Manuscript for *Patagonia Ice Fields Working Group* July 31, 2000

INTERPRETING CLIMATE SIGNALS FROM A SHALLOW EQUATORIAN ICE CORE: ANTISANA, ECUADOR

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INTRODUCTION

Tropical glaciers have been poorly studied, in part because they are generally located in countries with few resources and little need to study the glaciers. One of the best-studied systems of tropical glaciers is located on Mounta Kenya in Africa. Glaciers on Mount Kenya have retreated dramatically between 1963 and 1987, possibly as a result of greenhouse forcing [Hastenrath and Kruss, 1992]. In South America, there may be a strong connection between ENSO events and glacial mass balances of tropical glaciers. El Nino-Southern Oscillation Events have been recorded in the stratigraphy of the Quelccaya Ice Cap in Peru [Thompson et al., 1984]. More recent work has shown that there is a negative correlation between ENSO events and the glacial mass balance of glaciers in both Peru and Bolivia [Francou et al., 1995]. These small changes in climate have the capacity to cause large changes in glacial hydrology [Ribstein et al., 1995].

The increasing population pressure in Ecuador and other tropical mountain countries of South American has resulted in some urgency in understanding tropical glaciers and how these glaciers may respond to changes in climate. Mudslides from glaciers on Nevado Ruiz in Colombia killed 25,000 people and glacial avalanches from Huascaran in Peru have killed more than 20,000 people. Quito, the capital of Ecuador, now gets significant amounts of municipal and industrial water from the volcano Antisana's glacial runoff. Additionally, glacial runoff from Chimborazo, Cayambe, Cotopaxi, Carihuayrazo, and Altar provide water for irrigation and domestic use for local communities. The success of the Antisana water diversion has resulted in proposals to expand existing uses of glacial meltwater and a call for additional water diversions and hydroelectric plants in Ecuador using glacial runoff.

There is reason to suspect that Ecuadorian glaciers are very sensitive to climatic change. Glacier #15 of Antisana Volcano has retreated 150 meters between 1994 and 1997, most likely because of increases in air temperature. How glacial runoff in Ecuador may respond to changes in climate is unknown. It is possible that with a 2-3°C increase in global temperature, there would be massive glacial retreat throughout Ecuador. There may be a short-term increase in water availability as glaciers melt, followed by a dramatic decrease in water availability when glaciers melt-out completely.

Ice core records have the potential to provide proxy climate information that may provide information on the causes of this glacier retreat. Confounding the interpretation of the climate signal in tropical ice cores is the lack of seasonal changes in temperature and precipitation, which drive isotopic and chemical differences. Here we report on the results of a 16-meter ice core drilled on the summit of Antisana, Ecuador (0.481S 78.141W) in November, 1999, at an altitude of 5,752 meters. Our primary objectives were to: (1) evaluate whether there was sufficient range in the values of water isotopes such that a deep ice core could provide the potential for dating and determining precipitation sources; (2) evaluate whether there was a periodic signal in the water isotopes that may correspond to annual precipitation changes that could be used to date the ice core; (3) evaluate whether there was a change in water isotopes that may correspond with El Nino and La Nina events.

SITE DESCRIPTION

Antisana is an unusual combination of an active glacial system located on an active volcano at the equator. Antisana is 5,752m (18,871 ft) in elevation and located at 0°28’30"S latitude and 78°08’55"W longitude. The last eruption was in 1802; Antisana is still considered active. Antisana rises directly from the Amazon basin and forms the crest of the continental divide that separates drainage systems that flow into the Pacific Ocean to the west and the Atlantic Ocean to the east. The glacial hydrology of Antisana is of particular interest because glacial runoff supplies high-quality drinking water to Quito by two artificial collectors, one situated at Papallacta (North), another one at the new reservoir La Mica (South).

The shallow ice core on Antisana was part of a larger effort to understand the dynamics of glacial systems in South America. The Institut de Recherche pour le Developpement (France) has be actively monitoring glaciers in the tropical Andes since 1991. The glaciers on Antisana are the only intensively monitored glaciers in the Equatorial Andes.

