Glaciers of Asia—

THE PALEOENVIRONMENTAL RECORD PRESERVED IN MIDDLE LATITUDE, HIGH-MOUNTAIN GLACIERS—AN OVERVIEW OF THE U.S. GEOLOGICAL SURVEY EXPERIENCE IN CENTRAL ASIA AND THE UNITED STATES

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SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

Edited by RICHARD S. WILLIAMS, JR., *and* JANE G. FERRIGNO

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The Paleoenvironmental Record Preserved in Middle-Latitude, High-Mountain Glaciers—An Overview of the U.S. Geological Survey Experience in Central Asia and the United States

By L. DeWayne Cecil,[1] David L. Naftz,[2] Paul F. Schuster,[3] David D. Susong,[2] *and* Jaromy R. Green[4]

Abstract

The U.S. Geological Survey (USGS) is conducting a research program to study the geochemical and isotopic content of precipitation, snow, ice, and runoff samples from high-mountain glaciers in the middle latitudes of central Asia and the United States. Related topics of research, such as the reconstruction of paleoclimate records, the description of anthropogenic input of chemicals to the environment, and computer modeling of global climate change, are important to the well being of the Earth's human population. The collection and chemical analysis of snow and glacier ice cores can improve our knowledge of all of these topics. Nearly all of the chemical constituents that compose snow and ice-core samples contribute important scientific information. This research is made critical by the fact that middle-latitude, high-mountain glaciers, and the environmental and other information preserved in them, are rapidly disappearing as a result of global warming. Information collected to date includes the documentation of fallout from nuclear-weapons testing conducted during the 1940s, 1950s, and 1960s, quantification of pre-industrialization levels of mercury in the environment, evidence of rapid regional climate change, and identification of microbial communities entrained in the ice. Researchers from national and international academic institutions and from federal and provincial governmental agencies are collaborating on this project.

Introduction

Global environmental changes have occurred throughout the 4.5 billion-year history of the Earth, and such changes will continue to take place throughout the Earth System in the future. The changes are now recognized to have the potential for immediate as well as long-term consequences for the Earth's varied ecosystems. As a result, the importance of understanding current and potential global environmental change has dramatically increased (Cecil and others, 2004).

Archives of past climatic and environmental conditions are preserved in the Earth's alpine glaciers, ice caps, ice fields, and ice sheets. Ice cores from the polar regions have provided the scientific community with an unprecedented view of past environmental change through analysis of chemical, isotopic, and stratigraphic data. These records extend back in time for 110,000 years in ice

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cores from the Greenland ice sheet (Alley, 2000) and for more than 800,000 years (EPICA, 2004) in the Antarctic ice sheet. However, changes in weather and climate patterns affect high-latitude regions of the world differently than they do middle- to low-latitude regions because of latitudinal differences in global circulation. Because the majority of the Earth's population, at least 85 percent, lives between latitudes 50°N. and 50°S., it is of prime importance to understand potential environmental change in middle- and low-latitude regions; ice cores collected from selected high-mountain glaciers in temperate regions are valuable tools for this effort.

Although some middle-latitude, high-mountain regions of the Earth are glacierized, glaciers in these regions are generally considered to have unusable records of past environmental and climatic changes because of thawing and refreezing, and associated meltwater percolation. Recently, however, it has been shown that carefully selected middle-latitude, high-mountain glaciers accurately preserve isotopic and chemical records, thus providing information about climatic and environmental changes (Naftz and others, 1996, 2004; Cecil and Vogt, 1997; Cecil and others, 1998, 2004; Thompson, 2000, 2004, in press; Schuster and others, 2002, 2004; Green, Cecil, Synal, and others, 2004). Middle-latitude, high-mountain glaciers must have certain characteristics to preserve retrievable environmental records in glacier ice-cores. These include relatively simple ice-flow dynamics, flat to low-angle bedrock topography, limited redistribution of snow from wind and avalanches, minimal snowmelt during the summer season or minimal effects from the snow melt, and sufficiently thick glacier ice for maximum record length. To determine if a glacier has some of these characteristics, snow samples that fall on the glacier surface can be analyzed for lateral variability of chemical and particulate constituents across the glacier surface, caused by processes such as wind, temperature, and elevation gradients.

In addition to recording naturally occurring past environmental changes, middle-latitude, high-mountain glaciers also preserve a record of atmospheric input from human activities. Increased levels of many modern substances are archived in younger glacier ice (less than about 100 years old). Such substances include pollutants from refrigerants, sulfate from acid rain, mercury and other heavy metals from coal-burning power-plants and other industrial emissions, isotopic fallout from nuclear facilities including accidents such as at Chernobyl, Russia, in April 1986, and fallout from above-ground testing of nuclear weapons in the 1940s, 1950s and 1960s.[5] Detonation of nuclear devices by the United States and Great Britain over the Pacific Ocean in the mid-1960s created a significant quantity of radioactive isotopes, many of which were incorporated or injected directly into the upper atmosphere.[6] Chlorine-36 (^{36}Cl), tritium (^{3}H), and cesium-137 (^{137}Cs) with half-lives of 301,000, 12.26, and 30.2 years, respectively, are three isotopes that were spread throughout the atmosphere and deposited around the globe by means of both wet precipitation and dry deposition. During the nuclear-weapons-testing era, small amounts of these isotopes became trapped each year in the glacier ice, thus compiling an atmospheric-based record of the recent past.

