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Dating of two nearby ice cores from the Illimani, Bolivia

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[1] In order to establish a chronology of two nearby ice cores from a glacier at Illimani (6438 m), Bolivia, a broad dating approach is presented here, which in particular makes use of the fast, simple, and nearly nondestructive electrical conductivity method (ECM) that provides a highly resolved record. Thus, ECM is suited for counting annual layers in the ice, especially for ice cores extracted from high-mountain glaciers with a fast layer thinning. Furthermore, ECM can be used for detecting volcanic signals. Annual signals in the ECM record of the Illimani ice core were identified using the 1964 A.D. tritium reference horizon and were counted along 125 m or 90% of the core, representing the time period from 1200 ± 240 A.D. (estimated accumulated error) to 1999 A.D. The resulting age–depth relationship was supported by counting annual peaks in the microparticle record as well as by nuclear dating using the decay of ^{210}Pb. The identification of volcanic signals originating from eruptions such as Pinatubo (1991 A.D.), El Chichón (1982 A.D.), Agung (1963 A.D.), Krakatoa (1883 A.D.), Tambora (1815 A.D.), and the Unknown 1258 A.D. significantly reduced the uncertainty of annual layer counting (ALC) to ±2 years in the vicinity of these events. *INDEX TERMS:* 0370 Atmospheric Composition and Structure: Volcanic effects (8409); 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology

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1. Introduction

[2] A detailed knowledge of climate history is fundamental for the prediction of future climate variations. Paleoinformation deduced from polar ice cores has contributed immensely in understanding the climate system. Nonetheless polar areas are far away from the most populated regions on Earth, where the sources of atmospheric anthropogenic pollution are concentrated, and from the center of action of several climatic phenomena with large impact on the globe, such as the El Niño–Southern Oscillation (ENSO). Thus, additional information on a more regional scale is required and can be found in high-elevation glaciers located at midlatitude and low latitudes. Until now, only a few ice cores from these latitudes in the Southern Hemisphere have been retrieved, e.g., from Quelccaya and Huascarán in Peru and from Sajama in Bolivia. Major findings from these studies are that glacial stage conditions at high elevations in the tropics appear to have been cooler than today [*Thompson et al.*, 1995] and that hydrological conditions were much drier [*Thompson et al.*, 2000], whereas they were much wetter in the subtropics [*Thompson et al.*, 1998]. In order to investigate short term climate variations, for example related to ENSO or to the westerly and tropical circulation system, three new ice cores were recovered in 1999, one from the Cerro Tapado in Chile [*Ginot et al.*, 2001; *Stichler et al.*, 2001] and two nearby cores from the Illimani in Bolivia (Figure 1).

[3] Dating is a major concern for the interpretation of records from ice cores. Establishing a chronology for ice cores from high-mountain glaciers is more difficult than that for ice cores from polar ice sheets for several reasons: (1) Due to the limited thickness of at most a few hundred meters, a significant portion of the glacier is subjected to a bedrock induced, complex flow pattern. So far, glaciological flow models have not been able to simulate this complex flow near the bedrock and can therefore not be used for establishing the chronology. (2) On high-mountain glaciers annual layers thin out fast and the thinning is difficult to simulate with simple flow modeling [*Thompson et al.*, 1998]; very thin layers can make dating by annual layer counting (ALC) problematic in the deeper part of the core. (3) Horizons from volcanic eruptions normally used as time markers are more difficult to identify, since they are imprinted on a much higher and noisier background level of dust and anthropogenic sulfate than in polar ice. (4) The snow composition may be altered by postdepositional processes like sublimation [*Ginot et al.*, 2001] and melting of surface layers, possibly complicating the identification of annual layers.

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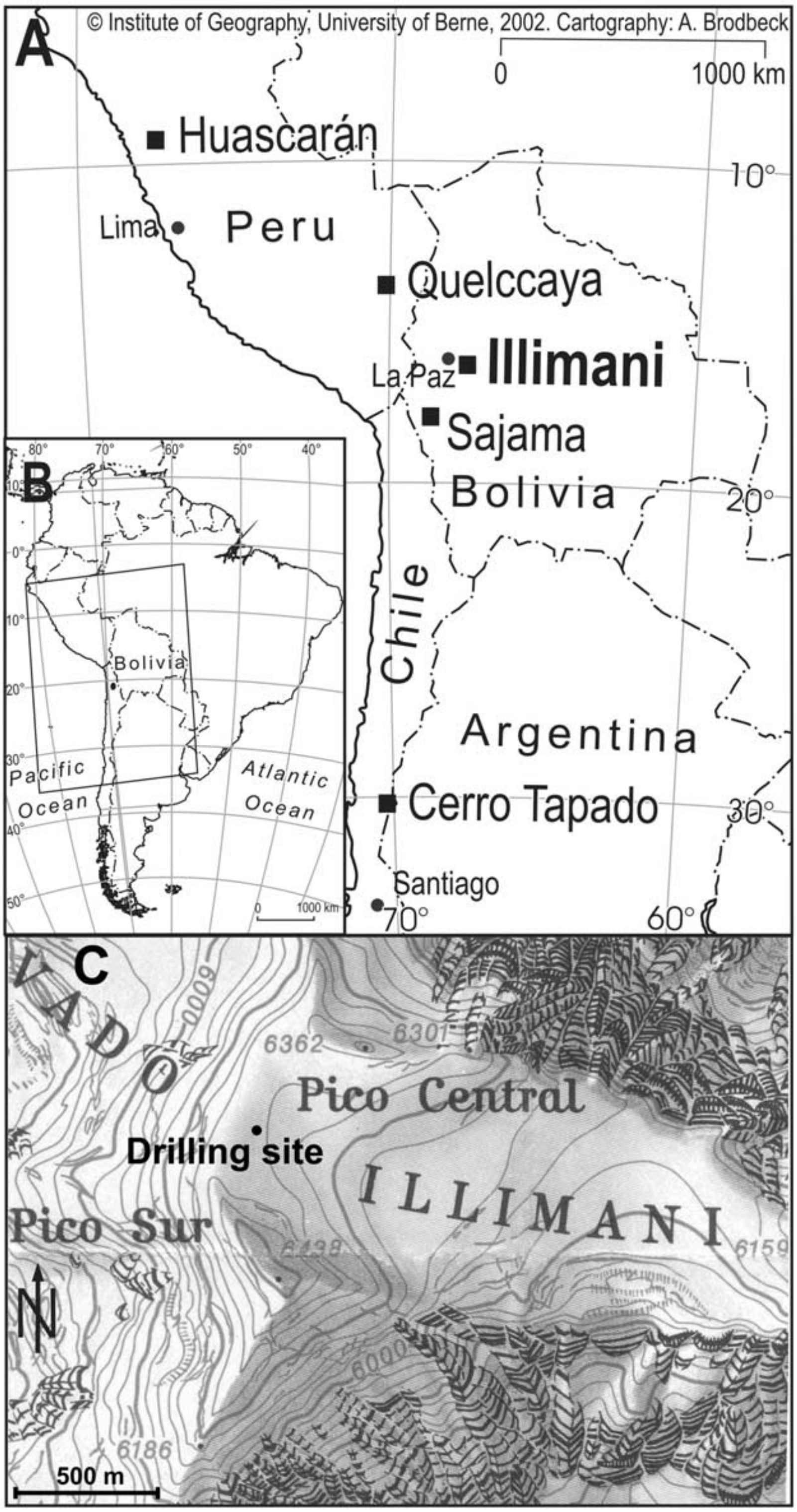

