AFRL-SR-BL-TR-98

0055

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
Nov. 30, 1997

3. REPORT **COVERED**
Final Technical, 01 Oct 94 to 30 Sep97

4. TITLE AND SUBTITLE
Detailed Solar Activity and Ionization Event Records in Polar Ice Caps

5. FUNDING NUMBERS
F49620-95-1-0003

6. AUTHOR(S)
Gisela A.M. Dreschhoff
Edward J. Zeller

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Center for Research, Inc.
University of Kansas
2291 Irving Hill Rd.
Lawrence, Kansas 66045

8. PERFORMING ORGANIZATION REPORT NUMBER
NA

9. SPONSORING / MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
Dr. Henry R. Radoski
AFOSR/ NM
110 Duncan Ave
Bolling AFB, DC 20332-8080

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

19980116 039

a. DISTRIBUTION / AVAILABILITY STATEMENT
UL

CODE

13. ABSTRACT *(Maximum 200 words)*

Nitrate analyses were made of ice cores taken from high altitude sites on the Antarctic plateau and central Greenland. The 430 year nitrate record from the Greenland ice cap is believed to provide an estimate of the occurrence frequencies and number of major solar flares / solar proton events. The results include: 1) Observed historical white light flares can be expected to be associated with major solar proton events, 2) The SPE's recorded in the nitrate sequence are most likely large proton fluence events originating near the central meridian of the sun as viewed from the earth, 3) Large events occurred at the end of the 18th century, 4) Increased solar activity for several solar cycles preceding deep and prolonged solar minima, 5) Deep minima are recorded in both polar regions, 6) The nitrate record provides an almost complete history of ionospheric conditions in terms of individual ionization events as well as himispheric or global effects via ionospheric-thermospheric coupling.

DTIC QUALITY INSPECTED 2

14. SUBJECT TERMS
Solar Activity, Solar Flares, Solar - Terrestrial Interaction, Space Weather

15. NUMBER OF PAGES
32

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT
UL

-1-

AFOSR F49620-95-0003

DETAILED SOLAR ACTIVITY AND IONIZATION EVENT RECORDS IN POLAR ICE CAPS

Gisela A. M. Dreschhoff
Edward J. Zeller*

FINAL TECHNICAL REPORT

November 30, 1997

THE UNIVERSITY OF KANSAS CENTER FOR RESEARCH, INC.
2291 Irving Hill Drive-Campus West
Lawrence, Kansas 66045

AFOSR F49620-95-1-0003

DETAILED SOLAR ACTIVITY AND IONIZATION EVENT RECORDS IN POLAR ICE CAPS

Gisela A. M. Dreschhoff
Edward J. Zeller*

FINAL TECHNICAL REPORT

November 30, 1997

Program Manager: Dr. Henry R. Radoski

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
BOLLING AFB, D.C., 20332-6448

(*Deceased January 14, 1996)

DETAILED SOLAR ACTIVITY AND IONIZATION EVENT RECORDS IN POLAR ICE CAPS

Summary

Nitrate analyses were made of ice cores taken from high altitude sites on the Antarctic plateau and central Greenland. The 430 year nitrate record from the Greenland ice cap is believed to provide an estimate of the occurrence frequencies and number of major solar flares / solar proton events. The results include: 1) Observed historical white light flares (WLF) can be expected to be associated with major solar proton events (SPE), 2) The SPE's recorded in the nitrate sequence are most likely large proton fluence events originating near the central meridian of the sun as viewed from the earth, 3) Large events occurred at the end of the 18th century, 4) Increased solar activity for several solar cycles preceding deep and prolonged solar minima, 5) Deep minima are recorded in both polar regions, 6) The nitrate record provides an almost complete history of ionospheric conditions in terms of individual ionization events as well as hemispheric or global effects via ionospheric-thermospheric coupling.

The information provided by this type of record could be extremely valuable in long-term planning of space operations in near earth orbit and for interplanetary missions. In general, a long time series in nitrate of ultra-high resolution would be extremely useful in understanding solar-terrestrial interactions and assessing the effects of solar variations on global weather and climate as well as on space weather.

DETAILED SOLAR ACTIVITY AND IONIZATION EVENT RECORDS IN POLAR ICE CAPS

I. INTRODUCTION

The polar regions of the earth are places where a long-term record of past atmospheric chemistry changes are preserved. We know that ionization in the middle atmosphere causes the formation of nitrate compounds, which are frozen out and incorporated into the layers of polar ice caps. Nitrates are produced at the poles when solar particles bombard the magnetosphere and subsequently interact with the molecules of the polar atmosphere, fall out and are buried in compacted layers of snow. The nitrate ion content of these layers have been studied at ultra-high resolution. Major solar proton events constitute large, pulse-like contributions to the polar atmosphere in the form of nitric acid. These type of events have been resolved and identified in the glaciological record (Shea et al., 1993). The data may well constitute the most accurate and complete index of solar activity ever obtained from the solid earth.

Satellite instruments look at solar particles as we are able to do via their effect on the polar ionosphere and stratosphere. In addition, the method of nitrates in polar ice cores allows us to look at long period fluctuations as well, which have to reflect deeper zones within the sun. In other words, this type of data provide a potential window through the photosphere of the sun. We have a view of the solar magnetic field which in turn is a window into the convection zone and possibly deeper.

The sun varies with time. Our data have proved that a variation exists between the intensity of the 11 and 22 year cycle through time as far back as 3000 years (Zeller and Parker, 1981; Parker et al., 1982; Dreschhoff and Zeller, 1989). From this one must conclude that the sun will not continue to behave as it has during the last 200 years of more exact observations. Periods of relative stability last only between five to ten Hale (22 year magnetic) cycles, after that rapid change tends to occur.

The nitrate concentrations in firn (compacted snow) and ice cores were measured by ultraviolet spectrophotometry under tightly controlled experimental procedures. It is reported in absorbance units (relative units) or as micrograms nitrate-nitrogen per liter. Electrical conductivity was measured in a stream flow and therefore on exactly the same sample as the nitrates. All details have been reported previously (Dreschhoff and Zeller, 1990; 1994). The electrical conductivity is measured as micro Siemens per cm, and is a relative measure of the amounts of anions and cations present, with sulfates (SO_4^{2-}) being one of the largest contributors.

II. DATA

Most of the data presented here involve the ultra-high resolution sampling, analysis, and interpretation of an ice core of 125.6 meters from the Summit/GISP2 site in central Greenland (Zeller and Dreschhoff, 1995). Other data referred to are part of earlier operations in Antarctica on the high polar plateau.

The complete nitrate sequence has been plotted in Figure 1 together with the simultaneously measured electrical conductivity data. The total number of data points are 8002 for each series. This translates into each individual sample representing on average about 1.57 cm along the entire ice core which represents a time scale on average of one week to one month.
The same data are displayed in greater detail in Plates I and II in Appendix A. On Plates I and II it is possible to read off every individual data point. The Plates, however, do not contain the most recent 3.6 meters added to the original 122 meters of core, which became available only recently for our analysis and evaluation. The addition to the original sequence is shown in Figure 2 (Figure 2a and 2b) and it represents about fourteen more years going back to the year 1561. In Figure 3 this part of the sequence has been plotted from sample number 7300 to 8000, which corresponds to the time period from 1600 to 1561. The nitrates are presented in relative units (Absorbance x 10^{-4}) and have superimposed by the conductivity data. Figure 3 shows the dating technique used, which includes the use of volcanic event horizons and seasonal/yearly counting of nitrate concentrations. The approximate number of samples per year is eighteen at this depth in the core, meaning that the time resolution is about one month for each sample.

II.1 LARGE PROTON FLUENCE EVENTS

In-situ data acquisition of nitrate concentrations in a firn core from Antarctica , location Windless Bight on the Ross Ice Shelf approximately S 78^0 and E 167^0 resulted in a very high resolution time series of about 80 years (see Figure 4). This data showed a statistically significant modulation of the background signal that was clearly traceable to solar activity. Several anomalously large concentration peaks were observed that were found to correlate with the major solar proton events of August 1972, July 1946, the major geomagnetic disturbance of July 1928, and a peak dated to occur in the year 1909 which may also be associated with a major geomagnetic storm (Dreschhoff and Zeller, 1990; Dreschhoff et al., 1993). Based on these results it has been possible to divide solar proton events into two categories, major SPE's being characterized either by large peak fluxes or by large particle fluences (Shea et al., 1993). In addition, the large fluence events are likely to be associated with a solar flare source near the central meridian of the sun as seen from the earth. Shea et al., (1993) concluded further that the events with large peak proton flux appear to be associated with solar flares near the west limb of the sun.