[5]Editors' note: The first above-ground test of a nuclear weapon was on 16 July 1945; most above-ground tests of nuclear weapons ceased in 1963, after 711 tests in the atmosphere or the ocean. According to Greenpeace, the source of information in this footnote, "the last atmospheric nuclear weapons test occurred on 16 October 1980 in China." *http://archive.greenpeace.org/comms/nukes/ctbt/read9.html*

[6]Editors' note: During 1962, five high-altitude atmospheric tests of nuclear weapons were conducted by the United States in the Pacific Ocean under Operation "Fishbowl." Four of the tests were 10s of kilometers above the Earth. The fifth test, "Starfish Prime," detonated a 1.4 megaton nuclear device 400 km above Johnston Island (exoatmospheric) on 9 July 1962. The tests produced many fallout products that were distributed globally.

With the advent of ultra-sensitive analytical methods such as accelerator mass spectrometry (AMS) and the collaboration of expert scientists with diverse expertise and experience, glaciers worldwide are more accessible for study. The USGS and other institutions (Thompson, in press) are currently conducting research on middle-latitude, high-mountain glaciers in central Asia and North America, applying new scientific methods to an understanding of human influence on global environmental processes. Sites in central Asia are located on the *Nangpai Gosum Glacier,* Nepal; Lednik Engil'chek,[7] Kyrgyzstan/Kazakhstan/China; and *Belukha Glacier*,[8] Russia/Kazakhstan. The site in North America is on the Upper Freemont Glacier, Wyoming (fig. 1). The studies described here are being carried out in collaboration with researchers from several domestic and foreign universities, U.S. national laboratories, and other federal and provincial governmental agencies.

The scientific validity of results from analysis of glacier ice cores is dependent on the following precise protocols for each step: ice-core collection, storage, analysis, and interpretation (Green, Cecil, and Frape, 2004). Mechanical drills were utilized for ice-core collection at the central-Asia sites, and a thermal drill was used for ice-core collection at the site in North America. This difference in drilling technique is a result of the difference in elevation of the sites. The site in North America is the lowest in elevation above sea level; therefore, a thermal drill was utilized to insure maximum ice-core recovery. The mechanical and thermal drills were used to obtain continuous ice-core samples for chemical and physical analyses. At each site, 1-m long ice-core sections were removed from an aluminum core barrel, quickly sealed in polyethylene bags, and placed in lexan core tubes by personnel wearing TyvekTM suits and powder-free latex gloves. The core tubes were stored at a maximum temperature of 0 °C in snow vaults constructed at each collection site. Immediately after drilling was completed, the ice-core containers were packed in dry ice and transported by yak, helicopter, jet aircraft, and/or freezer truck to cold storage in the United States. Temperature recorders were placed in the shipping containers to monitor any changes during the shipping phase. The temperature inside the containers did not exceed 0 °C during shipping. The cores were equilibrated to exam-room temperature, 10 °C to 24 °C, for 24 hours prior to processing for chemical and physical analyses.

Ice and meltwater samples from the glacier ice core were analyzed for their elemental and isotopic content using various laboratory methods and established protocols. After melting the ice in a controlled environment to ensure minimal or no contamination from ambient air, the resultant melt-water was prepared for analysis.

Certain constituents present in ice cores can be used to reconstruct the timing and significance of past environmental and climatic events. For example, radionuclides are useful for establishing time lines in ice-core records. Direct-current electrical-conductivity measurements (ECM), in combination with concentrations of selected anions, are used to document historic volcanic events that also aid in establishing time lines. Changes in the isotopic composition of the oxygen atom in ice molecules can be used to reconstruct changes in air temperature and relative precipitation rates during long time periods. Initial research indicates that microbial populations preserved in glacier ice may have responded to changes in atmospheric circulation patterns, land use, and biogeographical conditions.

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[7]Although Lednik Engil'chek is the officially approved version of the glacier name, the more commonly known and used versions are Inyl'chek or Inilchek Glacier.

[8] U.S. Government publications require that official place-names for foreign countries be used to the greatest extent possible. In this section, the use of geographic place-names is based on the U.S. Board on Geographic Names (BGN) website, as listed on the GEOnet Names Server (GNS): *http://earth-info.nga.mil/gns/html/index.html*. Names not listed on the BGN website are shown in italics.