Figure 1. (A and B) The location of the Illimani in South America. The prominent drilling sites (squares) at the Huascarán, Quelccaya, Sajama, and Cerro Tapado are indicated. (C) Map of the Illimani glacier with the drilling site (6300 m asl, 16°39′S, 67°47′W) on the saddle between the two summits Pico Central and Pico Sur. Reproduced with kind permission of the German Alpine Club (Deutscher Alpenverein).

[4] The most established and accurate method of ice core dating applied to both ice sheets and glaciers is ALC using seasonally varying signals. A signal can be a stable isotope ratio (e.g., $\delta^{18}O$ [*Cole Dai et al.*, 1997]), a concentration of chemical tracers, for instance sulfate [e.g., *Cole Dai et al.*, 1997] and ammonium [*Eichler et al.*, 2000], a bulk parameter such as dust [*Thompson et al.*, 1998], the acidity content (e.g., as indicated by electrical conductivity method (ECM) [*Meese et al.*, 1994]) or the visual stratigraphy [*Thompson et al.*, 1985, 1995]. Counting accuracy is increased when supported by known reference horizons such as the signals from known volcanic eruptions, nuclear bomb testing, or from the Chernobyl reactor accident. The limiting factors of the layer counting method are the layer thickness, which depends on annual accumulation and on layer thinning, and the noise and resolution of the analytical technique used.

[5] A technique, which gives a signal with an extremely high spatial resolution of 1 mm, is ECM [*Hammer*, 1980]. In polar snow and ice, the ECM signal is mainly responsive to the acid concentration [*Hammer*, 1980; *Legrand et al.*, 1987; *Taylor et al.*, 1992; *Moore et al.*, 1994], and so normally undergoes seasonal variations in polar ice cores [*Hammer*, 1983; *Hammer et al.*, 1994]. Layer counting of the ECM signal has been successfully used to date ice cores from Greenland [*Alley et al.*, 1993; *Zielinski et al.*, 1994]. In addition to annual layers, volcanic signals can also be detected in the ECM record of polar [e.g., *Clausen et al.*, 1997; *Zheng et al.*, 1998; *Karlof et al.*, 2000] as well as nonpolar ice cores [*Schuster et al.*, 2000], since these volcanic signals are normally characterized by increased acidity due to sulfuric acid input [*Hammer*, 1980]. The advantages of ECM, a nearly nondestructive method, are its simplicity and rapidity together with high resolution, making it ideal as a screening method for fast dating. The disadvantages of ECM include a relatively high noise level and a limited reproducibility [*Taylor et al.*, 1992], which makes it difficult to quantify the ECM signal in terms of acidity.

[6] In this study we adopt a broad dating approach with the intention to achieve minimum uncertainty in establishing a chronology of two nearby ice cores from the Illimani in Bolivia. In particular we make use of the ECM method, supported by other dating techniques, and demonstrate the potential of this dating approach for ice cores from small-mountain glaciers with strong layer thinning and irregular annual net accumulation.

2. Experimental Methods

2.1. Ice Core Drilling and Site Characteristics

[7] In June 1999 two nearby ice cores were recovered within about 10 m from each other from a glacier at about 6300 m above sea level (asl) on the Illimani, Bolivia (16°39′S, 67°47′W, Figure 1) by a joint expedition of scientists from the French Institut de Recherche pour le Developpement (IRD) and the Paul Scherrer Institute (PSI) in Switzerland. Both ice cores were drilled on the saddle between Pico Central and Pico Sur (Figure 1C) and reached bedrock at depths of 136.7 m (core A) and 138.7 m (core B), respectively. For drilling, a Fast Electromechanical Lightweight Ice Coring System (FELICS) [*Ginot et al.*, 2002b] was used, producing ice core sections with up to 0.9 m in length and 7.8 cm in diameter. The ice core sections were packed and sealed in polyethylene bags in the field, transported frozen to Europe, and kept frozen in a cold room (−25°C) until analysis.

[8] The mean temperature from May 1998 to March 1999 at the drilling site on the Illimani was −7°C (M. Vuille, University of Massachusetts, personal communication, 2002). Ice temperatures are −7°C at 10 m depth in the firn part of the glacier [*Ginot et al.*, 2002a] and −8.4°C near bedrock [*Zweifel*, 2000]. The firn−ice transition is at a depth of 37 m (density > 0.82 g cm^{-3} is considered to be ice), and the mean annual accumulation amounts to 0.58 m water equivalent (m weq) yr^{-1} (see below). A few faint dust layers were found in the cores, but no visible ash layers were observed. Air and ice temperatures indicate that dry firn prevails, which is corroborated by the fact that melt-feature percentages [*Kameda et al.*, 1995] are low, i.e., in the firn the average value is 6.8% (calculated for each ice core section separately), ranging from 1% to 22%. Thus, glaciochemical records are assumed to be preserved. Although high sublimation rates of 1.2 mm weq d^{-1} were observed at this site during the short dry season, the overall influence of sublimation on the ice core record seems to be limited [*Ginot et al.*, 2002a].