II.2 WHITE LIGHT FLARES

In our nearly 430 year ultra-high resolution time series, about 60% of the anomalous nitrate peaks (several standard deviations above the series' mean) seem to occur mainly on the downward side of the 11 year sunspot cycle. One of the exceptions to this trend is to be found in the 1859 solar flare which occurs near solar maximum of cycle 10. The nitrate signal is one of the most prominent anomalies in the entire nitrate record (Dreschhoff and Zeller, 1994; Zeller and Dreschhoff, 1995). This white light flare was observed by R.C. Carrington in London, September 1, 1859 as an extremely large, brilliant event on the solar disk. He reported this extraordinary occurrence with detailed drawings of the associated sunspot group (Carrington, 1860). The large magnetic storm that followed this event about 17 hours later led Carrington to believe that some type of matter had to have been released by the sun which was able to reach the earth, which was considered a revolutionary thought at that time. Almost one hundred years later this idea was restated and investigated within the framework of modern knowledge of solar flares and cosmic rays (McCracken, 1959). The details of the nitrate anomaly, most likely representing this white light flare is shown in Figure 5. The evaluation of this event is continuing in the context of the proton flux having produced such an anomaly. The quantitative evaluation of such an ionization event in the northern polar stratosphere requires the development of calibration sources that can be tested by evaluating their effect on the complex interaction between ionization, production, and fallout to the ice cap and various other atmospheric parameters that are site dependent. In fact, one such calibration standard may exist in the form of a kind of "standard candle" which constitutes the 60-megaton hydrogen bomb test fired on Novaya Zemlya on October 30, 1961. This nuclear explosion was the largest atmospheric test in history and occurred at very high latitude. We believe that the signal from this explosion can be pinpointed in our nitrate profile (see Figure 6). Preceding this nitrate anomaly is a large peak in conductivity which indicates the eruption of Askja volcano in central Iceland on October 26, 1961.

Another short-term event of ionization in the northern polar stratosphere is found to be recorded in the ice of Greenland (Figure 7). A large nitrate anomaly is accompanied by a conductivity anomaly as well. Tentatively, we interpreted this to be due to the unusual Tunguska event, the meteorite air burst over Siberia, June 30, 1908.

II.3 LARGE PROTON EVENTS AT THE END OF THE LAST CENTURY

Polar nitrate anomalies in association with solar proton events prior to direct solar proton measurements have been investigated (Dreschhoff et al., 1997, and Appendix B). With the likelihood that the nitrate records can be used to identify major solar fluence events, attention has been focused on relatively large nitrate anomalies which occur toward the end of the last century. Some of the peak amplitudes have been verified by resampling the core and analyzing the samples at the same resolution as the original samples (see Plate I in Appendix A). It appears that particularly solar cycle 13 was characterized by a relatively high level of activity, although the count in sunspot numbers throughout the period is only moderate.

Supporting evidence of unusually increased solar flare activity has resulted from a careful study of the high frequency components of secular variation of atmospheric ^{14}C (Damon and Peristykh, 1996). The results of this cosmogenic isotope work of intense solar flare activity at the end of the last century and its relatioship to nitrate concentrations in polar ice is shown in Figure 8. Damon and Peristykh state that "the event of AD 1892 (see Plate I in Appendix A), is confirmed by George Hale's optical astronomical observations of a remarkable solar disturbance on the 15th of July, 1892 that appeared as a large and active sunspot (Hale, 1931)." This qualitative confirmation is supported by estimates of proton fluence of approximately 10^9 particles cm $^{-2}$ based on the amount of ^{14}C production.

II.4 SOLAR ACTIVITY LEVELS PRECEDING THE MAUNDER MINIMUM

An examination of the nitrate sequence seems to indicate a relatively large number of nitrate anomalies for the period from 1561 to the beginning of the Maunder Minimum of approximately 1645 (see Figure 3 and Plate II in Appendix A). Of particular interest during this time period is the relatively large nitrate anomaly dated to occur in 1570 shown in Figure 3. This peak represents a seemingly major ionization event and coincides with the report of an unusual aurora seen January 12, 1570 in southern/middle Europe (Frazier, 1982). To get an objective estimate of any possible increase in activity throughout the period before the beginning of the Maunder Minimum, the nitrate concentration data were subjected to a 15-point moving average and the residuals were determined and plotted shown in Figure 9.(Figure 9.1 to 9.4). The eight different sections plotted by sample number each represent different number of years depending on the rate of precipitation (snow accumulation) and compaction with continued accumulation. The number of years have been indicated in each section. For the purpose of comparison all anomalies are counted which surpass at least the level of residual -50. To reduce the influence of local meteorological factors on the absolute peak height, three readings of the number of anomalies were averaged for the residual levels -50, -75, and -100. The results have been plotted in Figure 10. It shows that the average number of anomalies in section 8, the period of 60 years preceding the last deep minimum of solar activity compares closely with section 3 and 2, the periods toward the end of the last century and into the time of modern instrumental records.

II.5 ATMOSPHERIC RYTHMICITY IN NITRATE AND CONDUCTIVITY

When subjecting both sequences to a 15-point moving average which corresponds on an average to about one year it becomes clear that the background trends are very similar and undergo some kind of atmospheric rythmicity. This is demonstrated in Figure 11, which shows just the uppermost part of both sequences as an example. Another example is provided by comparing nitrate and conductivity in the lowest part of the sequences in Figure 12. The general rythmicity is clearly present, however, when normalizing the data, larger deviations between the two sequences are also clearly visible. These deviations are due to volcanic eruption signals (or volcanic sulfuric acid signal) in the case of conductivity, and ionization spike anomalies in the case of nitrates. The two large, highlighted deviations in nitrate shown will be discussed in the next section.

As pointed out, this type of results is most likely an indication of global atmospheric rythmicity. To understand this phenomenon at this time is beyond the scope of this research project. However, an attempt will be made of a qualitative description of coupling processes in the polar atmosphere, which ultimately will have to be put into a quantitative framework.

Assuming that the conductivity signal is mostly a signal of sulfate ion which originated in large volcanic eruptions and has been residing subsequently at the so called Junge layer in the stratosphere at an altitude near 24 km, and nitrate ion being produced at altitudes of the polar ionosphere and stratosphere, it is necessary to describe coupling mechanism which may possibly account for the rythmicity displayed by both sequences. Extensive high latitude studies have been in progress for several years investigating the thermospheric response to energy and momentum input from the magnetosphere (Hernandez et al., 1989). South Pole mesospheric and lower thermospheric (85 to 130 km) dynamics are related to forcings from below and above, such as wave and tidal activity and possibly to local auroral heating which occurs above it (Hernandez et al., 1990). Winds may superimpose on the tidal behavior which are generated through the coupling between high speed ions (E x B drift) in the lower ionosphere and surrounding neutral atmosphere. Ultimately, the power source is the solar wind with the energy and momentum coupled into the magnetosphere and eventually finds its way into the thermosphere as large-scale circulation, waves, and heat, as stated by Smith et al., (1994).

Polar heating and momentum is communicated to lower latitudes by the strong equatorward winds (of several hundred meters per second).The meridional component of the neutral wind induces field-aligned diffusion of ionospheric plasma, changing the F-layer height and density on a global scale, as well as the global F region energy budget through the movement of mass, energy, and reactive minor constituents via a giant pole-to-pole Hadley cell (Smith et al., 1989). The ionosphere and thermosphere can be viewed as interpenetrating fluids causing coupling phenomena, the strength of which is dependent on the variable ionization density of the ionosphere.

II.6 SUPERNOVA SIGNAL

It has been stated before, that the identification of nitrate anomalies with historic supernovae is highly speculative (Rood et al., 1979). However, the authors pointed out that the production of observed nitrate peaks by the hard X-rays generated by a supernova (SN) outburst does not seem inconceivable at least from the point of view of energy requirements and current SN models. Large stratospheric ionization events resulting in the production of nitrates can take place through the energy deposition of the X-rays which are capable of penetrating the earth's atmosphere to an altitude of 27 to 32 km before Compton scattering begins to convert their energy to that of ionizing electrons (Ruderman, 1974).

The supernovae of interest relative to the 430-year ultra-high resolution nitrate record from the Greenland ice cap are listed in Tabel I.

Tabel I. Historic Supernovae

SN	TIME		DISTANCE	VISIBILITY
CAS A	1700's		~10 kpc	
Kepler	1604	1 Nov.(max)	10 kpc	12 months
Tycho	1572	6-11 Nov.	7 kpc	16 months

Other historic supernovae within our galaxy would have still greater significance because of their closer proximity to our solar system. However, we find very significant ionization events in the nitrate record with peaks around the year 1604 and around 1572 in Figure 3 and Figure 12 (see the highlighted peaks) as well as around 1700 as seen in Plate II of Appendix A. Although the CAS A explosion has been backcalculated recently as having occurred in 1680 (Rood and Sarazin, pers. com.), the largest signal we see seems to be associated with ~1700, and the year 1680 is only represented by a smaller nitrate anomaly. Whereas the year for CAS A is not known precisely, the time of arrival of the optical signal of Kepler SN and Tycho SN is well known. Having the two signals of 1604 and 1572 in the nitrate data may provide for a strong case, especially in combination with a third signal (CAS A) and should reduce the possibility of pure speculation significantly. This is supported by the ultra-high resolution data series of the Greenland core (Zeller and Dreschhoff, 1995) with complete sample control, including resampling for confirmation of large anomalies. This has resulted in an independent check on the earlier results of Rood et al., (1979).

