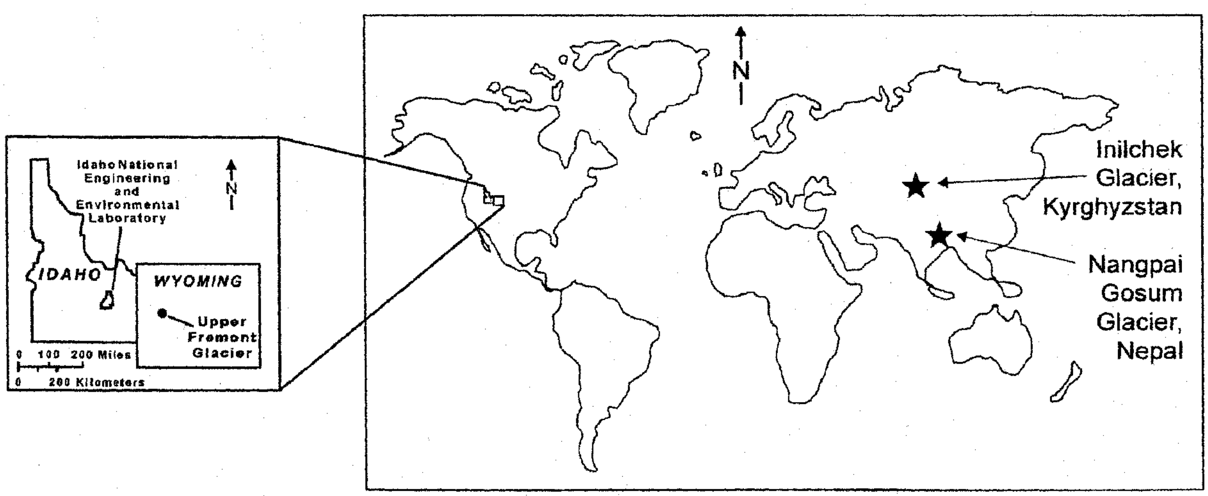

Figure 1. Locations of three mid-latitude glaciers and the Idaho National Engineering and Environmental Laboratory.

sufficient that minimal or no melting occurs (Aizen and others, 1997). In August 1998, a reconnaissance team traveled by helicopter to the Inilchek Glacier. A shallow 22-m ice core was collected and transported to the University of New Hampshire where analyses of the ice are underway. A return to the Inilchek Glacier is planned for the summer of 2000 to drill four additional ice cores. Two cores will be shallow, spanning the last 60 years. The other two cores will span the entire depth of the glacier and will be used to reconstruct an environmental and climatic record of the last 1,000 to 5,000 years.

RESULTS AND DISCUSSION

Various constituents from archived inventories of mid-latitude glacial snow and ice cores have been identified and determined. For the UFG, the ice-core snow data set is the most comprehensive of its kind for a mid-latitude glacier in the contiguous United States, owing to a decade of work at the glacial site. To date, ice cores from the Nangpai Gosum Glacier and Inilchek Glacier have only been analyzed for $\delta^{18}O$, ^{36}Cl, and ^{137}Cs since the initial work began on these glaciers in 1998.

Upper Fremont Glacier

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 isotopes, many of which were incorporated into the upper atmosphere. Chlorine-36 and ^{3}H, half-lives of 301,000 and 12.26 years respectively, are two isotopes that were spread throughout the atmosphere and deposited around the globe by means of wet precipitation and dry deposition. During the weapons-testing era, small amounts of these isotopes became trapped each year in glacial ice, thus preserving a chronology of these events. Chlorine-36 and ^{3}H have been measured in a series of precipitation, snow, ice, and runoff samples collected in 1991 and 1998 from the UFG. The ice core collected from the UFG in 1991 shows a profile with depth for ^{3}H and ^{36}Cl that is expected from a minimally disturbed temperate glacial environment (Naftz and others, 1996; Cecil and others, 1999) (figure 2.a,c). Tritium and ^{36}Cl concentrations near the surface of the glacier are similar to concentrations in recent precipitation measured in the Rocky Mountains. In deeper sections of the 1991 core, ^{3}H and ^{36}Cl concentrations increased, reaching maximums at 29 m below the glacial surface for ^{3}H and 32 m for ^{36}Cl. These "markers" represent the 1963 and 1958 peak productions from atmospheric weapons tests, respectively. The ^{3}H and ^{36}Cl concentrations decrease below these depths. Below a depth of 60 m, ^{3}H is essentially zero and ^{36}Cl concentrations return to pre-bomb levels, 10^{6} atoms/L or less.