The climate of Antisana is equatorial and wet, with precipitation occurring year round. Annual precipitation amounts to 1000 mm (measured) in the lower reaches of the glacierized area on the west side. However, interannual variability may be as high as 40%. Annual precipitation amount at the summit is unknown, but most likely greater than 2000 mm. There is no evidence of a clear seasonality trend in the precipitation and the most rainy month may occur at any time from February to October. Only November-January includes a period of decreasing precipitation, which corresponds to the *veranillo* or little summer. Temperature is almost constant during the year, but the interannual variability is significantly high, being about 2°C or even more. The 0°C isotherm is close to 5000 m asl. Liquid precipitation is possible at elevations less than 5000 m asl. The glacier is probably polythermal, with a cold surface limited to the summit.

METHODS

The ice core was collected over a three-day period from 2 to 6 November at the summit of Antisana. A snowpit was excavated to a depth of 200 cm, at which time the snow became too hard for further excavation. A sidewall of the snowpit was analyzed for physical and chemical properties, following the protocols in Williams et al. [1996, 1999]. A portable ice drill made by PICO was then utilized to collect samples from 200 cm to 1600 cm. The general length of cores retrieved using the coring device was 0.5 m. The core was then sliced into sections 10 to 20 cm in length, weighed, placed into plastic bags, and stored in a snow cave. Snow and ice samples were returned to Quito, melted, prepped for chemical and isotopic analyses, and immediately flown back to the United States.

Oxygen isotopes were analyzed using the CO_2 equilibration method of Epstein and Mayeda [1953]. Values for the oxygen-18 (^{18}O) isotope of oxygen in the CO_2 gas were analyzed by mass spectrometry at the Institute of Arctic and Alpine Research in Boulder, CO. The deuterium (D) isotope of hydrogen (H) in water was analyzed at the Institute of Arctic and Alpine Research following the protocol in Vaughn et al, [1998]. The ^{18}O and D values are expressed in the conventional delta (δ) notation as the per mil ($^{0}/_{00}$) difference relative to the international Vienna-

Standard Mean Ocean Water (VSMOW):

$$\delta^{18}\mathrm{O} = \frac{{}^{18}\mathrm{O}/{}^{16}\mathrm{O}_{sample} - {}^{18}\mathrm{O}/{}^{16}\mathrm{O}_{standard}}{{}^{18}\mathrm{O}/{}^{16}\mathrm{O}_{standard}} \times 1000$$

$$\delta D = \frac{\mathrm{D}/H_{sample} - \mathrm{D}/\mathrm{H}_{standard}}{\mathrm{D}/\mathrm{H}_{standard}} \times 1000$$

RESULTS and DISCUSSION

The ^{18}O content of the ice ranged from a minimum value of -23.4 $^{0}/_{00}$ to a maximum value of -9.9 $^{0}/_{00}$ (Figure 1). The range of 13.5 $^{0}/_{00}$ was quite surprising. Moreover, changes in the ^{18}O values occurred very rapidly, from -9.9 $^{0}/_{00}$ at a depth of 80 cm to -23.4 $^{0}/_{00}$ at a depth of 200 cm. The large range in the ^{18}O values indicates that water isotopes may provide information that is helpful for dating ice cores and for evaluating sources of precipitation.

There appears to be an oscillating signal in the isotopic content of the ice core. Periodic maxima of about -10 to -12 $^{0}/_{00}$ occurred at depths of 80, 510, 860, 1300, and 1520 cm. Whether this oscillation in the isotopic content of the ice core represents an annual signal is unknown. The oscillations in the ^{18}O values are encouraging and suggest that additional effort is warranted to investigate the possible use of water isotopes to date equatorial ice cores.