2.2. Sample Preparation and Analyses

[9] ECM measurements were performed at the Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE) in Grenoble. The lengths of the ice cores and the positions of the breaks were recorded manually. A layer of about 1 cm was removed longitudinally from the ice core with a band saw and the new surface was polished with a scalpel to remove possible unevenness and snow shavings. Two electrodes, separated by 22 mm, were slid along the freshly cut surface with an applied potential difference of 1500 V. A depth resolution of about 1 mm was achieved, given by the sliding speed along the ice core and the sampling time for each data point. The two cores were analyzed at different temperatures (core A: −15°C, core B: −20°C) and at different times after the recovery. In core B, the current measured in the firn part was higher than in the ice part. The opposite was observed in core A. We suggest that this phenomenon is due to a different contact between the ice and the electrodes (contact pressure) [*Legrand et al.*, 1987] and a different temperature while measuring.

[10] At the LGGE, the topmost 50 m of core A was subsampled, mostly continuously, by cutting half of the core in 6–10 cm sections in a cold room. The outer layer of each section was removed using a specially designed stainless steel plane in a laminar flow bench. Melting and partitioning for ion chromatography and microparticle analyses was carried out in a class 100 clean room. The samples were kept frozen in precleaned containers until analysis.

[11] Microparticle size distributions in 256 size intervals from 0.67 to 20.89 μm diameter were measured by a Coulter Multisizer IIe with a 50 μm orifice. For counting a prefiltered NaCl solution was added to 0.5 mL of sample to obtain an electrolyte solution of 1% NaCl. All samples were shaken gently three times before measurement to reduce the

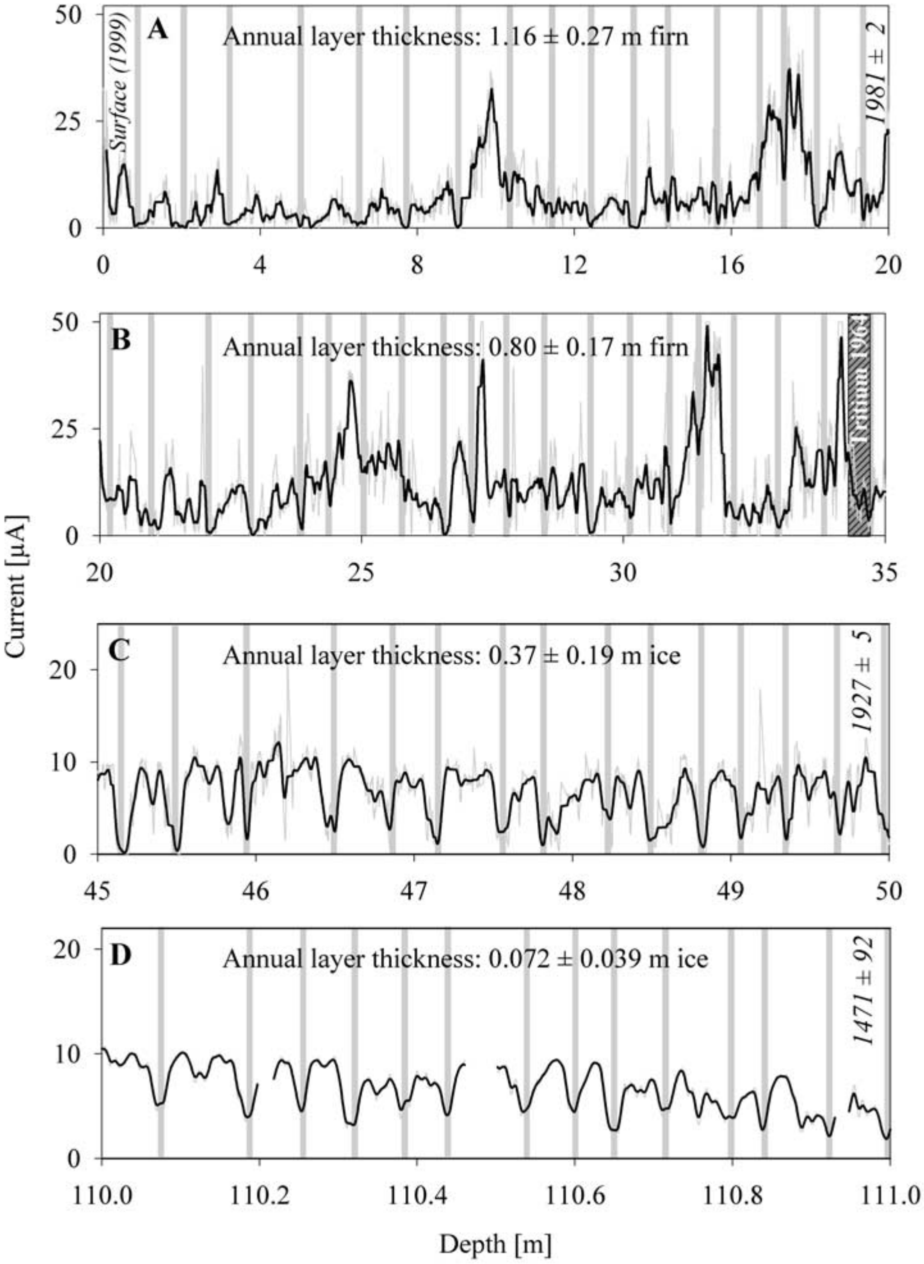

Figure 2. (A–D) The general appearance of the raw (thin line) and Gaussian-filtered (thick line) ECM signals of core B. A Gaussian filter with a depth-adapted width (σ = 200, 15, and 3 at a depth of 0–30, 45–50, and 110–111 m, respectively) was applied to remove high-frequency noise. Gaps correspond to breaks in the ice core. (A and B) The ECM signal in the firn part of the core (e.g., between surface and 35 m depth) is noisier. Between the surface in 1999 A.D. and the tritium peak in 1964 A.D. (hatched mark), 37 ± 3 annual layers were counted (the gray vertical lines mark the years). The age from ALC with the corresponding estimated error is given.

sedimentation of large particles. Blank values were typically 300–600 particles per mL, i.e., about 1 order of magnitude lower than the cleanest samples analyzed.