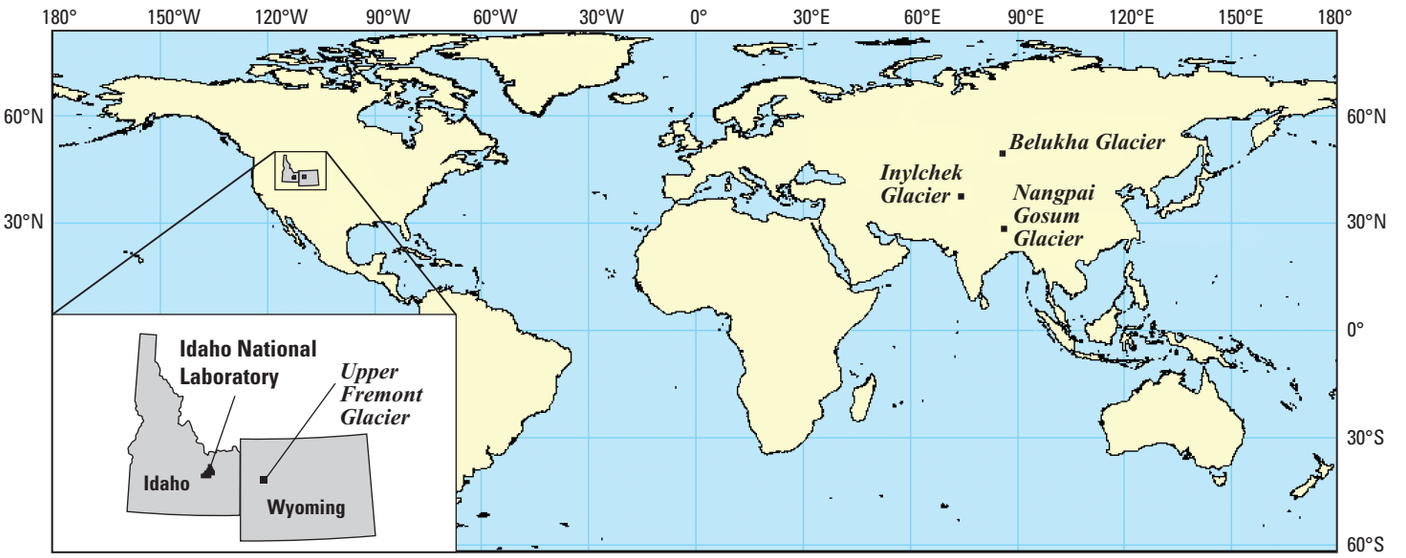

***Figure 1.**—Locations of the* Nangpai Gosum Glacier*, Nepal; Lednik Engil'chek (Inylchek Glacier), Kyrgyzstan/Kazakhstan/China;* Belukha Glacier*, Russia/Kazakhstan; and the Upper Fremont Glacier, Wyoming, U.S.A.; and the Idaho National Laboratory, U.S.A.*

For the research described here, the radionuclides chlorine-36 (^{36}Cl), cesium-137 (^{137}Cs), and carbon-14 (^{14}C) were analyzed by accelerator mass spectrometry (AMS) methods (Currie and others, 1985; Elmore and Phillips, 1987). Tritium (^{3}H) was analyzed by using electrolytic enrichment (Ostlund and Werner, 1962; Thatcher and others, 1977). Concentrations of chloride (Cl^-), nitrate (NO_3^-), and sulfate (SO_4^{-2}) are determined by ion exchange chromatography (Fishman and Friedman, 1989). Concentrations of sodium (Na^+), magnesium (Mg^{++}), and calcium (Ca^{++}) 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 (NH_4^+) and potassium (K^+), at small environmental concentrations. Values for delta oxygen-18 ($\delta^{18}O$) were determined using a gas- or solid-source mass spectrometer (Kendall and Caldwell, 1998). The mercury (Hg) analyses presented here were performed by Dual Amalgamation Cold Vapor Atomic Fluorescence Spectrometry (USEPA Method 1631, 1999).

The electrical-conductivity measurements (ECM) were performed by drawing a pair of electrodes along the entire length of an ice core at a constant velocity (Schuster and others, 2000). For microbiological analyses, total numbers of microbial cells and organic matter were determined by acridine-orange, direct-count microscopy at the U.S. Department of Energy's Idaho National Laboratory (INL), Idaho, USA (M. Delwiche, oral commun., 2005). The glacier ice cores were melted according to protocols described by Naftz (1993) that were modified for microbial analyses. Standard quality assurance and quality control protocols and guidelines were followed for all analyses presented in this paper.

Study Sites

Nangpai Gosum Glacier

Researchers from the University of New Hampshire are studying the *Nangpai Gosum Glacier*, located 25 km west northwest of Mount Everest in the Nepal Himalaya (fig. 1). It is located at lat 28°02′N., long 86°36′E. The ice-core drilling site is situated at 5,700 m above mean sea level. In 1998, a 37-m ice core was extracted from the glacier by Cameron P. Wake of the University of New Hampshire and transported to the University of New Hampshire for analysis. At the request of the USGS study team, radionuclide analyses were performed for ^{36}Cl and ^{137}Cs on selected sections of the ice core by Hans-Arno Synal at the Paul Scherrer Institut (PSI) in Villigen, Switzerland.

Lednik Engil'chek

The Lednik Engil'chek (fig. 1) is being studied in collaboration with researchers from several U.S. and foreign universities. It is located in the Tien Shan of central Asia at lat 42°10′N., long 80°15′E. It is located in 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 is estimated to contain 1,000 to 5,000 years of accumulation. The elevation of our selected drilling site, 5,300 m, is high enough that minimal or no melting occurs (Aizen and others, 1997). In the summer of 2000, two deep ice cores, 162 m and 165 m in length, fresh snow, snow pit, and crevasse-wall samples were also recovered from this site (Kreutz and others, 2003, 2004; Green, Cecil, Synal, and others, 2004). Ice chips from the uppermost 100 m of one of the deep cores were shipped frozen to PSI where ^{36}Cl analyses were performed with the AMS. The cores provide a high-resolution isotopic and geochemical record that spans approximately the last 200 years.