Sulfur-35 can be used in conjunction with ^{3}H and ^{36}Cl to determine the relative age of meltwater flowing off

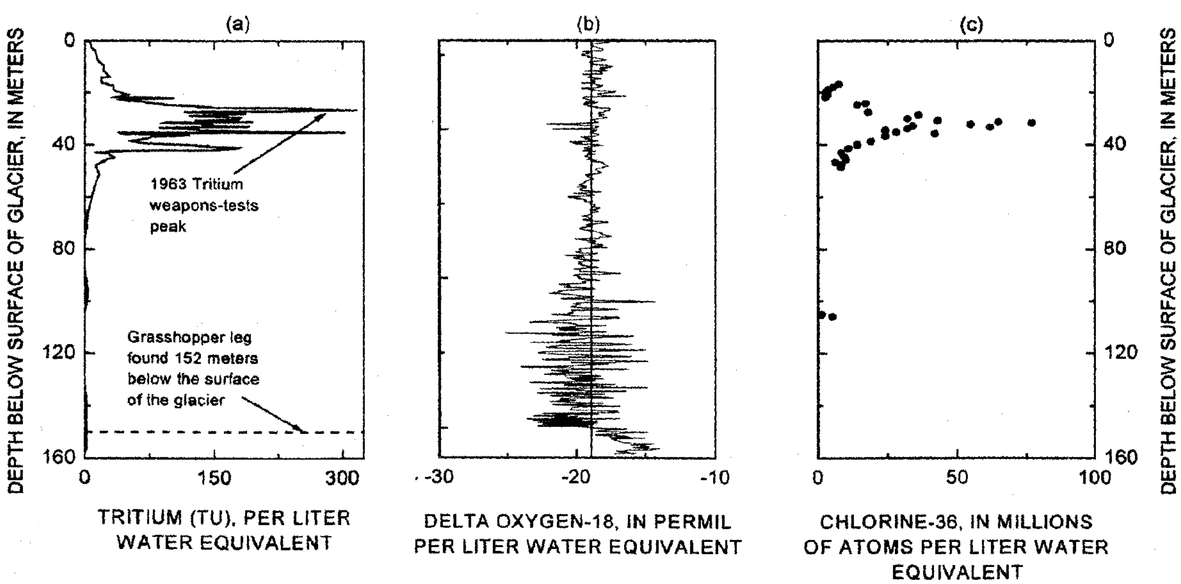

Figure 2. Concentrations in ice-core samples collected from the 1991 Upper Fremont Glacier ice core for (a) tritium (data from Naftz and others, 1996), (b) delta oxygen-18 (data from Naftz and others, 1996), and (c) chlorine-36 (data from Cecil and others, 1999).

glaciers. Produced in the upper atmosphere, ^{35}S is rapidly oxidized to sulfate and deposited on the Earth's surface. Because of its short half-life, 87 days, the presence of ^{35}S in runoff indicates a part of recharge that is less than 2 years in age. Measurements for ^{35}S, ^{3}H, and ^{36}Cl in glacial runoff were performed on samples collected from the UFG in 1991 and 1998. The samples collected in 1991 had a wide range of concentrations for these isotopes (Michel and Naftz, 1995; Cecil and others, 1998). This range reflects the relative age of the glacial samples. The lesser ^{35}S concentrations found in some samples indicate water that was derived primarily from precipitation deposited the previous year. In some cases, the small ^{3}H concentrations indicated that a large fraction of the meltwater was derived from precipitation that had been deposited on the glacier prior to 1953. Snow samples collected in 1998 were obtained earlier in the melt season and had larger ^{35}S and ^{3}H concentrations corresponding to recent precipitation but typical post-weapons tests ^{36}Cl concentrations. It has been seen in other watersheds that runoff from early in the melt season tends to be derived from relatively recent precipitation (Cecil and others, 1998; Michel and others, in press). The combined use of these three isotopes can help to determine the timing of the release of relatively older meltwater from glaciers.