II.7 THE MAUNDER MINIMUM

From the sunspot record as assembled by J. Eddy the period between 1645 to 1715 has been a time of no or almost no visible sunspots (Eddy, 1976).

The Maunder Minimum thus defined was a period of prolonged reduced levels of solar activity. However, the nature of this extended activity minimum needs to be examined more closely not only in terms of a prolonged decline of sunspot numbers. This has been pointed out by Silverman, (1993) with emphasis on the presence of a prolonged minimum rather than the complete absence of activity. He summarized by stating that from the data available, the Maunder Minimum consisted of a significantly lowered solar activity in the latter half of the 17th century, the period in which auroral activity was at its lowest.

The nitrate signal that we report as consisting of basically two components, a background reflecting mostly general auroral activity and a superimposed signal of individual ionization events in the polar stratosphere, very clearly seems to reflect the characteristics of the Maunder Minimum. The total number of nitrate anomalies are reduced to less than one third of the occurrences throughout the 430-year Greenland record of ultra-high concentrations (Zeller and Dreschhoff, 1995). Furthermore, by converting the nitrate concentrations to relative flux values per year, the signal of the period of the Maunder Minimum displays a level of auroral ionization closely resembling the conditions as described by Silverman, (1993), reduced levels of activity during the first half of the period, followed by a still deeper minimum. This result is shown in Figure 13 and can be compared to a similar result that was obtained for the South Pole (Zeller and Parker, 1981). Since the signals show such a high degree of similarity in both polar regions, which are subject of very different rates of snow accumulation and generally very different atmospheric dynamical conditions, this agreement of data cannot be attributed to chance at one site or purely due to local meteorology.

It is concluded that the nitrate signal during the Maunder Minimum should be interpreted in terms of reduced levels of ionization in the auroral zones above both polar regions, thereby producing a similar signal in both polar ice caps.

III. CONCLUSIONS

The nitrate data from both polar regions, Greenland and Antarctica, are a signal of ionization spikes from the polar stratosphere, general levels of ionization reflecting the ionization density of the auroral zone, and of atmospheric rythmicity possibly influenced by the polar middle and upper atmosphere (mesosphere with inclusion of the ionosphere and thermosphere). The ultra-high resolution, and totally sequential data series we have acquired representing the last 430 years can serve as a basis for relatively precise estimates of major solar proton events, particularly in the framework of variations of solar activity on longer time scales. This may be demonstrated by the results of the number of major nitrate anomalies, or almost non-occurrence of anomalies during the Maunder Minimum, but very clearly also during the Dalton Minimum as shown in Figure 9.2. If we consider the statement by Silverman, (1993), that the Dalton Minimum may be the deepest and most significant minimum of the past 500 years, data may contribute significantly to the understanding of the frequency and depth of prolonged solar activity minima.

ACKOWLEDGEMENTS

This work was supported by U.S. Air Force contract AFOSR 88-0065 and AFOSR F49620-95-0003. Gratitude is expressed to the Office of Polar Programs of the National Science Foundation, and the Polar Ice Coring Office (PICO/NSF) for logistics and drilling support in Greenland and Antarctica. The availability of core storage and laboratory facilities at the National Ice Core Laboratory in Denver, Colorado, and generous help are also greatly appreciated. Thanks are also extended to P. Damon for permission to reproduce one of his unpublished figures.

REFERENCES

Carrington, R.C., Description of a Sigular Appearance Seen in the Sun on September 1, 1859, Monthly Notices of the Royal Astronomical Society, 20(1), 13-15, 1860.

Damon, P. and A. Peristykh, Cosmogenic Isotope Evidence of Very High Solar Flare Activity at the End of the XIX Century, 1996, personal communication.

Dreschhoff, G. and E.J. Zeller, On the 11/22 Year Solar Cycle in Antarctic Snow, Annual Technical Report, U.S. Air Force, AFOSR 88-0065, Nov.1, 1989.

Dreschhoff, G. and E.J. Zeller, Evidence of Individual Solar Proton Events in Antarctic Snow, Solar physics, 127, 333-346, 1990.

Dreschhoff, G., E.J. Zeller, D. Qin and B.C. Parker, Major Solar Flares and Long-Term Variability in Antarctic Ice Cores, Adv. Space Res., 13 (9), 443-446, 1993.

Dreschhoff, G. and E.J. Zeller, 415-Year Greenland Ice Core Record of Solar Proton Events Dated by Volcanic Eruptive Episodes, Inst. Tertiary-Quaternary Studies, TER-QUA Symposium Series, 2, 1-24, 1994.

Dreschhoff, G., M.A. Shea, D.F. Smart and K.G. McCracken, Evidence for Historical Solar Proton Events from NO(X) Precipitation in Polar Ice Cores, 25th Int. Cosmic Ray Conf., Contributed papers, 1, 89-92, 1997.

Eddy, J., The Maunder Minimum, Science, 192, 1189, 1976.

Frazier, K., Our Turbulent Sun, Prentice Hall, Englewood Cliffs, N.J., 198pp., 1982.

Hernandez, G., R.W. Smith, K.C. Clark, Global Thermospheric Dynamics and Thermodynamics from South Pole, Antarctic Journal of the U.S., 24(5), 245-248, 1989.

Hernandez, G., R.W. Smith and S.D. Kauffman, South Pole Mesospheric and Lower-Thermospheric Dynamics, Antarctic Journal of the U.S., 25(5), 278-279, 1990.

McCracken, K.G., A Correlation Between the Emission of White Light and Cosmic Radiation, by a solar flare, Il Nuovo Cimento, Serie X, 13, 1081-1085, 1959.

Parker, B.C., E.J. Zeller and A.J. Gow, Nitrate Fluctuations in Antarctic Snow and Firn: Potential Sources and Mechanisms of Formation, Annals of Glaciology, 3, 243-248, 1982.

Rood, R.T., C.L. Sarazin, E.J. Zeller and B.C. Parker, X- or Gamma-Rays from Supernovae in Glacial Ice, Nature, 282 (5740), 701-703, 1979.

Ruderman, M.A., Possible Consequences of Nearby Supernova Explosions for Atmospheric Ozone and Terrestrial Life, Science, 184, 1079-1081, 1974.

Shea, M.A., D.F. Smart, G. Dreschhoff and E.J. Zeller, The Flux and Fluence of Major Solar Proton Events and their Record in Antarctic Snow, 23rd Int. Cosmic Ray Conf., 3, 846-849, 1993.

Silverman, S., Is the Maunder Minimum Real?, EOS, Transactions American Geophysical Union, 74 (40), 460, 1993.

Smith, R.W., J.W. Meriweather, g. Hernandez, D. Rees, v. Wickwar, O. de la Beaujardiere and T.L. Killeen, Mapping the Wind in the Polar Thermosphere, EOS, Transactions American Geophysical Union, 70 (11), 161, 1989.

Smith, R.W., G. Hernandez, K. Price, G. Fraser, K.C. Clark, W.J. Schulz, S. Smith and M. Clark, The June 1991 Thermospheric Storm Observed in the Southern Hemisphere, J. Geophys. Res., 99 (A9), 17609-17615, 1994.

Zeller, E.J. and B.C. Parker, Nitrate Ion in Antarctic Firn as a Marker for Solar Activity, Geophys. Res. Lett., 8 (8), 895-898, 1981.

Zeller, E.J. and G. Dreschhoff, Anomalous Nitrate Concentrations in Polar Ice Cores - Do they Result from Solar Particle Injections into the polar Atmosphere? Geophys. Res. Lett., 22 (18), 2521-2524, 1995.