Empirical results have shown that hydrogen and isotopic values in precipitation co-vary and are generally described by the relationship [Craig, 1961]

$$\delta D = 8\,\delta^{18}\mathrm{O} + 10$$

which is defined as the global meteoric water line. Deuterium values in the Antisana ice core were highly correlated with ^{18}O values (R^2 = 0.99, n = 88) (Figure 2). Our local meteoric water line has a similar slope but a different y-intercept (or deuterium excess value):

$$\delta D = 8.1\,\delta^{18}\mathrm{O} + 12$$

The similar values in slope between our results (8.1) and the global meteoric water line (8.0) suggests an absence of complex kinetic fractionation processes affecting precipitation on the summit of Antisana. However, the enriched deuterium excess value of 12 at Antisana compared to the global mean of 10 suggests that some of the water vapor that formed precipitation was derived from evaporation of localized water sources.

A closer look at the deuterium excess values from the Antisana ice core shows that they ranged from 8.6 to 18.1 (Figure 3). The higher deuterium excess values of around +15 are correlated with enriched ^{18}O values of about -10 $^{0}/_{00}$. The elevated deuterium excess values and enriched ^{18}O values are consistent with a source of moisture that has undergone evaporation. Recycled water vapor from the Amazon Basin that originated from the Atlantic Ocean may be indicated by the elevated values for deuterium excess and ^{18}O. The lower deuterium excess values and ^{18}O values are consistent with equilibrium reactions and indicate a Pacific Ocean source.

One hypothesis for the trends in the $\delta^{18}O$ is that the variations reflect seasonality in moisture sources rather than differences in temperature. For example, migration of the Intertropical Convergence Zone (ITCZ) could provide changing sources of cloud moisture. The dampening of the isotopic signal at depth may be caused by isotopic diffusion. However, if accumulation rates are on the order of 2 meters per year, diffusion is probably not an important process at this site. The alternative hypothesis is that the heavier peaks in the $\delta^{18}O$ record at depths of 100 and 400 cm may be related to changes in moisture sources caused by ENSO events in the last couple of years. Without adequate depth-age constraints, absolute connections between ENSO events and isotopic signatures remain difficult. In either case, it appears that the trend of the base line shifts to lighter values in the top 4 meters.

ACKNOWLEDGEMENTS

We greatly appreciate the logistical support provided by Instituto Nacional de Meteorología e Hidrología (Ecuador) and Empresa Municipal de Alcantarillado y Agua Potable de Quito (Ecuador). Funding was provided in part by a Fulbright Fellowship, a Faculty Fellowship from the University of Colorado-Boulder, a UROP award from CU-Boulder, and several programs within the National Science Foundation, including International Programs, Hydrology, Long-Term Ecological Research, and GRT-international.

LITERATURE CITED

Craig, H.. 1961. Isotopic variations in meteoric waters. Science 133: 1702-1703.

Epstein, S. and T. Mayeda. 1953. Variations of the 18O content of waters from natural sources. Geochim. Cosmochim. Acta 4: 213-224.

Francou, B., P. Ribstein, H Se´miond, and A. Rodriquez. 1995. Balances de glaciares y clima en Bolivia y Peru: impactos de los eventos ENSO. Bull. Inst. Fr. Et. And. 24: 661-670.

Hastenrath, S. and P. D. Kruss. 1992. The dramatic retreat of Mount Kenya's glaciers between 1963 and 1987: greenhouse forcing. Annals of Glaciology 16: 127-134.

Ribstein, P., E. Tiriau, B. Francou, and R. Saravia. 1995. Tropical climate and glacier hydrology. Journal of Hydrology 165: 221:234.

Thompson, L. G., E. Mosley-Thompson, and B. M. Arnao. 1984. El Nino-Southern Oscillation Events Recorded in the Stratigraphy of the Tropical Quelccaya Ice Cap, Peru. Science 226: 50-53.