In glacial environments, any plant or animal material trapped in the ice can potentially be dated by ^{14}C (5,730 year half-life). Several assumptions apply when using this method of dating organic materials incorporated into the ice. The assumptions include: (1) the organic material was incorporated into the snow and ice at the actual time of death; and (2) the initial concentration of ^{14}C in the plant or animal material is well known and is independent of time, geographic location of the sample, and species of plant or animal. Naftz and others (1996) dated a species of grasshopper trapped in the ice from the UFG, Wyoming. This sample was taken from the ice core at a depth of 152 m below the surface (figure 2.a). The ^{14}C age of the sample (1729±95 A.D.) indicates that the grasshopper was deposited on the glacier surface sometime in the early- to mid-1700s. This information was very important in the establishment of the glacial ice chronology for the UFG.

Major ion analyses of ice cores are essential components of ice-core interpretation. Changes in the concentrations of selected major ions can be used to identify specific events (natural or human induced) that affect the chemistry of precipitation deposited on a glacier. For example, increases in chloride, nitrate, and sulfate concentrations can provide supporting evidence for volcanic event horizons used as time markers to develop ice-core chronologies. Colder periods are typically windier and dryer, leading to increased deposition of dust layers (rich in magnesium and calcuim). Increased concentrations of these same constituents can be caused by anthropogenic influences such as acid rain and bio-mass burning. Soduim, potassium, magnesium, and calcium can also be enriched in seasonal dust layers deposited on the surface of a glacier. Increased concentrations of these constitiuents not only provide a potential mechanism for development of an ice-core chronology through counting annual dust layers, but also may serve as indicators of paleoclimate change.

Changes in the $\delta^{18}O$ concentrations in ice cores can be used to reconstruct changes in air temperature from the water-vapor source region to the ice-core site (White and others, 1989). Values for $\delta^{18}O$ change in relation to temperature, distance from source water, storm track, altitude, and evaporation. In most ice cores, more negative $\delta^{18}O$ values represent cooler air temperatures. Relative changes in air temperature at the UFG were reconstructed by determining the $\delta^{18}O$ values from equally spaced samples along the entire length of the 1991 ice core (figure 2.b). Between the depths of 102 and 150 m, numerous high-amplitude ocsillations in the $\delta^{18}O$ values were detected. The mean $\delta^{18}O$ value for this depth range abruptly shifted to more negative values, corresponding to the approximate time interval from the mid-1700s to mid-1800s A.D. This period of time coincided with the latter part of what is known as the Little Ice Age (Naftz and others, 1996).

Atmospheric circulation can deposit microbial cells on snowfields and ice surfaces. Some of these wind-borne organisms may survive in a preserved state for extended times, and some types may colonize microhabitats within the accumulated snow layers. It is possible that preserved microbial ice populations contain a record of atmospheric circulation patterns, land use, and biogeographical conditions up wind from deposition sites. In addition, due to the intensity of high altitude sunlight, radiation-tolerant species may prevail in these mid-latitude glacial sites and may act as monitors to changes in ultraviolet radiation due to ozone depletion. Scientists at INEEL have begun their investigation on microbial organisms by studying the 1991 UFG ice core. These ice samples, which have been in frozen storage since collection (Naftz, 1993), are being used to determine total biomass content and to estimate viability of entrained populations. For microbiological analyses, total numbers of microbial cells and organic matter from nine core samples were determined. Significant numbers of "cell-like" objects were observed in most ice samples from the UFG. Total numbers were as high as 2.1×10^{5} cells per milliliter of melt water with numerous discernable morphologies; clumps of brightly fluorescing rods associated with inorganic particles were common in at least one third of the samples and appeared to be more numerous in upper levels. There was, however, no perceptible correlation between depth in the core and microbial numbers. Samples also contained numerous insect parts and large cellular objects believed to be unicellular algae. These results are consistent with reports in the literature from polar ice cores (Karl and others, 1999; Priscu and others, 1998) and appear to correspond with expectations of the subsurface microbial ecology community (Pedersen, 1993; Phelps and others, 1994).