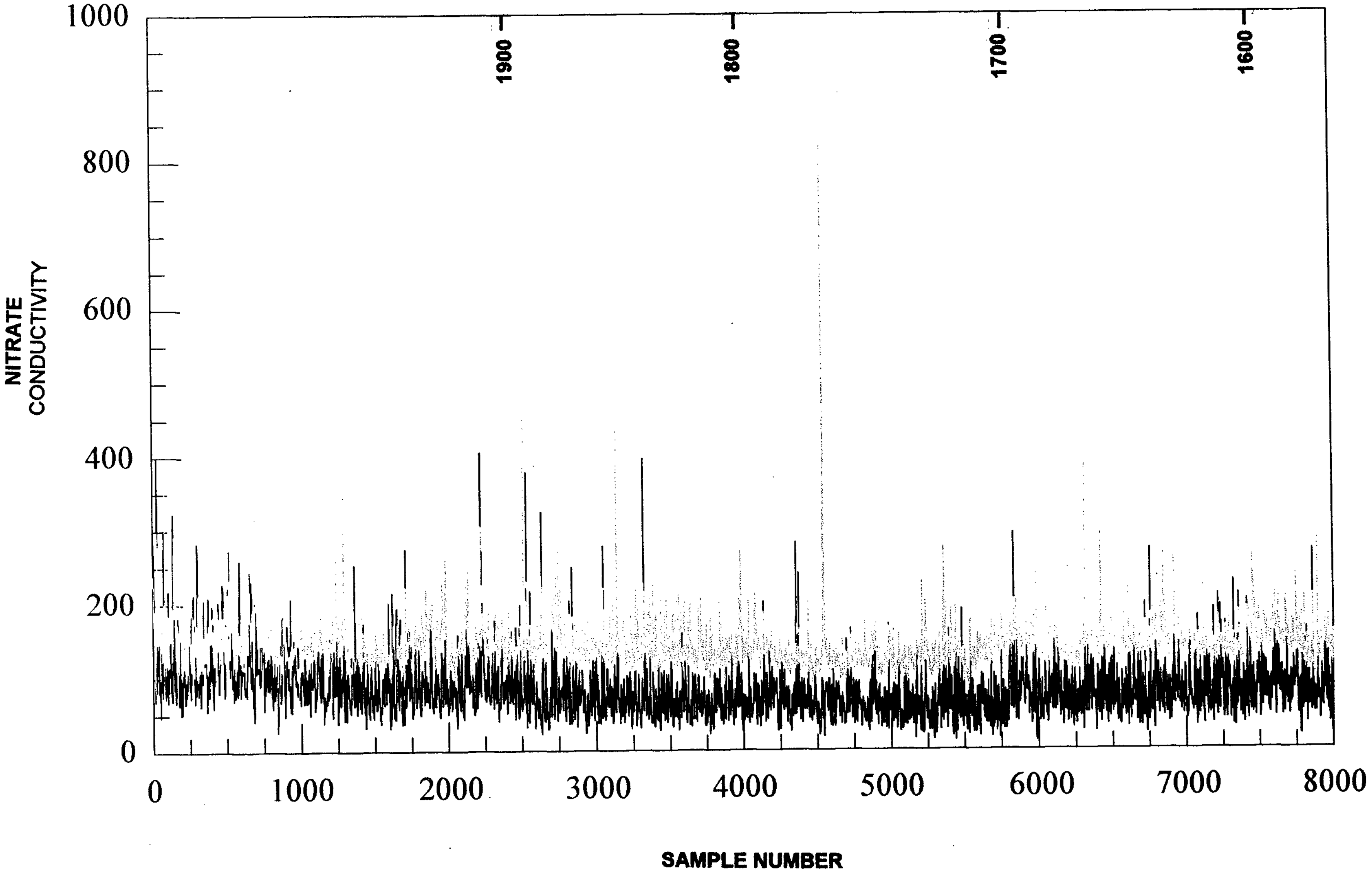


Figure 1. Complete 430-year record of nitrate concentrations (black) and electrical conductivity (gray) from an ice core drilled on the central Greenland ice sheet in June 1992. Each *sample number represents about 1.57 cm cut from the interior of the 125.6 meter ice core. The century time scale has been marked at the top of* the graph. Large anomalies in conductivity are due to large volcanic eruptions, and the large nitrate anomalies are the result of large individual events of ionization in the polar atmosphere. (For detail see Plate I and II in Appendix A).

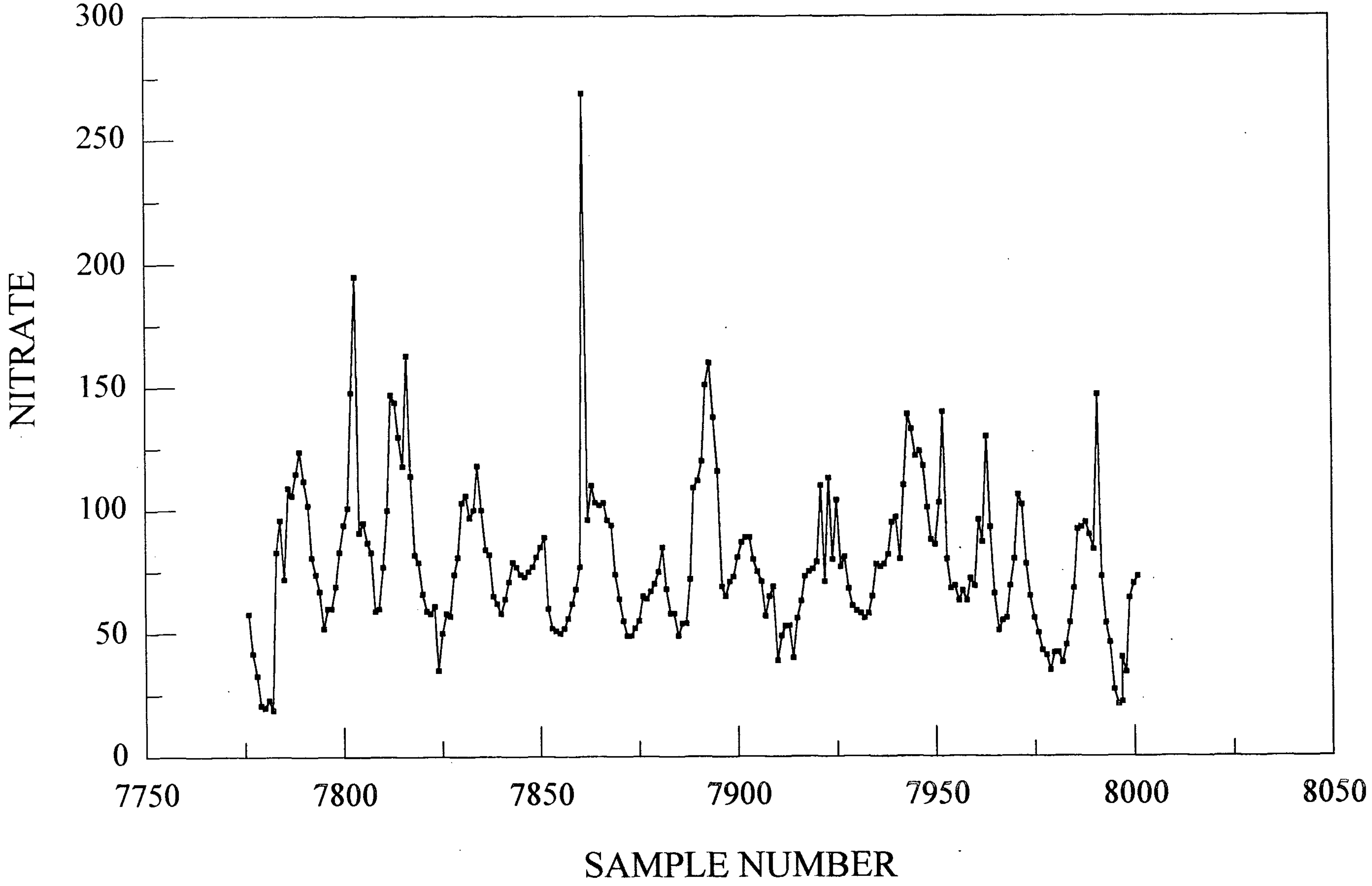


Figure 2. (2a) Nitrate concentrations of the lowermost portion of the ice core. Each data point represents ~1.57 cm along this 3.6 m section of the core, which have been added recently. Two relatively large nitrate anomalies are visible, which are superimposed on the seasonal nitrate signal.