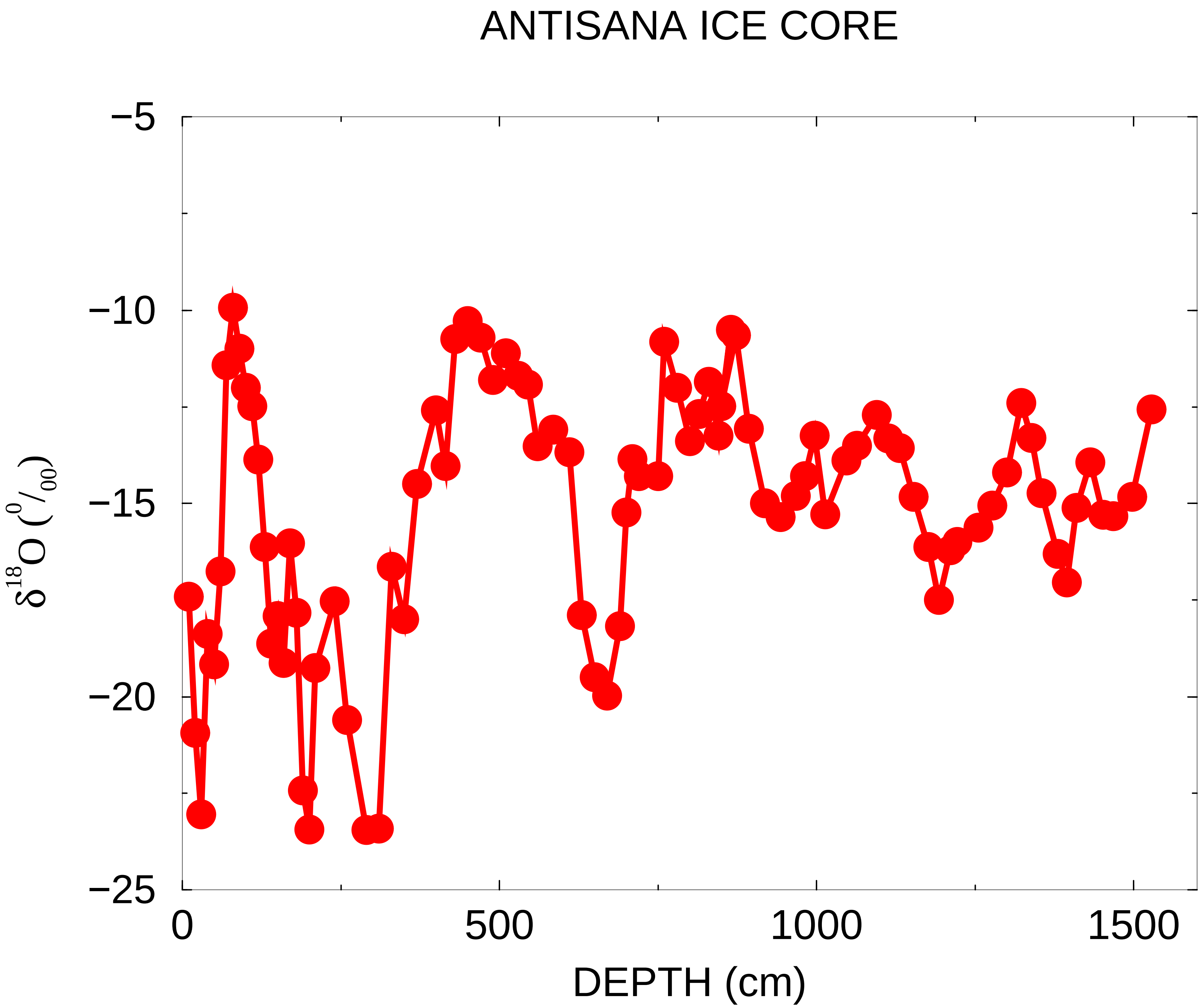
Williams, M. W., P. D. Brooks, A. Mosier, and K. A. Tonnessen. 1996. Mineral nitrogen transformations in and under seasonal snow in a high-elevation catchment, Rocky Mountains, USA. Water Resources Research 32: 3175-3185.

Williams, M. W., D. Cline, M. Hartman, and T. Bardsley. 1999. Data for snowmelt model development, calibration, and verification at an alpine site, Colorado Front Range. Water Resources Research 35: 3205-3209.