Belukha Glacier

The *Belukha Glacier* [also called the *Belukha Firn Plateau*] is situated at an elevation of about 4,000 m in the Altay mountains of southern Siberia, at lat 49°48'26"N., long 86°34'43"E. on the border of Kazakhstan and Russia (fig. 1). The glacier's remote location makes it potentially an ideal site for environmental studies. A team of scientists, including Americans, Russians, and Japanese, traveled to this remote glacier in the summer of 2001 to assess the feasibility of studying the glacier and extracting ice cores at the site. A Swiss-Russian team also worked on the glacier in 2001. Research was carried out from 2001 to 2003; glaciological observations were made, and both shallow cores and cores to bedrock were extracted and analyzed (Olivier and others, 2003; Fujita and others, 2004). Based on tritium analysis to date, the deeper cores may contain as much as 3–5,000 years of climatic and environmental records (Aizen, oral commun., 2005)

Upper Fremont Glacier

The Upper Fremont Glacier (fig. 1) is located at lat 43°07'52"N., long 109°36'55"W., in the Wind River Range of Wyoming (figs. 18 and 19 on p. J360 and J361, respectively, in Krimmel, 2002). It is a relatively large middle-latitude glacier with a surface area between 2.5 and 3 km^2, a maximum altitude of 4,100 m above sea level, and an ice thickness greater than 150 m. It is located nearly 40 km inside the boundary of a designated wilderness area; access to the glacier requires a rigorous 2-day hike from the nearest road as well as the use of pack goats to transport scientific equipment and supplies. Continuous ice cores were collected

from the glacier in 1991 and 1998. The site contains an ice-core record that is representative of past climatic and environmental changes, and of precipitation falling in remote, high-altitude environments in this part of North America (Naftz, 1993; Naftz and others 1993, 1996, 2004, 2009; Cecil and Vogt, 1997; Cecil and others, 1998, 1999, 2004; Schuster and others, 2000, 2004).

Selected Results and Discussion

Various constituents from archived inventories of snow-and-ice cores from middle-latitude glaciers have been identified. To date, ice cores from the *Nangpai Gosum Glacier*, Lednik Engil'chek, and the *Belukha Glacier* have only been analyzed for select constituents (for example, $\delta^{18}O$, ^{36}Cl, and ^{137}Cs). The initial work involving researchers from the USGS began on these glaciers in 1998. For the Upper Fremont Glacier, the ice-core and snow dataset is the most comprehensive of its kind for a middle-latitude glacier in the contiguous United States, the result of more than a decade of work on this glacier (Naftz and Miller, 1992; Naftz, 1993; Naftz and others, 1993, 1996, 2004, 2009; Cecil and Vogt, 1997; Cecil and others, 1998, 1999, 2004; Schuster and others, 2000, 2004).

Nangpai Gosum Glacier

Many radioactive isotopes were produced during the 35 years of above-ground nuclear-weapons testing, including ^{137}Cs. As with ^{36}Cl and ^{3}H, a small amount of ^{137}Cs (greater than background concentrations) became trapped in glacier ice during the 1940s, 1950s, and 1960s. Analysis of the 37-m ice core collected from the *Nangpai Gosum Glacier* in 1998 showed a distinct peak of anthropogenic ^{36}Cl and ^{137}Cs concentrations (fig. 2), just as for ^{36}Cl in the Upper Fremont Glacier ice core (fig. 3*C*). It was determined that the peak nuclear-weapons-tests fallout of ^{36}Cl and ^{137}Cs occurs at a depth of about 31 m in this glacier.

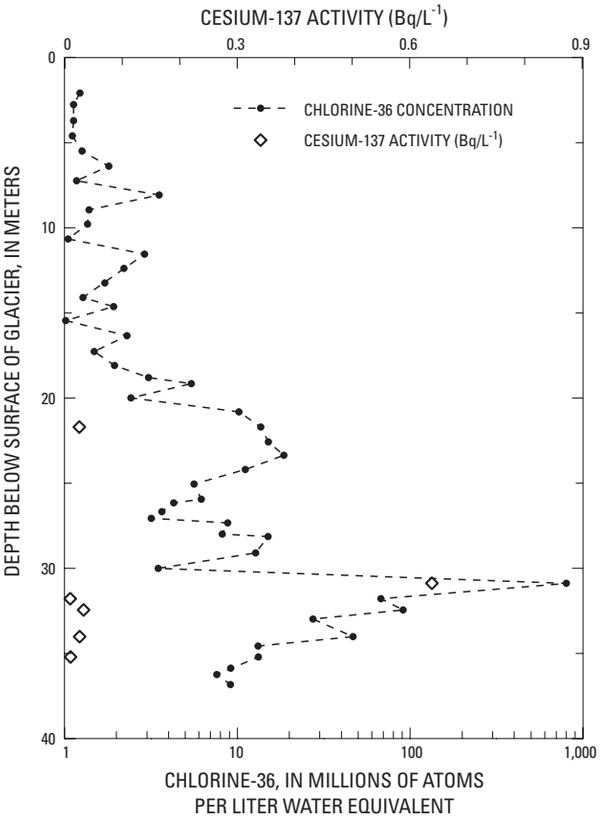

***Figure 2.**—Chlorine-36 and cesium-137 concentrations in the ice core collected from the* Nangpai Gosum Glacier *in 1998. BqL^{-1} (Becquerels per liter) is a measure of radioactivity.*