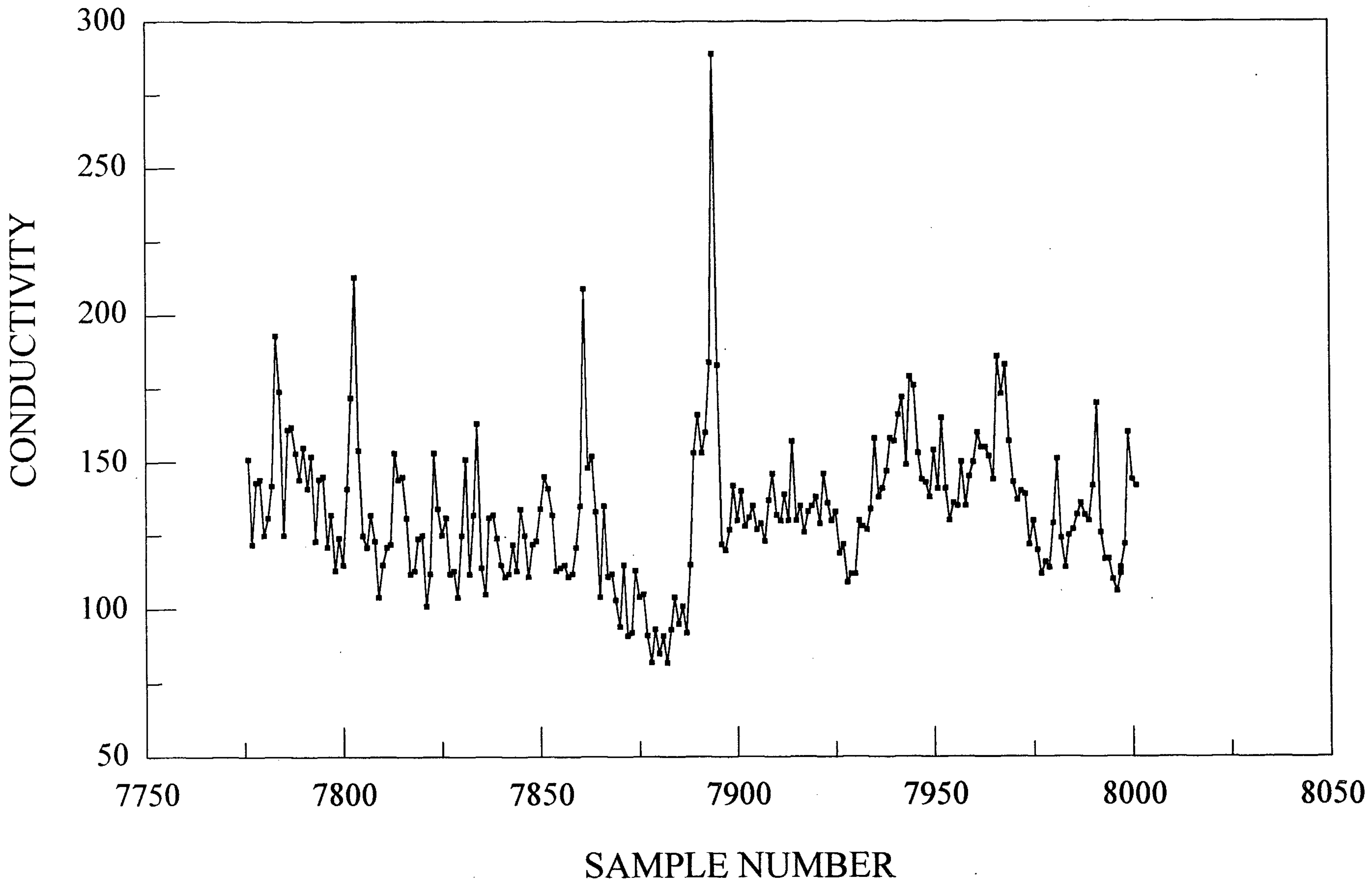


Figure 2. (2b) Electrical conductivity of the lowermost portion of the ice core. Each data point represents ~1.57 cm along this 3.6 m section of the core, which were measured simultaneously with the nitrates shown in (2a). Some of the conductivity anomalies can be identified from historical volcanic eruptive events.

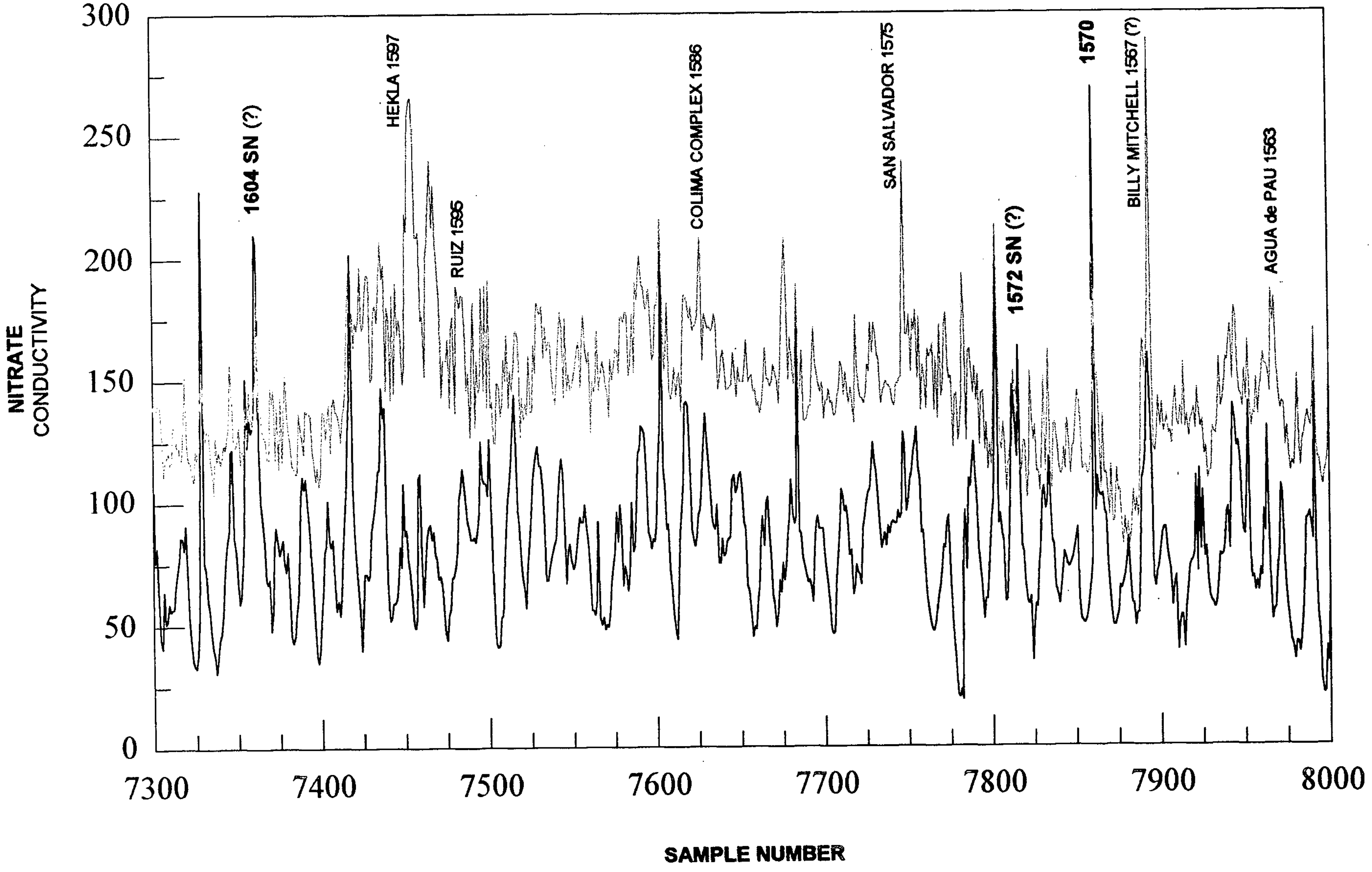


Figure 3. Dated lower portion of the core, showing conductivity (gray) and nitrate (black). Time markers by historic volcanic eruptions are indicated as are the nitrate anomalies, with 1570 representing most likely a major solar proton event which would have caused the reported large auroral event (Frazier, 1982).