[12] The pH in the upper part of ice core B was determined using an 8103 Orion Electrode with a Metrohm pH meter 605 (sample volume 1 mL, addition of 10 μL 1 M KCl) and was converted to H^+ concentrations. The error in the H^+ concentration was estimated to 3 μmol L^{-1} due to uncertainties in measuring electrode potentials and low ionic strength of the melted sample. For this purpose, ice core segments were decontaminated in a cold room at the PSI by using a modified band saw (stainless steel blades, with Teflon covered table tops and saw guides) and prepared according to *Eichler et al.* [2000].

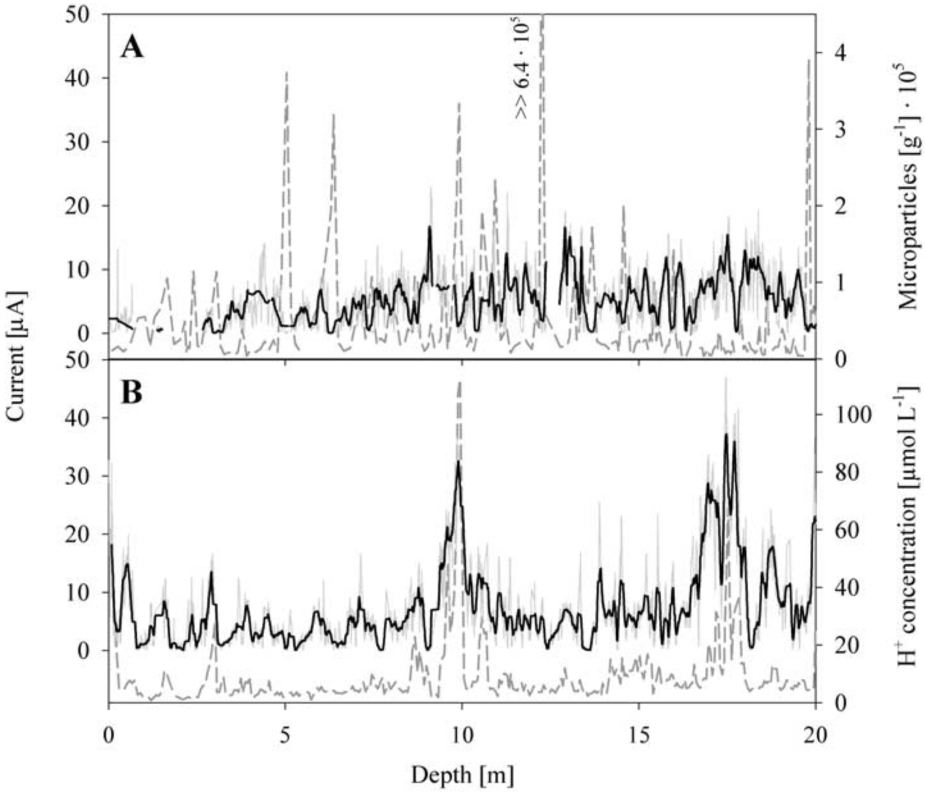

Figure 3. Comparison of the ECM signal (raw data: thin line, Gaussian-filtered data: black line; both left-hand scale) with microparticle and H^+ concentrations. (A) ECM and the microparticle record (dashed line, right-hand scale) of core A. (B) ECM signal of core B and the H^+ concentrations (dashed line, right-hand scale) calculated from the pH. The error of the H^+ concentration is around 3 μmol L^{-1}. High H^+ concentration induces large ECM peaks, whereas at maxima of microparticle concentrations minima in the ECM record are observed.

[13] For the analysis of tritium originating from nuclear weapons testing, the outer parts (as contamination is not a problem) of ice core B were scraped off in the cold room with a scalpel and used for analysis. The depth resolution was about 0.7 m. Samples of 50–70 mL volume were melted and subsequently analyzed by direct liquid scintillation counting in a low level laboratory at the University of Bern [*Schotterer et al.*, 1998].

[14] ^{210}Pb was measured by α-detection of its granddaughter ^{210}Po. Samples of 100 or 200 mL with a depth resolution of about 0.7 m were melted, chemically prepared and ^{210}Po was electrolytically deposited on silver plates as described by *Gäggeler et al.* [1983].

2.3. Data Analysis

[15] The ECM signal had to be processed for breaks, since they induce a low current in this record. These artifacts were removed manually by deleting data around 1 cm to the right and left of the position of the break in the data set. The total length of the breaks was around 10% of the entire ice core. To remove high-frequency signals (noise), a Gaussian filter over 100 data points with a manually chosen depth-dependent width was applied to the ECM signal. For using this filter, data gaps originating from artifacts were ignored, which means that data were treated as if they were adjacent.

3. Results and Discussion

3.1. The Tritium Peak

[16] The tritium activity maximum was observed at a depth of 31.9–34.7 m (not shown). In the Southern Hemisphere the tritium activity maximum due to nuclear weapons testing occurred in 1964–1967 A.D. and has already been detected in ice cores from southern latitudes (e.g., Cerro Tapado, Chile [*Ginot*, 2001], and Sajama, Bolivia [*Thompson et al.*, 1998]). Therefore we attribute the high tritium activity at 34.7 m to the year 1964 A.D.

3.2. Dating by ALC

3.2.1. ECM Record

[17] The general appearance of the ECM signal is illustrated in Figures 2A and 2B for the topmost 35 m of core B. Most of the peaks show a complex structure. The minima between peaks are mostly pronounced and were therefore used for counting the supposed annual layers. Counting these minima down to a depth of 35 m resulted in an age of 37 ± 3 years. This corresponds well to the 1964 A.D. tritium