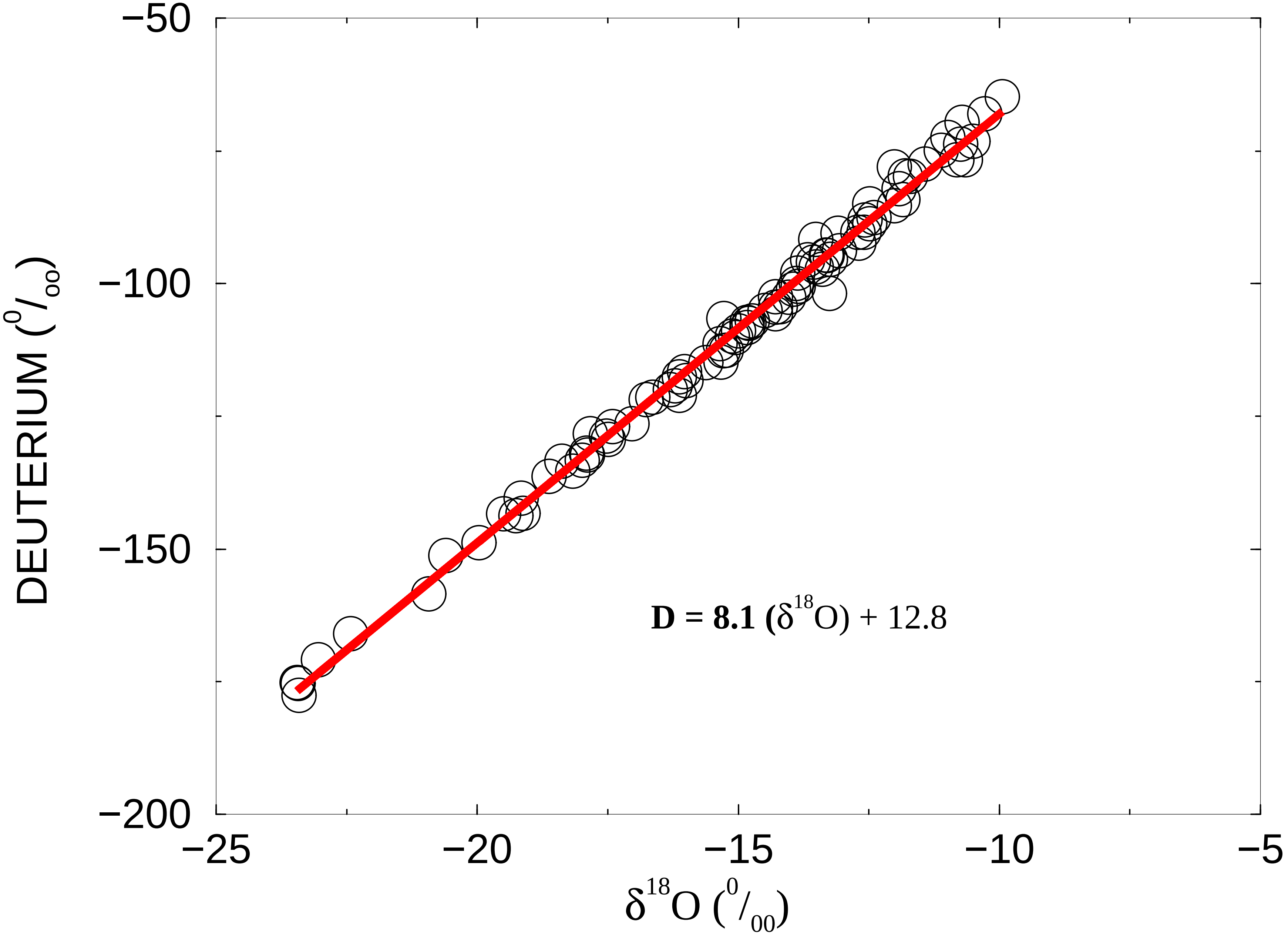
Figure 1. The isotopic content of ^{18}O as a function of ice depth on Antisana. The shallow ice core was collected using a hand-drill.