Nangpai Gosum Glacier

Another isotope produced in large quantities during the era of nuclear weapons testing was ^{137}Cs. Like ^{36}Cl and ^{3}H, a small amount of this isotope became trapped each year in glacial ice. Analysis of the 37-m ice core collected from the Nangpai Gosum Glacier in 1998 showed a distinct rise and fall of anthropogenic ^{36}Cl concentrations (figure 3), just as in the UFG ice core. A maximum ^{137}Cs concentration of 0.79 Bq/L was also measured in the ice core (Green and others, in press). This concentration was nearly the same as the maximum weapons-tests ^{137}Cs fallout measured in the Alps, 0.8 Bq/L (H.A. Synal, pers. comm., 1999).

Inilchek Glacier

Sections of the 22-m ice core collected from the Inilchek Glacier in 1998 have been analyzed for $\delta^{18}O$ and major ion concentrations. The $\delta^{18}O$ measurements have shown that the glaciochemical signals at the site are preserved, providing the possibility to reconstruct past summer temperature profiles at the site (Kreutz and others, in press). Cores collected in the summer of 2000 will also be analyzed for $\delta^{18}O$ and major ion concentrations as well as weapons-tests isotopes.

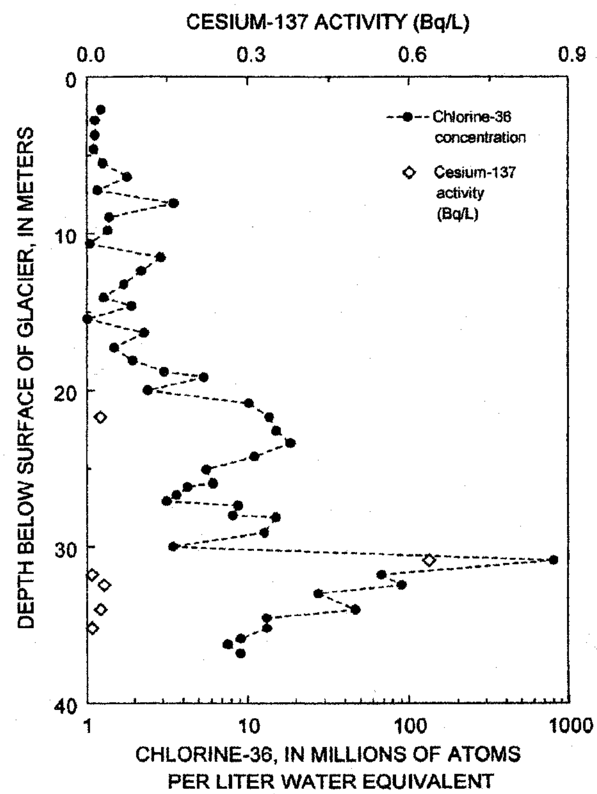

Figure 3. Concentrations of chlorine-36 and cesium-137 in the ice core collected from the Nangpai Gosum Glacier in 1998.

APPLICATIONS

Future information obtained from the study of these three glaciers will add significantly to our understanding of atmospheric processes and possibly provide a linkage to other mid-latitude ice cores recording global environmental changes. Mid-latitude glacial research can potentially be applied to numerous climatic and environmental studies worldwide. Two applications that are discussed below are reconstructing paleoclimate records on a global scale and ground-water modeling.

Paleoclimate Records

Direct current ECMs, used to determine the acidity of ice cores, can be used to assist in the determination of ice-core chronology. ECM application includes the identification of seasonal/summer dust layers for layer counting and the identification of volcanic events to be used as time line markers. Schuster and others (2000) used the original 1991 UFG ice core to produce an ECM log. Together with major ion analyses, ^{3}H, ^{36}Cl, and ^{14}C data, two of the largest volcanic events in the last 10,000 years (Krakatau and Tambora) were identified in the UFG ice core (figure 4) along with more than 30 other speculated volcanic events. The ^{14}C age date of 1729±95 A.D. was subsequently refined to 1736±10 A.D. The refined ice-core chronology also indicated that the transition from the Little Ice Age occurred around 1845 A.D. Additionally, the transition was abrupt, probably fewer than 10 years, in the alpine regions of the Wind River Range, Wyoming (Schuster and others, 2000).