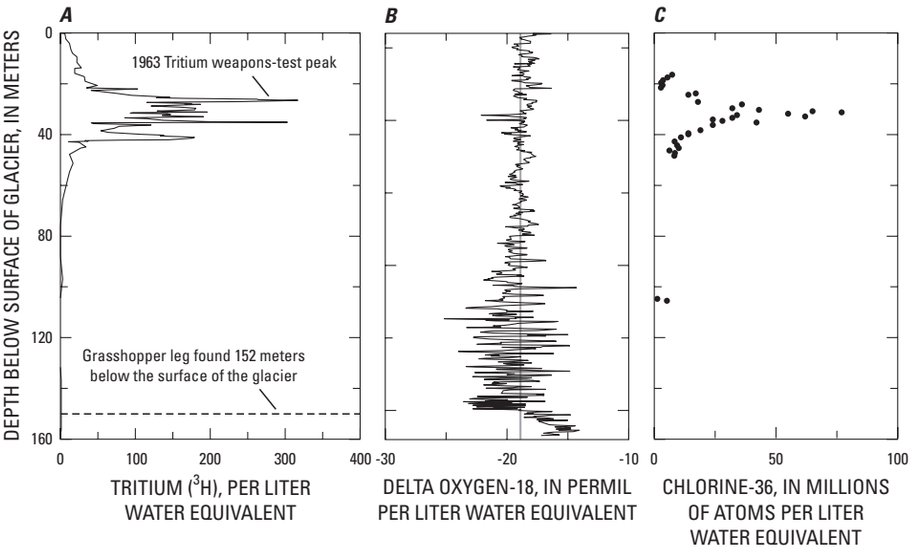

Figure 3.—*Concentrations of* **A**, *Tritium (^3H) (data from Naftz and others, 1996),* **B**, *delta oxygen-18 ($\delta^{18}O$) (data from Naftz and others, 1996) and* **C**, *chlorine-36 (^{36}Cl) (data from Cecil and others, 1999) in ice-core samples from the 1991 Upper Fremont Glacier expedition.*

Lednik Engil'chek

Kreutz and others (2004) documented the limited spatial and elevational dependence that exists in isotopic and major ion data from the fresh snow pack at the Lednik Engil'chek site. There was no apparent trend with increasing elevation for any of the isotopic or geochemical variables measured. These findings lead to the conclusion that snow formation occurs from a horizontal cloud base across the Lednik Engil'chek and vicinity. In addition, based on the estimated accumulation rates at this site (1.6 m a^{-1}), it was reported that the interannual-scale variability in the ice-core profiles is significantly greater than the spatial variability during individual snowfall events. The conclusion from this analysis is that the majority of the down-core isotopic variability may be a reflection of climate changes rather than ice-flow effects or noise in the snow-deposition signal.

These conclusions have implications for further interpretation of the apparently high-resolution isotopic and geochemical records that will be developed from the two deep cores collected in 2000 (Kreutz and others, 2003). The implications are: (1) the high-resolution records may be used to evaluate the time-series, signal-to-noise ratio related to small-scale deposition processes, (2) given the relatively high accumulation rate at this site, it may be possible to reconstruct climate and environmental change on a snowfall-event basis, and (3) given the isotopic signals observed in the fresh snow events and the snow pits, it may be possible to investigate moisture sources and pathways to the Lednik Engil'chek through time on a subannual scale.

For example, Green, Cecil, Synal, and others (2004) reported a high-resolution subannual record of nuclear-weapons-test era ^{36}Cl from an ice core collected at the Lednik Engil'chek in 2000. In spite of the accumulation differences between the Upper Fremont Glacier and Lednik Engil'chek, 0.76 m a^{-1} and 1.6 m a^{-1}, respectively, the peak ^{36}Cl concentrations were remarkably similar in shape and magnitude. However, because of the greater accumulation rate calculated for the Lednik Engil'chek site, it is possible that the isotopic and geochemical record archived in this glacier will provide the opportunity for detailed study

of environmental changes during the last 150 years. Each section of the Lednik Engil'chek ice core that was analyzed for ^{36}Cl was representative of as little as one-third of the annual accumulation; the same volume of ice used for ^{36}Cl analyses at the Upper Fremont Glacier may have been representative of more than one year's accumulation. This high-resolution record from Lednik Engil'chek may aid in the study of the documented diminishing water resources that may be one of the results of global warming in heavily-populated central Asia.