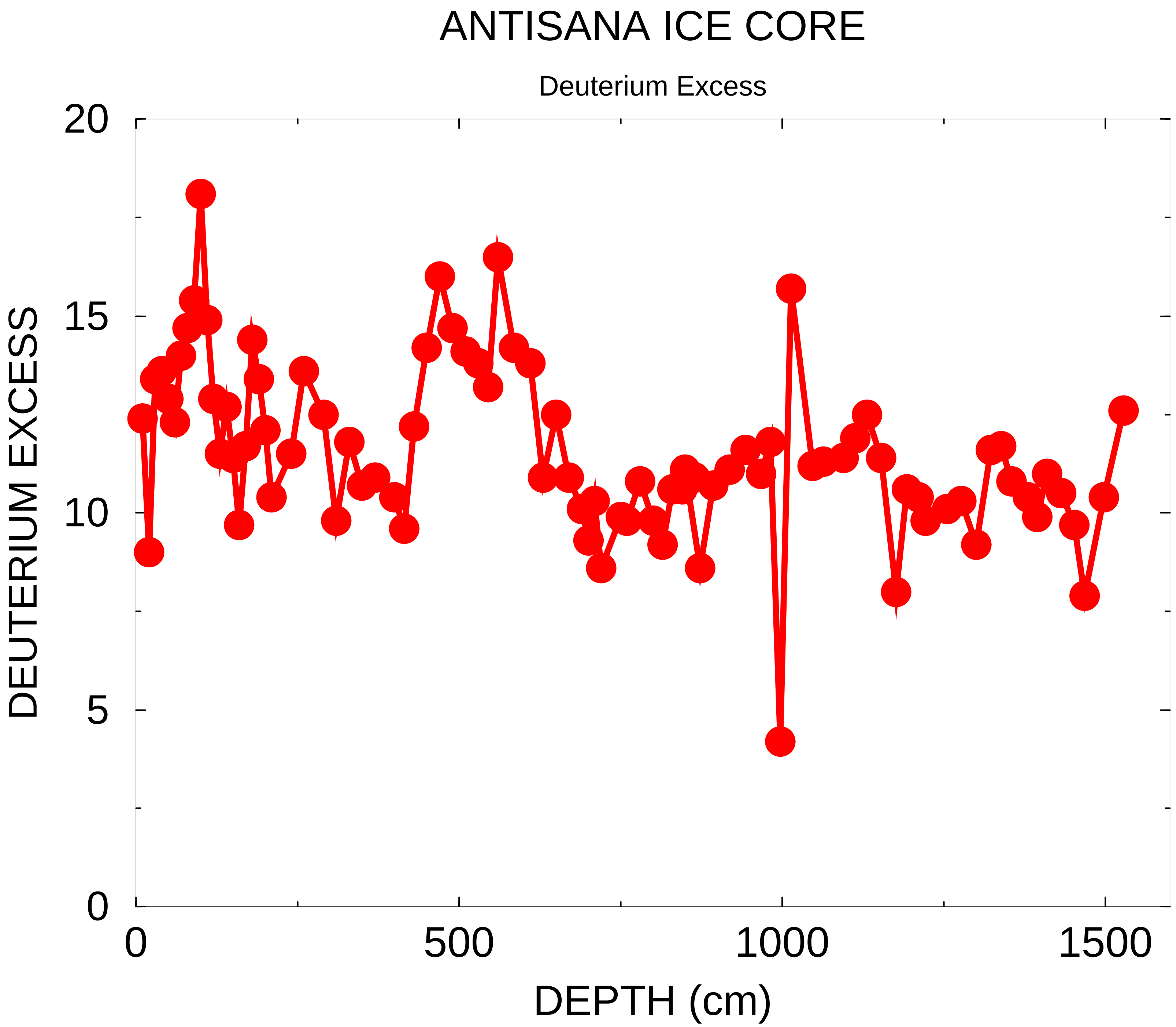
Figure 2. Local meteoric water line from the Antisana ice core.

Figure 3. Deuterium excess as a function of ice depth on Antisana.


ANTISANA ICE CORE
$\delta^{18}O$ ($^{0}/_{00}$)
−5
−10
−15
−20
−25
0
500
1000
1500
DEPTH (cm)

LOCAL METEORIC WATER LINE




ANTISANA ICE CORE
Deuterium Excess
DEUTERIUM EXCESS
20
15
10
5
0
0
500
1000
1500
DEPTH (cm)