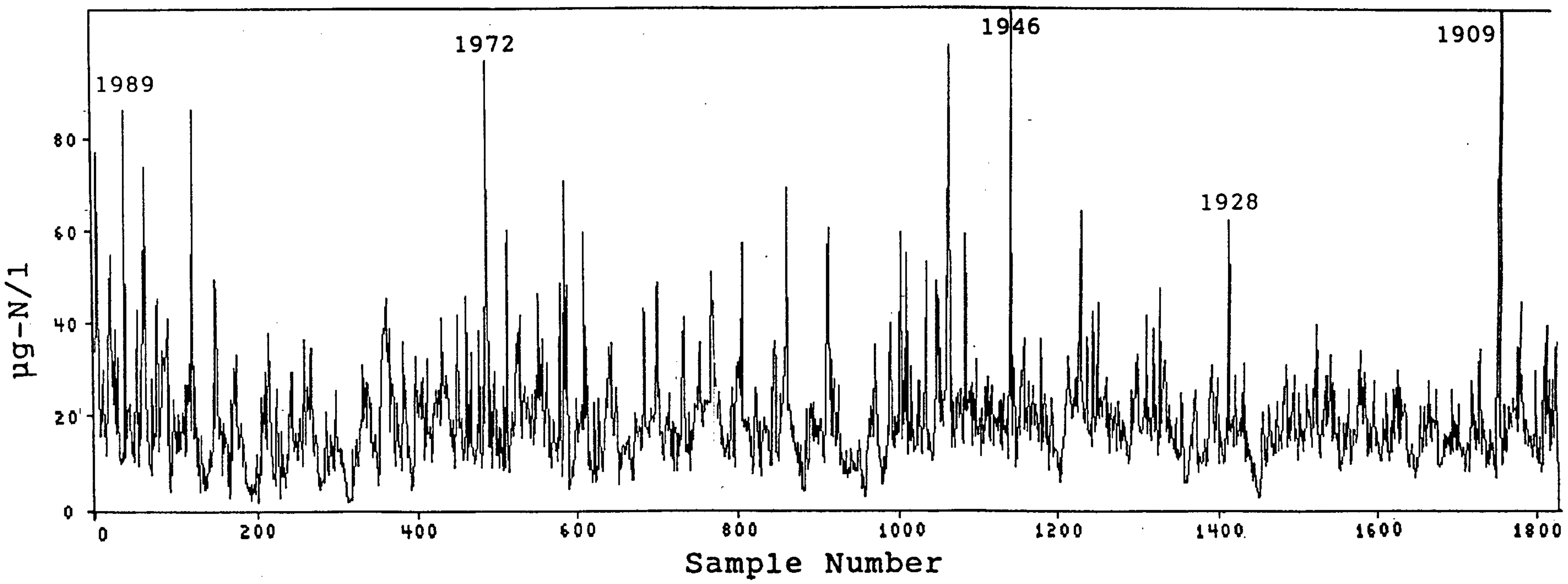


Figure 4. Variations of nitrate concentrations in micrograms – Nitrogen per liter from the surface (representing the year 1990) to a total depth of 29.4 meters (representing the year 1905). Total number of samples is 1800. Major peaks are identified by the year of their occurrence in the sequence.

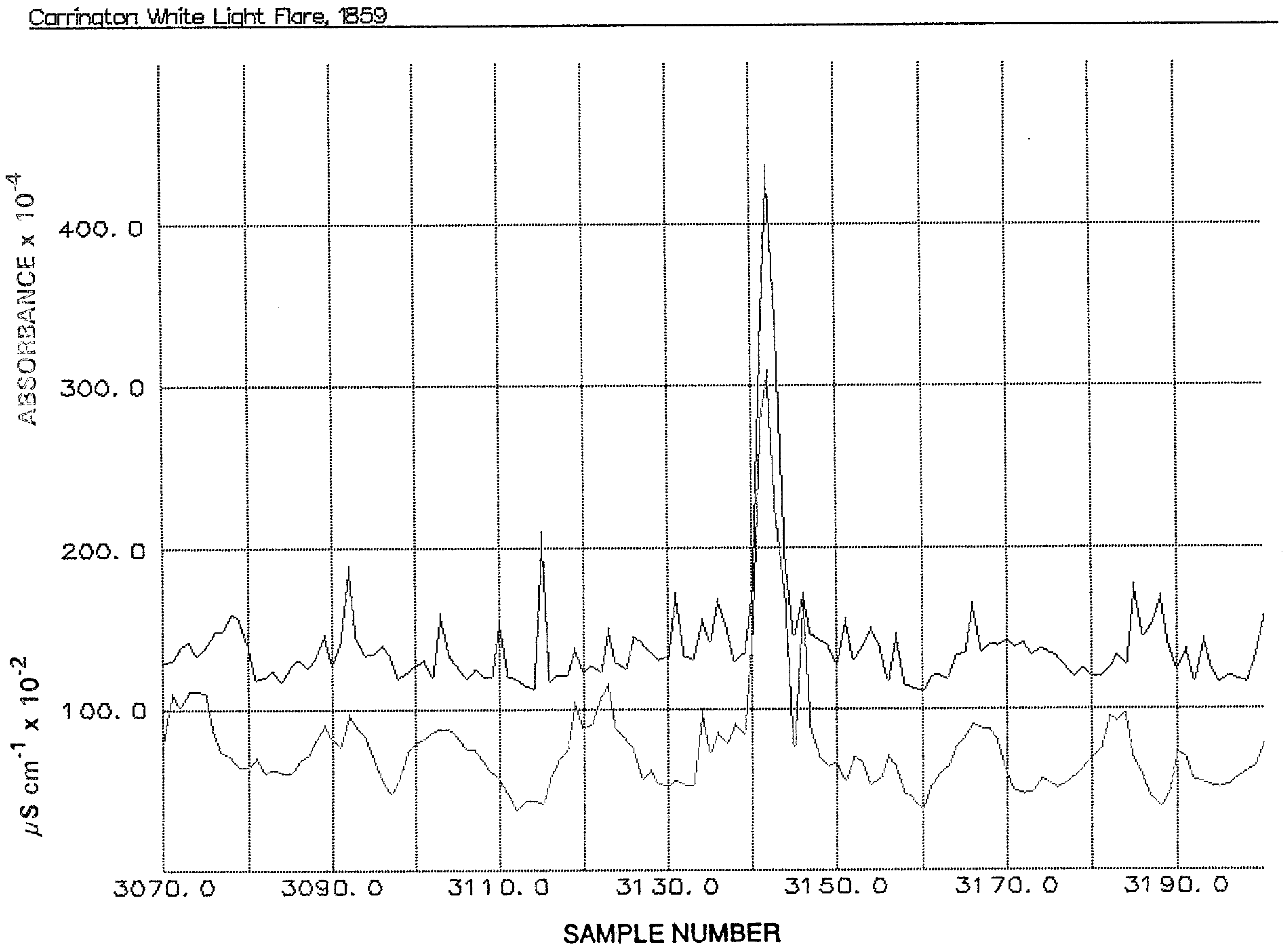


Figure 5. Short segment of the GISP2 H-core. Each sample number represents 1.5cm along the core. The large nitrate anomaly has been tentatively identified as the result of the unusual white light flare of September 1859, observed by Carrington in England.