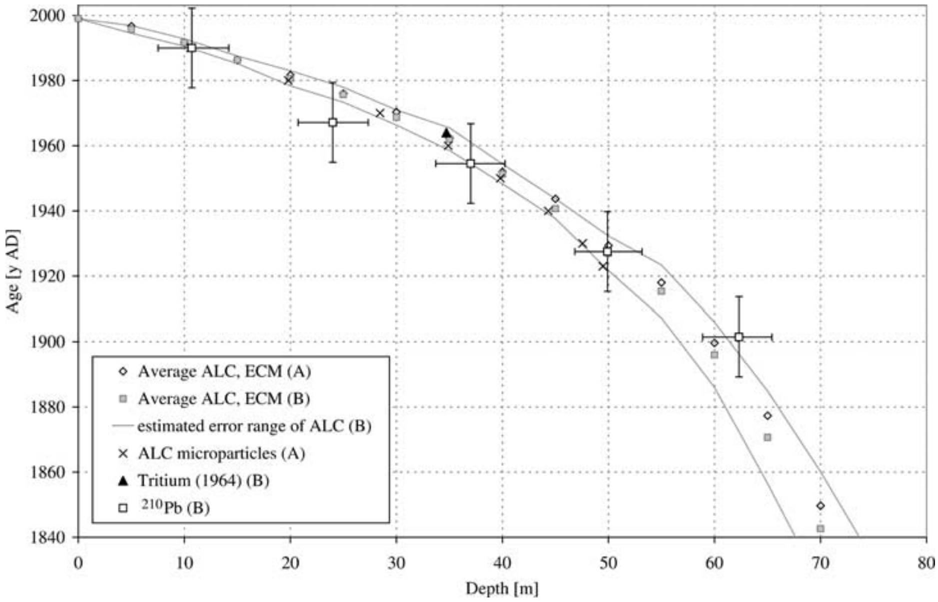

Figure 4. Age–depth relationship for the upper 70 m of the two ice cores obtained by ALC using the ECM signal (for both cores A and B, core labels are given in parentheses) and the concentration of microparticles (core A only). The averaged ages from ALC are shown along with the estimated error range (vertical distance between top and bottom line) for core B. In addition, age–depth points from ^{210}Pb nuclear dating and the tritium horizon in 1964 A.D. from the bomb testing are indicated (both core B). The error on the ^{210}Pb age determination is the mean two-sigma standard deviation of single ^{210}Pb activities averaged over 7 m depth (range indicated by the horizontal bars). The error includes variations in the annual ^{210}Pb deposition and the counting error of the activity measurement.

horizon at a depth of 34.7 m. Therefore, the peaks in the ECM signal (Figure 2) are assumed to represent annual layers. Additional examples showing the annual layers deeper in the ice core are given in Figures 2C and 2D.

[18] Figure 3 illustrates the relationship between ECM and microparticle concentrations in core A and between ECM and H^+ concentrations in core B. At high microparticle concentrations low ECM currents are observed (Figure 3A), whereas large ECM peaks are accompanied by high concentrations of H^+ in the ice (Figure 3B). Thus, we assume the annual variations in the ECM record are due to varying H^+, microparticle, and major ion concentrations, whereas large ECM peaks are related to high H^+ concentrations.

[19] In order to determine the error of ALC, ECM layer counting was performed three times. In the first counting minima were counted without applying a strict criterion. To estimate the error margins, the second time pronounced minima were considered as years, whereas the third time only the fewer minima reaching the baseline were counted. For core B, annual layers are identified down to a depth of 125 m, representing 90% of the total core. The mean age was calculated by averaging the results from the three counts, and the estimated accumulated error is the two-sigma standard deviation. The age obtained for 125 m is 1200 ± 240 A.D., corresponding to 800 ± 240 years covered by this section of the core. The estimated accumulated error in core B with the corresponding ages in parentheses is 5 years at 50 m (72 years), 66 years at 100 m (397 years), and 175 years at 120 m (680 years). For core A, ECM data are available down to 96 m. Between 96 and 112 m measurements could not be performed due to poor core quality. Deeper in the ice core the ECM resolution is reduced because of a technical difficulty. Thus, ALC was conducted for the top 96 m, corresponding to 380 ± 68 years. The chronologies of the two ice cores agree well in the overlapping section from the surface to 96 m depth.

[20] There are two primary reasons why the counting error is high. First, counting of peaks with a complex structure leads to a higher error, as the peak structure sometimes has pronounced minima, which could be mistaken for an annual layer. An example of this can be seen in Figure 2A at a depth of 4 m, where it is not clear whether this broad peak with a central minimum corresponds to 1 or 2 years. Second, the large counting error cannot be reduced by counting annual layers of different parameters as performed in other studies [e.g., *Meese et al.*, 1994; *Cole Dai et al.*, 1997].

3.2.2. Microparticle Record

[21] The fluctuations in the microparticle concentration were also used for ALC in core A down to a depth of 50 m (Simões et al., Forty years of environmental record form the Nevado Illimani ice core, central eastern Andes, manuscript, in preparation). The appearance of the distinct seasonal maxima is shown in Figure 3A.

3.3. Nuclear Dating by ^{210}Pb

[22] An additional and independent timescale was obtained by ^{210}Pb dating. The time range accessible using this method is about 100 years and is determined by the 22.3 year half-life of ^{210}Pb. From the linear regression of the ^{210}Pb activities plotted on a logarithmic scale against depth,