Upper Fremont Glacier

Chlorine-36 (^{36}Cl) and ^{3}H have been measured in a series of precipitation, snow, ice, and runoff samples collected in 1991 and 1998 from the Upper Fremont Glacier. The ice core collected from the Upper Fremont Glacier in 1991 shows a profile with depth for ^{3}H and ^{36}Cl that is expected from a minimally disturbed, temperate-glacier environment (fig. 3*A, C*) (Naftz and others, 1996; Cecil and others, 1999). Tritium (^{3}H) 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 are higher, reaching maximums at 29 m below the glacier surface for ^{3}H and 32 m for ^{36}Cl. These "markers" represent the 1963 and 1958 peak productions from atmospheric weapons tests, respectively (Cecil and others, 1999). The ^{3}H and ^{36}Cl concentrations decrease below these depths. Below a depth of 40 m, ^{3}H concentrations are essentially zero and ^{36}Cl concentrations return to pre-nuclear weapons test levels of 10^{6} atoms per liter (l^{-1}) water equivalent or less.

In glacier environments, any plant or animal material within the ice potentially can be dated by determining the amount of ^{14}C in the sample (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 of the plant or organism; 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 contained in the ice core collected from the Upper Fremont Glacier in 1991. The sample was taken from the ice core at a depth of 152 m below the surface (fig. 3*A*). The ^{14}C content of the grasshopper was determined using AMS (Currie and others, 1985). The ^{14}C age of the sample (A.D. 1,729 ±95 years) indicates that the grasshopper was deposited on the glacier surface sometime in the mid-1600s to the mid-1700s. To build confidence in this ^{14}C age, additional grasshopper parts were extracted from a depth of 146 m in the ice core collected in 1998. The ^{14}C model age for the grasshopper parts was determined to be A.D. 1,680 ±80 years. This information, coupled with the mercury (Hg) profile (discussed below) and the nuclear weapons-testing dates provided by the ^{3}H and ^{36}Cl profiles was instrumental in establishing a detailed glacial ice-core chronology and age-to-depth profiles for the Upper Fremont Glacier.

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 anthropogenic) that affect the chemistry of precipitation deposited on a glacier. For example, increases in Cl^{-}, NO_3^{-}, and SO_4^{-2} concentrations can provide supporting evidence for volcanic-event horizons used as time markers to develop an ice-core chronology. Colder periods are typically windier and dryer thus facilitating increased deposition of dust layers (rich in Mg^{++} and Ca^{++} in western North America). Increased

concentrations of these same constituents can be caused by anthropogenic influences, such as acid rain and bio-mass burning; Na^{+}, K^{+}, Mg^{++}, and Ca^{++} can be enriched in seasonal dust layers deposited on the surface of a glacier. Increased concentrations of these cations not only provide a potential mechanism for development of an ice-core chronology through counting annual dust layers, but they also may serve as indicators of paleoclimatic 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 of $\delta^{18}O$ change in relation to temperature of formation of and 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 Upper Fremont Glacier were reconstructed by determining the $\delta^{18}O$ values from equally spaced samples along the entire length of the 1991 ice core (fig. 3*B*). Between the depths of 102 m and 150 m, numerous high-amplitude oscillations 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-A.D. 1700s to mid-A.D. 1800s. This period of time coincides with the latter part of the "Little Ice Age" (LIA) (Naftz and others, 1996, 2004).

Atmospheric circulation can deposit microbial cells on snowfields and glacier-ice surfaces. Some of these windborne 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 upwind from deposition sites. Upwind sources of heavy metals from mining and smelting operations may have an influence on the microbial communities that can survive and flourish at higher altitudes; where heavy metal fallout is significant at the glacier's surface, metal-reducing microbial types may prevail. In addition, because of the intensity of high-altitude sunlight (for example, more intense UV radiation), radiation-tolerant species may dominate in these middle-latitude glacier sites and may act as monitors to changes in ultraviolet radiation caused by thinning of the ozone layer. Scientists at the INL have begun investigations on microbial organisms found in ice cores from our study sites. The ice samples, which have been in frozen storage since collection, are being used to determine total biomass content and to estimate viability of englacier populations.

The total number of microbial cells and organic matter from nine ice-core samples collected from the Upper Fremont Glacier have been determined (M. Delwiche, personal commun., 2005). After melting, 0.1 milliliter (mL) of core interior meltwater was immediately plated onto rich (R2A) and lean (1 percent PTYG) types of standard solid medium for growth of heterotrophic microorganisms (Gerhardt and others, 1994). Also, 5 mL of each inner core and of each "rinse" from the core exterior, and 10 mL of filtered DI water as a negative control were stained with 0.01 percent acridine orange fluorescent dye. Standard microscopy methods were used for preparation and counting of stained cells on black polycarbonate membrane filters (Hobbie and others, 1977). In all, 8 negative controls, 18 core, and 9 rinse slides were counted. In addition to analyses performed immediately after melting, meltwater was stored and retested after time periods of 12 days and 2 months to test the effects of storage on culturability of contained microbial populations. All plates and meltwater were stored at 12 °C.

Significant numbers of "cell-like" objects were observed in most ice samples. Total numbers were as high as 2.1×10^{5} cells mL^{-1} of melted ice 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 the shallower sections of the ice core. There was no perceptible correlation between depth in the core and microbial numbers. Samples also contained numerous arthropod parts and large cellular objects believed to be unicellular algae. The results are consistent with reports in the literature from polar ice cores (Priscu and others, 1998; Karl and others, 1999) and appear to correspond with expectations of subsurface microbial communities (Pedersen, 1993; Phelps and others, 1994).