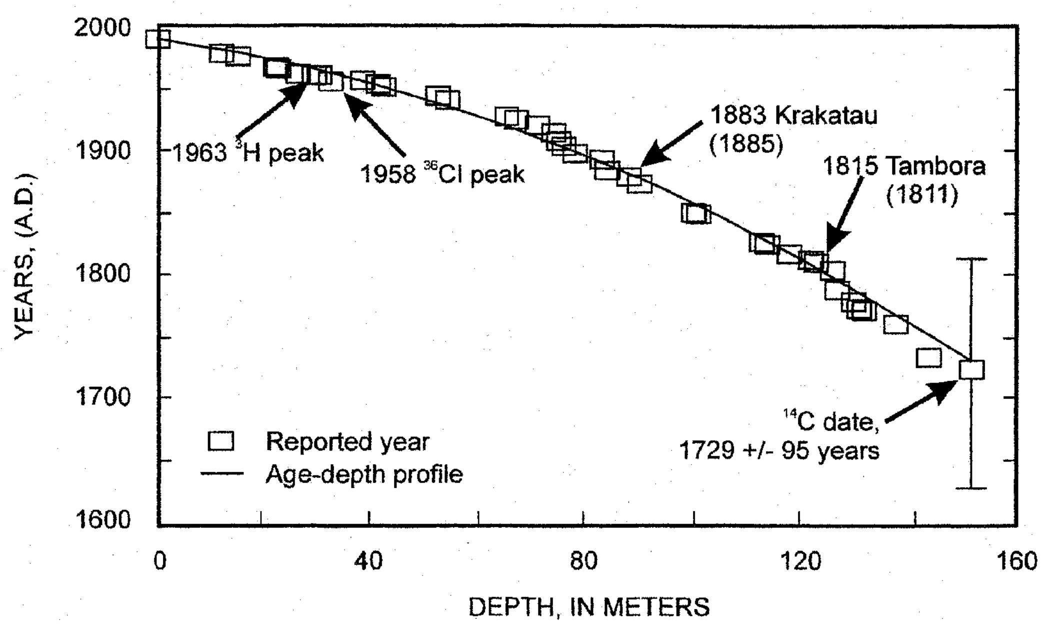

Figure 4. Refined age-to-depth profile for the 1991 Upper Fremont Glacier ice core (modified from Schuster and others, 2000). Boxes are the reported year for historic events that are preserved in the ice.

Ground-Water Modeling

The USGS is working with the U.S. Department of Energy's Idaho National Engineering and Environmental Laboratory (INEEL) in Idaho (figure 1) to study ground water. Measurable amounts of ^{36}Cl have been detected in ground water in the far field at the INEEL. It is desirable to determine how much of the ^{36}Cl in the ground water is due to natural *in situ* production, how much is due to nuclear-weapons input, and how much is due to nuclear-waste disposal practices at the INEEL so that the influences of the INEEL on the environment can be better understood.

Because the INEEL is at nearly the same latitude as the UFG (N. 43° to 44°), similar amounts of ^{36}Cl were deposited in the mountains around the INEEL as were incorporated into the ice of the UFG. 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 the ground water already present. Determination of ^{36}Cl concentrations in the UFG ice core and calculation of *in situ* ^{36}Cl production within the rock matrix have allowed more accurate determination of the origin of ^{36}Cl in far-field ground water at the INEEL (Cecil and others, 2000). Using this data, a one dimensional systems response model that predicts aquifer dispersivity in the eastern Snake River Plain of Idaho has been developed (Cecil and others, in press).

SUMMARY

Precipitation, snow, ice, and runoff samples from three mid-latitude glaciers are currently being analyzed and studied because the majority of the world's population lives in mid-latitude regions. Input from nuclear-weapons tests of the mid-1900s, large volcanic events, and radiocarbon dating of organic material, have been identified as time markers in the UFG and Nangpai Gosum Glacier ice cores. These event markers, in conjunction with other types of analyses such as $\delta^{18}O$ and ^{35}S, aid in refining the chronology of the ice cores. The reconstruction of ice core chronologies provides critical support to many areas of research, such as describing anthropogenic input of chemicals to the environment and ground-water modeling. Linking data from mid-latitude glaciers around the world will also aid in modeling climate change and reconstructing paleoclimate records on a global scale.

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