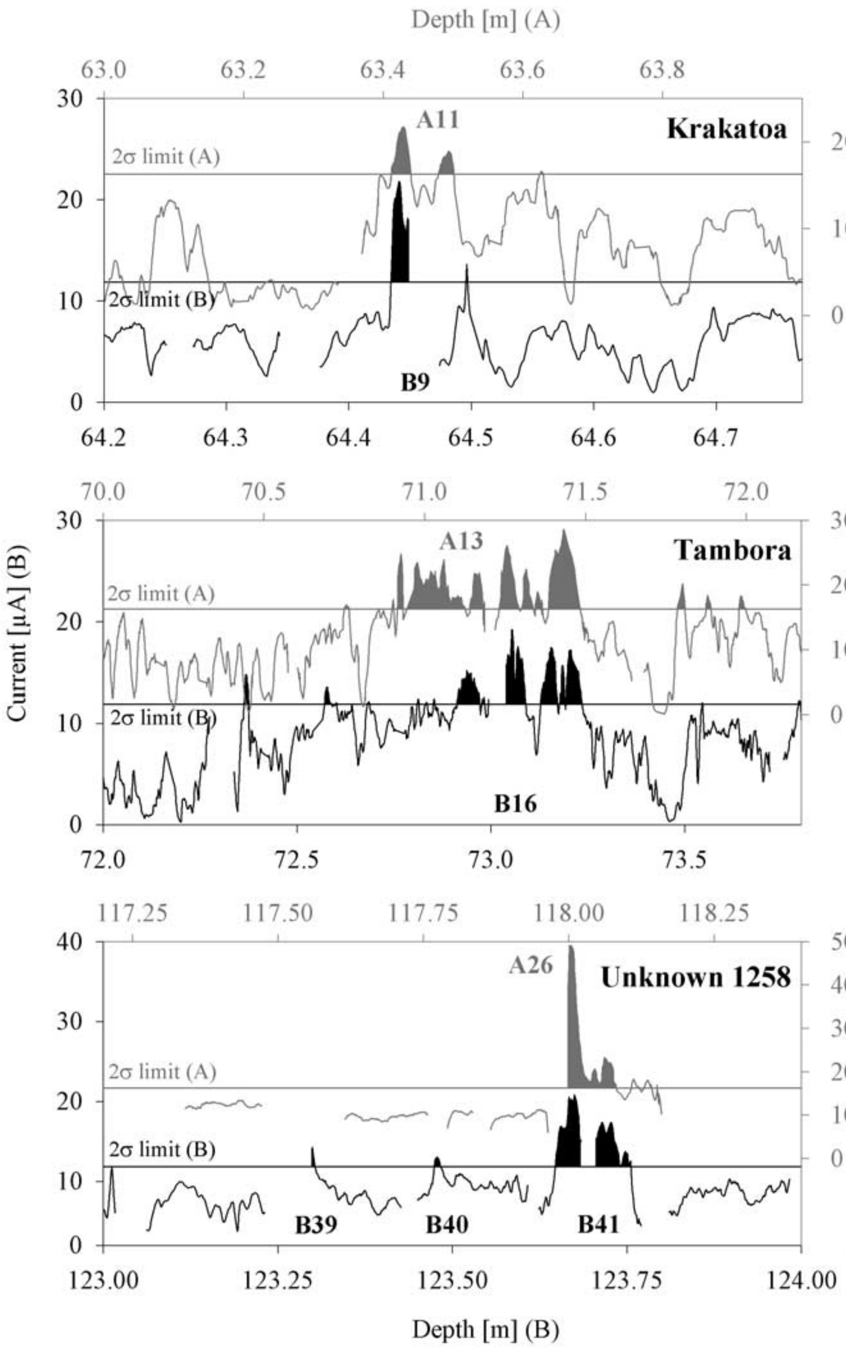

Figure 5. Examples of the ECM signatures in core A (gray) and B (black) showing pronounced similarities. The signals were attributed to the volcanic eruptions of Krakatoa (1883 A.D., peak A11/B9), Tambora (1815 A.D., peak A13/B16), and the Unknown 1258 A.D. (peak A26/B41). The horizontal lines depict the two-sigma limits used for identifying volcanic signals. The two peaks B39/B40 probably belong to the very prominent triplet observed several years following the eruption in 1258 A.D.

we derived an age–depth relationship [*Eichler et al.*, 2000], which agrees well with the chronology obtained from ALC results for the period from 1900 to 1999 A.D. (Figure 4).

3.4. Identification of Volcanic Signals

[23] Major volcanic eruptions eject large amounts of sulfur, mostly as sulfur dioxide, into the atmosphere. Oxidizing processes in the atmosphere transform this gas to sulfuric acid, which is deposited by precipitation on the glacier. High acid levels in ice increase the electrical conductivity [*Hammer*, 1980; *Legrand et al.*, 1987; *Taylor et al.*, 1992; *Moore et al.*, 1994], which can be detected by ECM measurements. In the Illimani ice cores, large ECM peaks also correspond to high H^+ concentrations, as illustrated in Figure 3B.

Table 1. Characteristics of ECM Peaks Selected by the Criteria Larger Than a Two-Sigma Limit, Duration of at Least 0.5 Years and Similar Peak Shape

Peak		Depth [m]		Duration [years][a]		Starting date [years A.D.][b]	
(A)	(B)	(A)	(B)	(A)	(B)	(A)	(B)
A1	B1	9.1	9.9	1	1	1993 ± 1	1992 ± 1
A2	B2	18.4	17.5	3	3	1982 ± 3	1982 ± 2
A4	B5	33.5	34.2	4	2	1962 ± 5	1963 ± 3
A6	B6	38.9	38.6	1	1	1954 ± 6	1955 ± 2
A11	B9	63.4	64.4	1	1	1884 ± 14	1876 ± 6
A13	B16	71.3	73.2	4.5	5	1841 ± 27	1823 ± 21
A26	B41	118.1	123.7	–	4.5	no ALC	1236 ± 221

Core labels are given in parentheses.
[a]Duration estimated by ALC.
[b]The starting date was estimated by ALC.

3.4.1. Criteria for Detecting Volcanic Signals in the Ice Cores

[24] For the detection of ECM peaks from volcanic eruptions the firn and ice part were treated separately (see section 2.2). The detection criteria were developed according to *Cole Dai et al.* [1997, 2000] and *Karlof et al.* [2000] using a two-sigma limit. Peaks larger than the two-sigma limit were considered to be of volcanic origin. The data were then reprocessed, as it is important to average the seasonal signal, but not to include the formerly attributed ECM peaks. A second two-sigma limit, again for firn and ice separately, was calculated after removing data previously identified as volcanic signals. The resulting two-sigma limits with core labels in parentheses are 11.7 μA (A) and 18.3 μA (B) in the firn and 16.3 μA (A) and 11.9 μA (B) in the ice part of the core.

[25] The first criterion for detecting peaks of volcanic origin involved the selection of peaks larger than the second two-sigma limit with duration of at least half a year. In order to eliminate false-positive ECM peaks caused by the high noise level of the ECM in the Illimani ice cores, a second criterion was applied where only peaks with similar signature in both cores were considered. Figure 5 illustrates the remarkable similarity of three of these volcanic signals. Using the first criterion, 26 peaks were identified in core A and 49 in core B (continuous numbering of the ECM peaks). After applying the second criterion, only seven peaks remained. Table 1 lists these seven peaks, including depth, approximate age (estimated by ALC) and peak duration for both cores. Since the reproducibility of ECM is limited, peak intensity data are not presented.