Direct current electrical conductivity measurements (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, 2004) used the 1991 Upper Fremont Glacier ice core to produce an ECM log (fig. 4). Together with major ion analyses, ^{3}H, ^{36}Cl, and ^{14}C data, two of the largest explosive volcanic eruptions during the last 10,000 years (fig. 5) (Krakatau, Indonesia, on 27 August 1883; and Tambora, Sumbawa, Indonesia, on 10-11 April 1815) (Simkin and Siebert, 1994) were identified in the ECM signal produced from

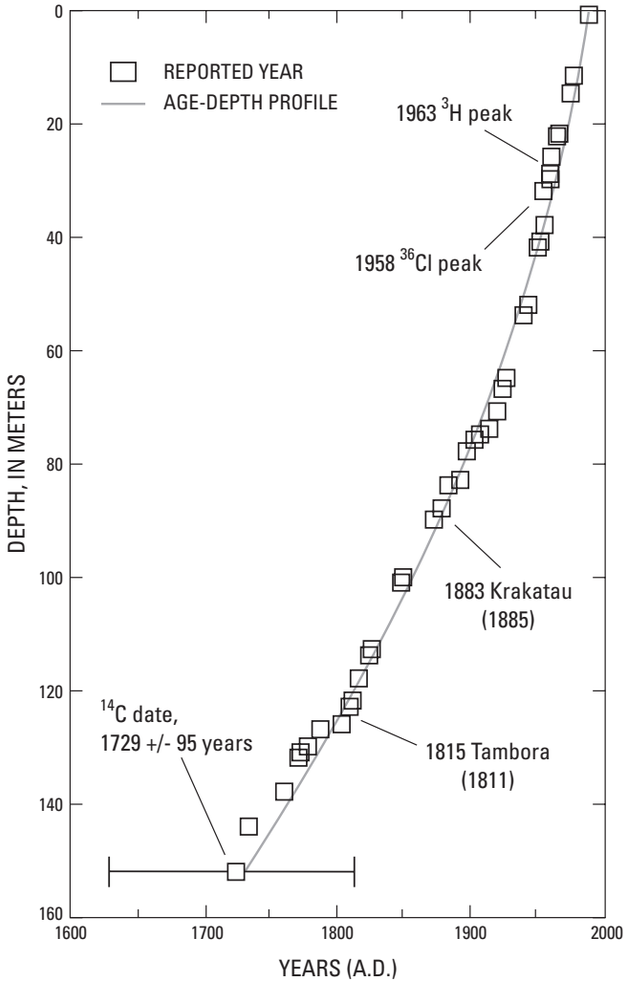

***Figure 4.**—Refined age-to-depth profile for the 1991 Upper Fremont Glacier ice core. Modified from Schuster and others (2004). Boxes are the reported year for historic events that are preserved in the ice.*

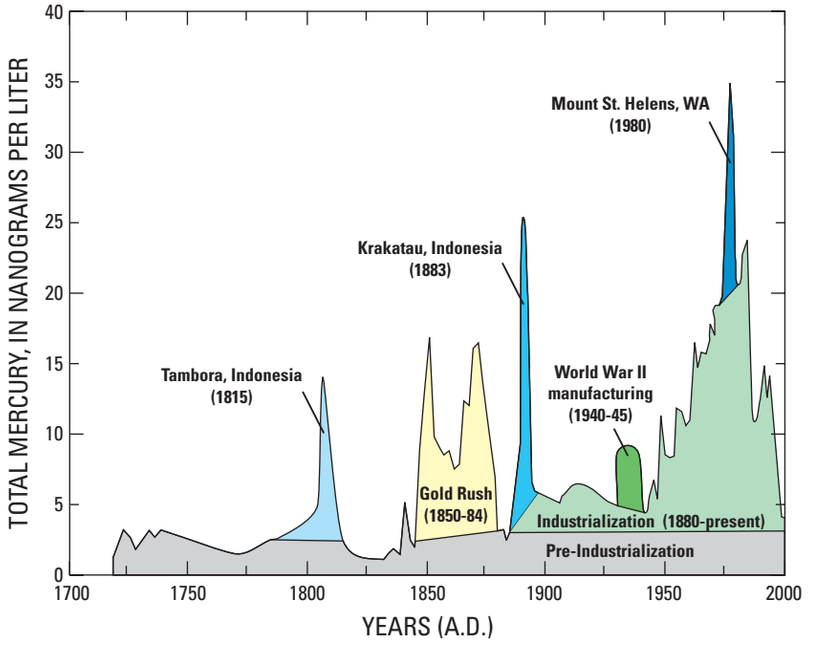

***Figure 5.**—Profile of historic concentrations of mercury (Hg) measured in selected ice-core sections from the Upper Fremont Glacier. Modified from Schuster and others (2000).*

the Upper Fremont Glacier ice core along with more than 30 lesser volcanic eruptions. The refined ice-core chronology indicated that the transition from the LIA that was preserved in the ice core occurred around A.D. 1845. Additionally, the transition was abrupt, probably fewer than 10 years, in the alpine regions of the Wind River Range, Wyoming U.S.A. (Naftz and others, 1996, 2004; Schuster and others, 2000, 2004).