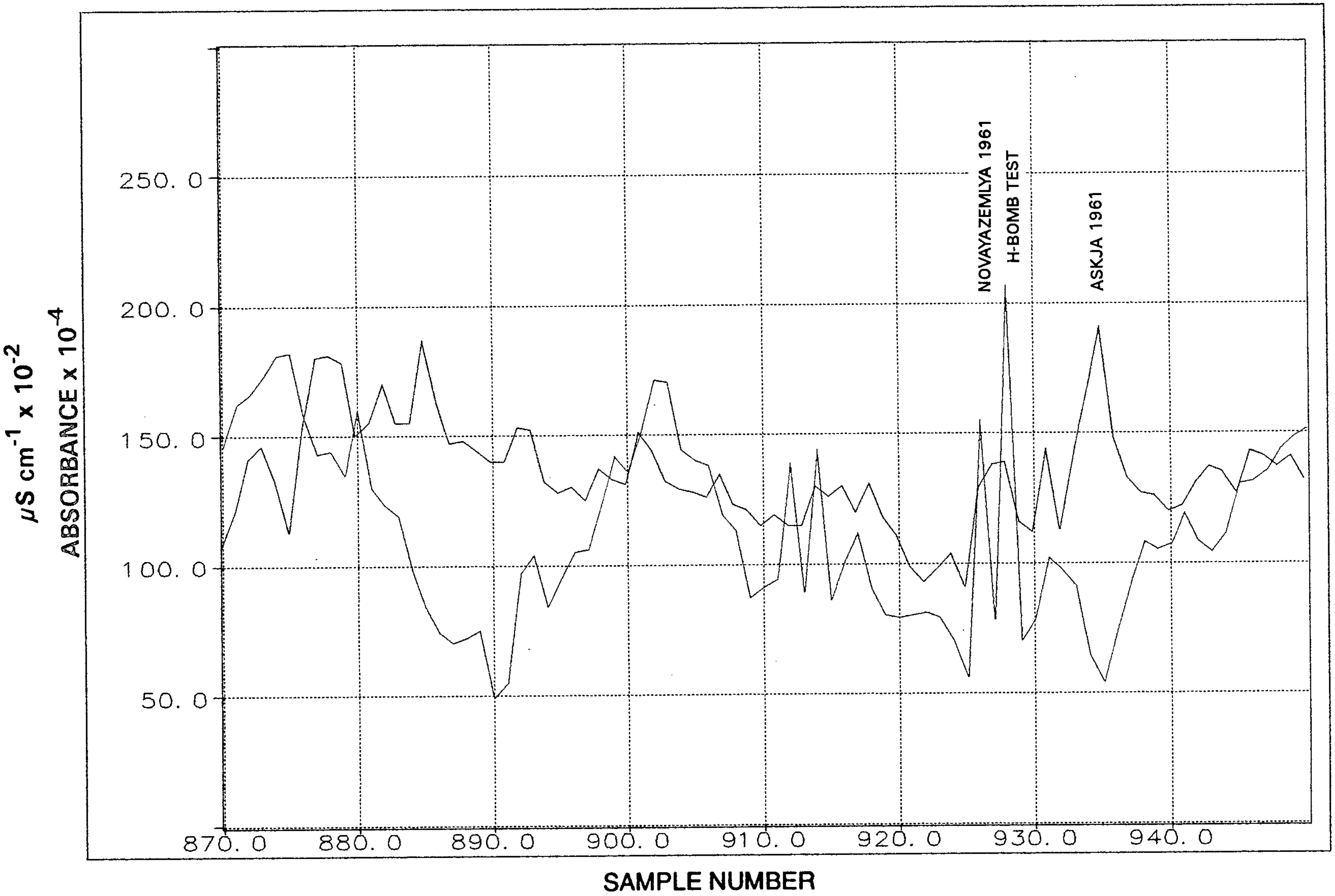


Figure 6. Short segment of the GISP2 H-core. Each sample number represents ≥ 1.5 cm along the core. The nitrate anomaly at sample number 928 has been interpreted as resulting from stratospheric ionization from the largest known nuclear detonation (~60 megatons). Our micro-resolution records permit a temporal resolution of two high latitude events that left a signal in the Greenland snow. They were the eruption of Askja in Iceland (conductivity) on 26 Oct. 1961 and the H-bomb test on Novaya Zemlya on 30 Oct. 1961.

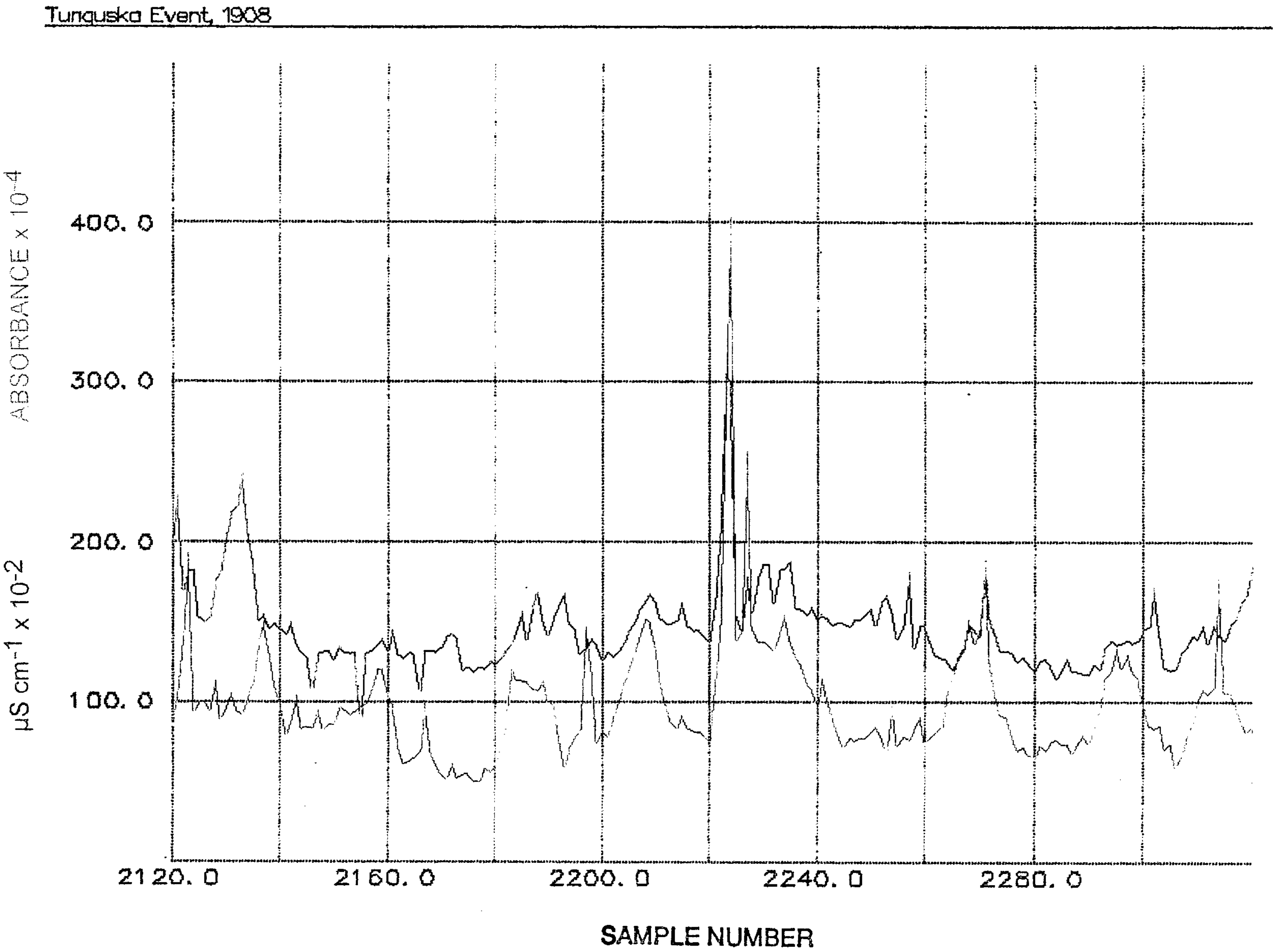


Figure 7. The anomalous nitrate peak, which is accompanied by a conductivity anomaly as well, has been tentatively interpreted to be due to the meteorite air burst over Siberia in June 1908.

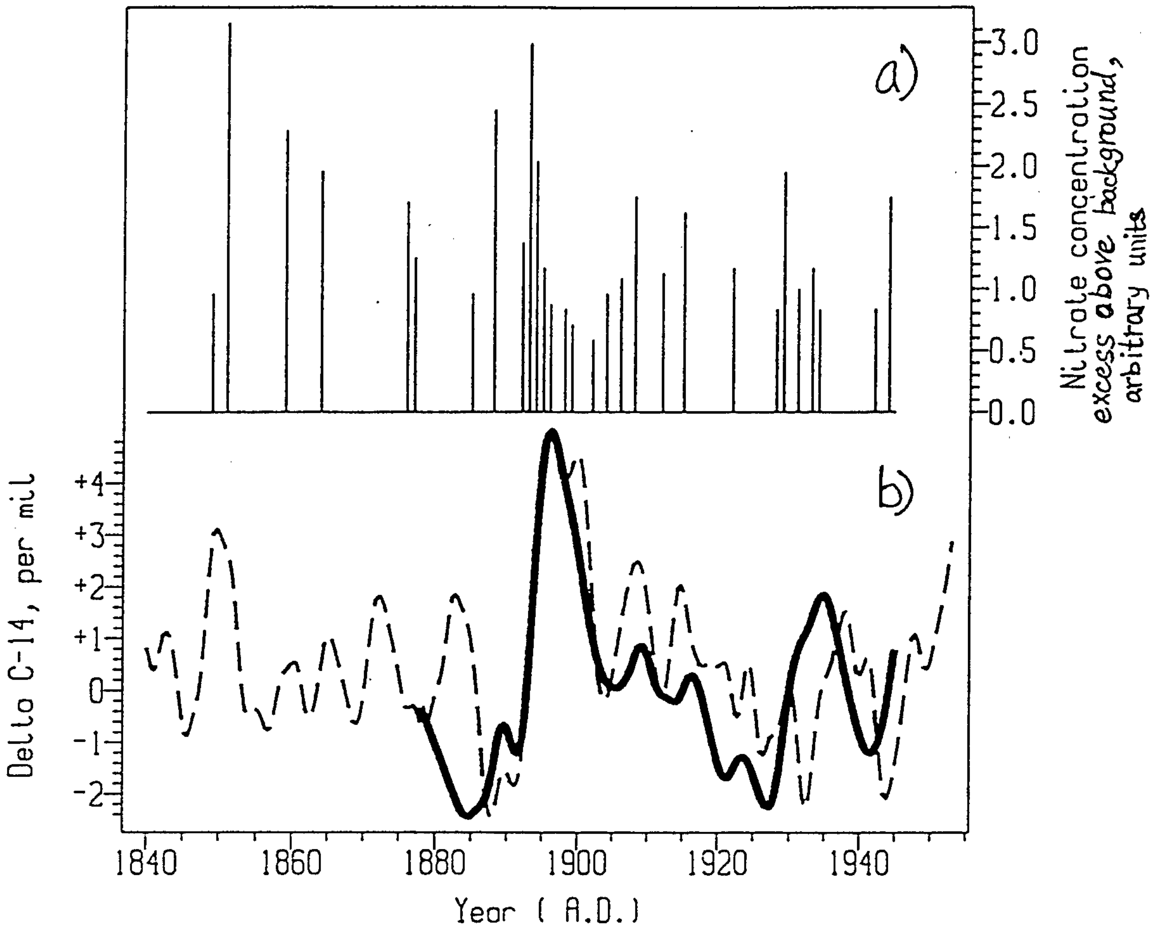


Figure 8. (a) Nitrate anomalies with background removed from a portion of the Greenland ice core.
(b) Cosmogenic isotope C – 14 data (dashed line) have been plotted as the difference between measured atmospheric C – 14 and simulated 11 – year radiocarbon variations. Superimposed is a curve representing simulated C – 14 derived from the sequence of nitrate anomalies after spline smoothing.