3.4.2. Assignment of the Volcanic Signals to Known Eruptions

[26] The eruptions described below might imprint a volcanic signal in the ice cores from the Illimani. Volcanic eruptions detected in ice cores of both polar regions (so-called bipolar events [*Langway et al.*, 1995]) may be observed as an ECM peak in the Illimani cores. Moreover, volcanic eruptions with a Volcanic Explosivity Index (VEI) equal to or greater than 4 may produce a signal in the ice (VEI from the study of *Simkin et al.* [1981]). However, volcanic eruptions north of about 60°N were not considered here, since, e.g., the major eruption of Laki (Iceland, 64.1°N, 18.2°W, VEI 4) in 1783 A.D. was not visible in both cores. An additional criterion, the strength of a volcanic eruption as indicated by the dust veil index (DVI) from the study of *Lamb* [1970] was used, because it is sometimes difficult to derive the aerosol loading from the VEI [*Robock and Free*, 1995]. Furthermore, no visible ash layers were observed in the ice cores from the Illimani, so local eruptions seem to be of minor importance.

[27] Known major volcanic eruptions were assigned to the seven ECM peaks satisfying both selection criteria in the ice cores, considering the approximate age from ALC and the signal duration. For a rough comparison, the duration of different volcanic eruptions were taken from ice core records of volcanic signals from Greenland [e.g., *Zielinski et al.*, 1994; *Clausen et al.*, 1997] and Antarctica [e.g., *Moore et al.*, 1991; *Cole Dai et al.*, 2000; *Karlof et al.*, 2000].

[28] The assignment of ECM peaks to volcanic eruptions is listed in Table 2. ECM peaks from large volcanic events such as the eruption of Pinatubo (1991 A.D.), El Chichón (1982 A.D.), Agung (1963 A.D.), Krakatoa (1883 A.D.), Tambora (1815 A.D.), and the Unknown 1258 A.D. (see Table 2 and Figure 6) are observed in these midlatitude ice cores. However, signals from other important volcanic eruptions might be missing due to the poor quality of core A from 96 to 112 m combined with the restrictive second criterion.

[29] The large volcanic signals of Tambora are remarkably similar in both cores (Figure 5). The duration of this volcanic signal is 4.5 years (A) and 5 years (B) and this agrees well with the duration of 2.5–4 years reported in the

Table 2. Large ECM Peaks Assigned to Prominent Volcanic Eruptions

Peak number (A)/(B)	Volcanic eruption	Location	Eruption date [years A.D.][a]	VEI[a]/DVI[b]
A1/B1	Pinatubo	15.1°N, 120.4°E	1991	6
A2/B2	El Chichón	17.3°N, 93.2°W	1982	5
A4/B5	Agung	8.3°S, 115.5°E	1963	4/400 (SH)
A6/B6	Bezymianny or Nilahue?	56.0°N, 160.6°E; 40.4°S, 72.1°W	1956; 1955	5; 4/(10 NH); –
A11/B9	Krakatoa	6.1°S, 105.4°E	1883	6/1000[c]
A13/B16	Tambora	8.3°S, 118.0°E	1815	7/1500 (SH)
A26/B41	Unknown 1258	?	1258[d]	n.a.

n.a.: not available.
DVI values in brackets are free estimate of DVI.
NH: Northern Hemisphere, SH: Southern Hemisphere.
[a]From the study of *Simkin et al.* [1981].
[b]DVI values are from the study of *Lamb* [1970].
[c]Total veil in group of eruption years.
[d]From the study of *Stothers* [2000].

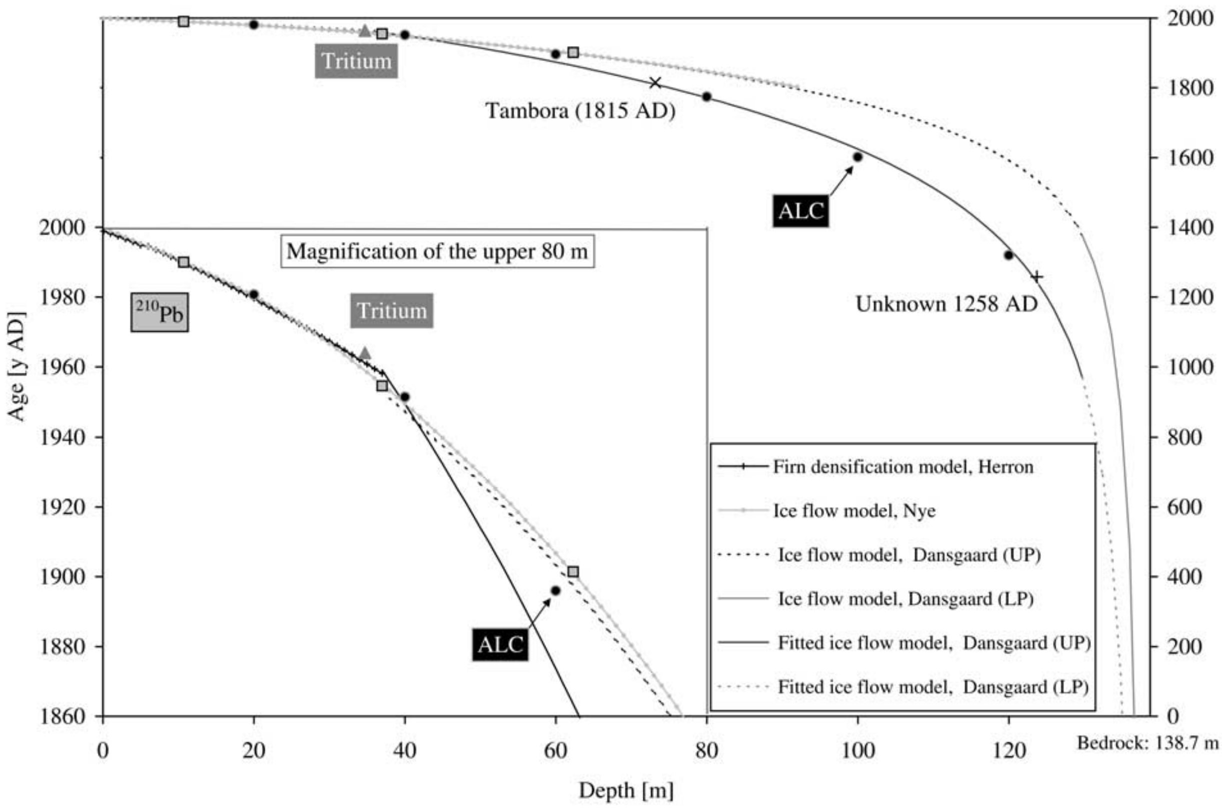

Figure 6. Age–depth relationship obtained by a firn-densification model [*Herron and Langway*, 1980] (magnification of the upper 80 m, left-hand scale) and by two ice-flow models [*Dansgaard and Johnsen*, 1969; *Nye*, 1963] (UP: upper part, LP: lower part). Model results near bedrock are rather uncertain, as the model ignores bedrock topography. Additionally, a fit of the ice-flow model [*Dansgaard and Johnsen*, 1969] through the age–depth points from the ALC, the ^{210}Pb dating, and the volcanic signals of Tambora and the Unknown 1258 A.D. is shown (forced to go through the age at the firn–ice transition received by the firn-densification model). This, together with the results of the firn-densification model [*Herron and Langway*, 1980], forms the final continuous age–depth relationship of the Illimani ice core.