Applications

Future information obtained from the study of these glaciers will add significantly to our understanding of atmospheric processes and possibly provide a linkage to other middle-latitude ice cores that record global environmental changes. Middle-latitude glacier research can potentially be applied to numerous climatic and environmental studies worldwide. Applications of the results from the Upper Fremont Glacier study site are discussed below and include reconstructing paleoclimatic records on a global scale and documentation of environmental mercury concentrations during the past 270 years. Similar interpretations and applications of the datasets from the central Asia glacier sites are underway.

Paleoclimatic Records

In addition to the documentation of an abrupt end to the LIA, Naftz and others (2004) developed a transfer function for estimating the change in ambient air temperature over time using the $\delta^{18}O$ profile from the Upper Fremont Glacier ice core and on-site snow-depth sensor data. The transfer

function was then used to reconstruct trends in average air temperature during the last 300 years. Based on this transfer function, an increase in air temperature of about +2 °C has occurred at the Upper Fremont Glacier site from the end of the LIA to the present, a relatively rapid air-temperature change.

A consequence of this apparent rapid change in climate was documented in the form of a glacier-outburst flood event (jökulhlaup) (GLOF) that occurred at Grasshopper Glacier in September 2003, 14 km north of the Upper Fremont Glacier (Naftz and others, 2009). A 12-hectare lake at the head of Grasshopper Glacier instantaneously burst releasing approximately 3.2×10^6 m^3 of water, with an associated maximum stream flow of about 35.7 m^3 s^{-1} on Dinwoody Creek downstream from the lake. Annual peak stream flows on this creek generally occur during middle- to late-June as a result of snowmelt runoff and average 26.7 m^3 s^{-1} based on 38 years of record. As a result of the jökulhlaup, there may be an increased flood risk in the upper reaches of the drainage basin because of aggradation of the stream channels. Continued warming and melting of glaciers in the Wind River Range may result in future and perhaps more frequent jökulhlaups.

Environmental Concentrations of Mercury

A record of atmospheric mercury (Hg) deposition has been documented in ice from the Upper Fremont Glacier (Schuster and others, 2000, 2004). Although some polar ice-core studies have provided a limited record of past Hg deposition, polar cores are, at best, proxy indicators of historic Hg deposition in the middle-latitudes, where 80 to 90 percent of the Earth's human population resides. Two ice cores extracted from the Upper Fremont Glacier in 1991 and 1998 (each totaling 160 meters in length) provided a chronology and paleoenvironmental framework that were essential to the interpretation of the Hg deposition record. A total of 97 ice core samples were selected using low-level processing methods and were analyzed to reconstruct a 270-year atmospheric Hg deposition record for this part of North America. Trends in Hg concentration measured in ice from the Upper Fremont Glacier record major releases to the atmosphere of both natural and anthropogenic Hg from regional and global sources (fig. 5).

The record shows that Hg concentrations are significantly, but for relatively short-time intervals, elevated during periods corresponding to explosive volcanic eruptions, an indication that natural volcanic events "punctuate" the record. Anthropogenic activities, such as industrialization (global-scale), gold mining, and wartime manufacturing (regional scale), indicate that chronic levels of elevated Hg emissions have a greater influence on the historical atmospheric deposition record from the Upper Fremont Glacier. In terms of total Hg deposition recorded by the Upper Fremont Glacier during approximately the past 270 years: anthropogenic inputs appeared to contribute 52 percent; volcanic events contributed 6 percent; and pre-industrialization (or background level) accounted for 42 percent of the total input. More significantly, during the last 100 years, anthropogenic sources contributed 70 percent of the total Hg input. A declining trend in Hg concentrations is obvious during the past 20 years. Declining Hg concentrations in the upper section of the ice-core profile (fig. 5) are corroborated by recent declining trends observed in sediment cores (Engstrom and Swain, 1997; Norton and others, 1997; Bindler and others, 2001). This is also verified by similar concentrations in Upper Fremont Glacier snow samples collected in 1999 (P.F. Schuster, written commun., 2005). This decline may be in response to the United States Clean Air Act of 1970.

Summary

Precipitation, snow, ice, and runoff samples from four glaciers, widely distributed geographically in the middle latitudes of the Northern Hemisphere, are currently being analyzed utilizing a wide array of geochemical, physical, and isotopic-measurement techniques. Radioactive fallout from nuclear-weapons testing in the 1940s, 1950s, and 1960s, large explosive volcanic eruptions with regional and global fallout, and radiocarbon dating of bio-organic material, have been identified as time markers in selected ice cores from the *Nangpai Gosum Glacier*, Nepal; Lednik Engil'chek, Kazakhstan/Kyrghyzstan/China; *Belukha Glacier*, Kazakhstan/Russia; and Upper Fremont Glacier, Wyoming, U.S.A., ice cores. These time markers, in conjunction with other types of analyses such as the delta oxygen-18 ($\delta^{18}O$) and mercury (Hg), aid in refining the chronology of the ice cores. The reconstruction of ice-core chronologies provides critical support to other areas of research being undertaken. Linking data from middle-latitude glaciers around the world will aid in the reconstruction of paleoclimatic and paleoenvironmental records on regional and global scales.

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