literature [e.g., *Delmas et al.*, 1992; *Langway et al.*, 1995; *Cole Dai et al.*, 2000; *Karlof et al.*, 2000]. The intensity of peak A26 is the highest observed in the entire core A. From the age estimated by ALC we attribute the two volcanic peaks A26 and B41 to a massive volcanic eruption in 1258 A.D. [*Stothers*, 2000]. The duration of the volcanic aerosol loading in the atmosphere was estimated by *Stothers* [2000] to be 4 years, agreeing well with the observed duration of 4.5 years (B). In core B, a few years following this signal, two additional peaks are visible (Figure 5, B39, B40), possibly belonging to the well-known triplet after the 1258 A.D. event [*Langway et al.*, 1995].

3.5. Firn-Densification and Ice-Flow Behavior

[30] Firn-densification and ice-flow models were applied to investigate the glacier flow behavior and to compare the resulting age–depth relationship with the chronology obtained above. As input for the models, a mean annual layer thickness of 0.58 m weq yr^{-1} was used, which was calculated from the depth of the tritium peak. The firn-densification model considers only compaction of the layers, ignoring layer thinning, whereas ice-flow models take into account only thinning processes. These models were originally developed for large ice sheets, not for high-mountain glaciers. They ignore bedrock topography and assume steady state conditions.

[31] The firn-densification model of *Herron and Langway* [1980] was applied using the parameters accumulation, density of ice ρ_i of 0.917 g cm^{-3}, initial snow density ρ_0 of 0.42 g cm^{-3} and temperature of -8°C. The temperature-dependent rate constants k_0 and k_1 were 0.11 and 0.035, respectively.

[32] The ice-flow behavior was also modeled using a simple kinematic ice-flow model [*Nye*, 1963], which is only valid for two thirds of the total ice thickness [*Hammer et al.*, 1978]. The parameters used were the absolute ice thickness (H) of 113 m weq and an initial annual layer thickness λ_0 of 0.58 m weq. Moreover, a two-stage ice-flow model from the study of *Dansgaard and Johnsen* [1969] was also applied, assuming a nonuniform vertical strain rate. In addition to the parameters H and λ_0 used above, the height, h, of transition from one model stage to the other was calculated by fitting the two models to the previous established depth–age relationship and h was chosen by the least squares method.

[33] The results of the model predictions are illustrated in Figure 6. The age–depth relationships obtained by the

firndensification model [*Herron and Langway*, 1980] and the previously described dating methods agree very well. Good agreement is also observed for the ice-flow models [*Nye*, 1963; *Dansgaard and Johnsen*, 1969], but only down to a depth of about 60 m with a corresponding age of 1900 A.D. Deeper in the ice, the annual layers thin out faster than predicted by both models. This is obvious when comparing with the ice-flow model of *Dansgaard and Johnsen* [1969] fitted through age–depth points from ALC, ^{210}Pb dating, and the volcanic signals of Tambora and the Unknown 1258 A.D. eruption (Figure 6). This faster thinning has already been observed for other midlatitude glaciers [e.g., *Thompson et al.*, 1998]. Possible explanations of this are that steady state conditions are not applicable for midlatitude glaciers or that these ice-flow models were developed for larger, flatter ice sheets, where a horizontal flow is negligible.

[34] The final continuous age–depth relationship of the Illimani ice core is obtained in the firn part from the firn-densification model [*Herron and Langway*, 1980] and in the ice part from the fit mentioned above, taking into account the results from the various dating methods (parameters resulting from this fit are H of 101 m weq and λ_0, of 0.3 m weq).

4. Conclusion

[35] The ECM was used for establishing the chronology of two nearby ice cores from the Illimani, demonstrating the potential of this fast screening technique for dating ice cores from high-mountain glaciers. ECM peaks were identified as annual layers using the 1964 A.D. tritium peak as a reference horizon. Counting of annual layers was performed over 125 m or 90% of one of the cores, representing the time period 1200–1999 A.D. ECM-based chronologies of both cores showed good agreement. The resulting age–depth relationship was supported by two independent methods, i.e., counting of annual peaks of microparticle concentrations as well as nuclear dating using the ^{210}Pb activity. The estimated accumulated error of ALC with the corresponding age in parentheses is 5 years at 50 m (72 years), 66 years at 100 m (397 years), and 175 years at 120 m (680 years).

[36] ECM peaks larger than a two-sigma limit with duration of at least half a year and with similar signature in both cores were selected and assigned to volcanic eruptions. The very prominent peaks from the major volcanic eruptions of Pinatubo (1991 A.D.), El Chichón (1982 A.D.), Agung (1963 A.D.), Krakatoa (1883 A.D.), Tambora (1815 A.D.), and the Unknown 1258 A.D. were identified in the ECM record and confirm the previously established chronology (Table 2 and Figure 6). Assuming that this identification is correct, the error of ALC is significantly reduced to ±2 years in the vicinity of the volcanic time markers and is only determined by the uncertainty in the timing of the arrival of the volcanic plume at the glacier site and the sometimes imprecise eruption date of the volcano. Additionally, approximately halfway between two assigned volcanic signals, the error from ALC can also be reduced due to the fixing of known time markers to (estimated error from ALC in parentheses) 5 years between the volcanic signal of Krakatoa and Tambora at a depth of 69 m (17 years) and to 102 years between the volcanic signal of Tambora and the Unknown 1258 A.D. at a depth of 114 m (120 years).

[37] Using this detailed chronology we can now proceed with a more thorough interpretation of the climatic records preserved in these cores. This will be the subject of future work on this precious midlatitude archive.

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