(Reproduced with permission of P. Damon)

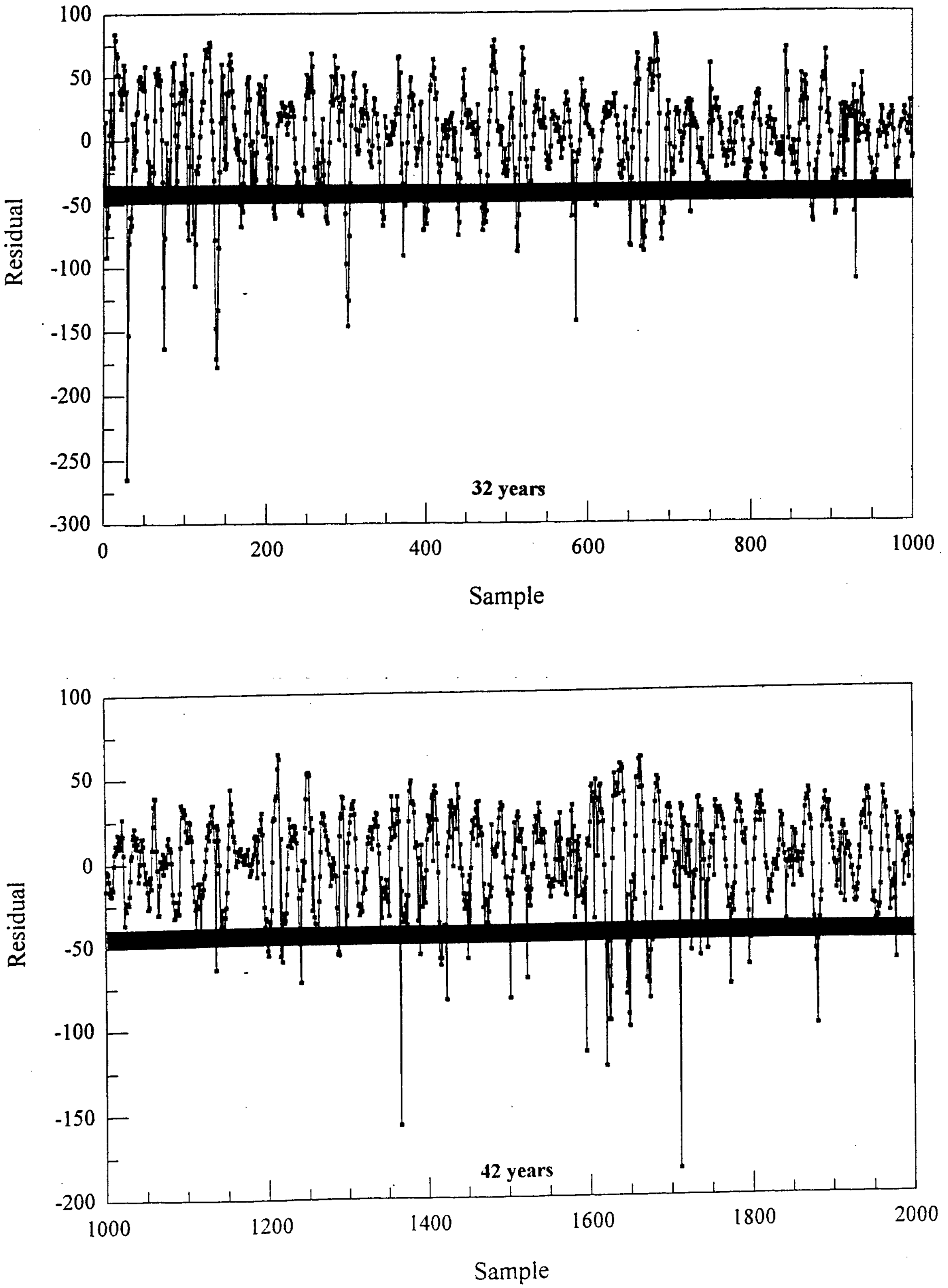


Figure 9. (9.1) Residuals from a 15-oint moving average (~ 1 year) of the nitrate concentrations of the Greenland ice core. Two sections of 1000 data points each have been plotted going down from the surface and back in time. The total number of years for each section has been added. A line has been drawn at the residual – 50 level for easier comparison with other sections along the core.

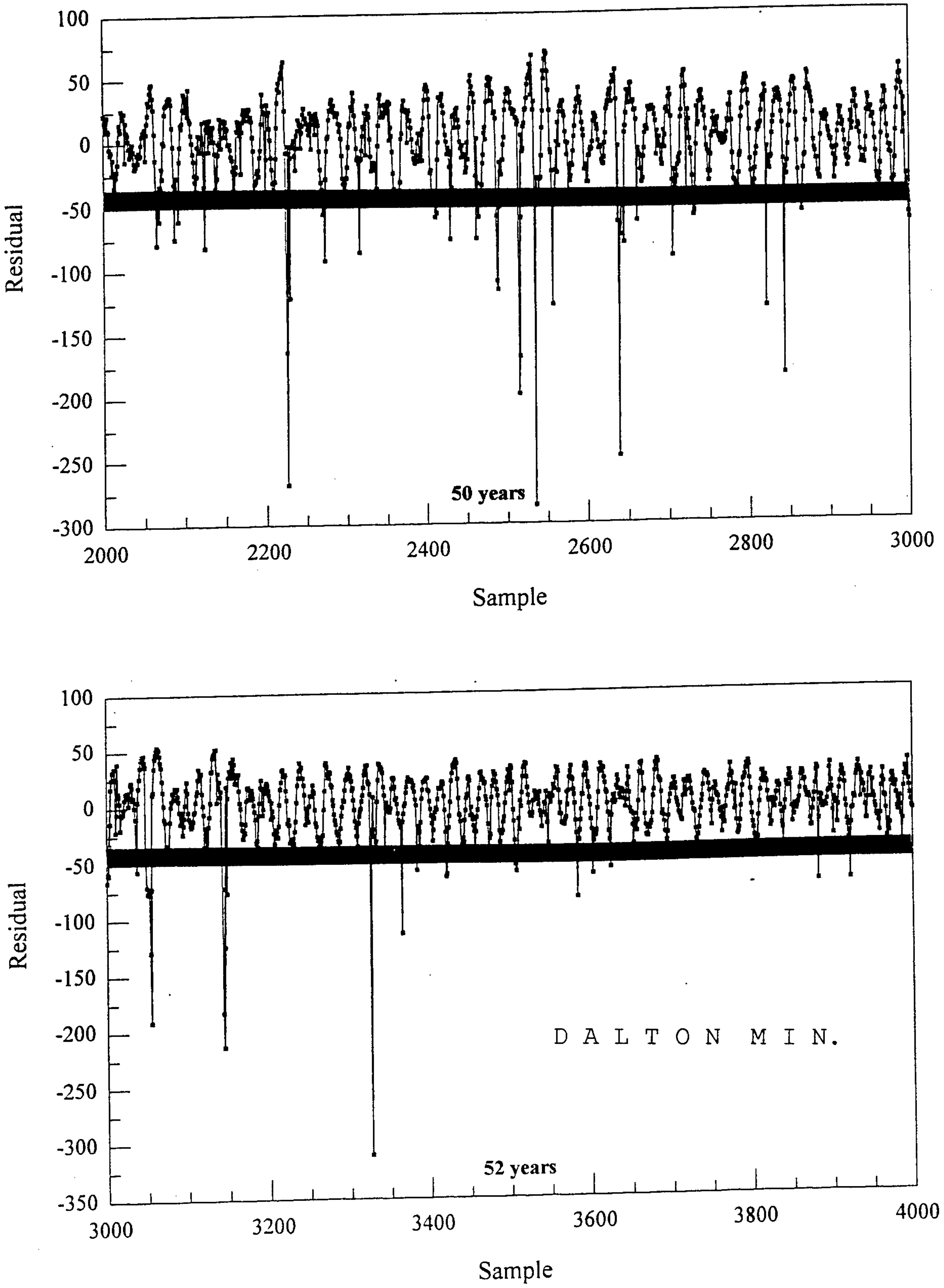


Figure 9. (9.2) Same as Figure 9.1, except the two sections range from data point 2000 – 4000.

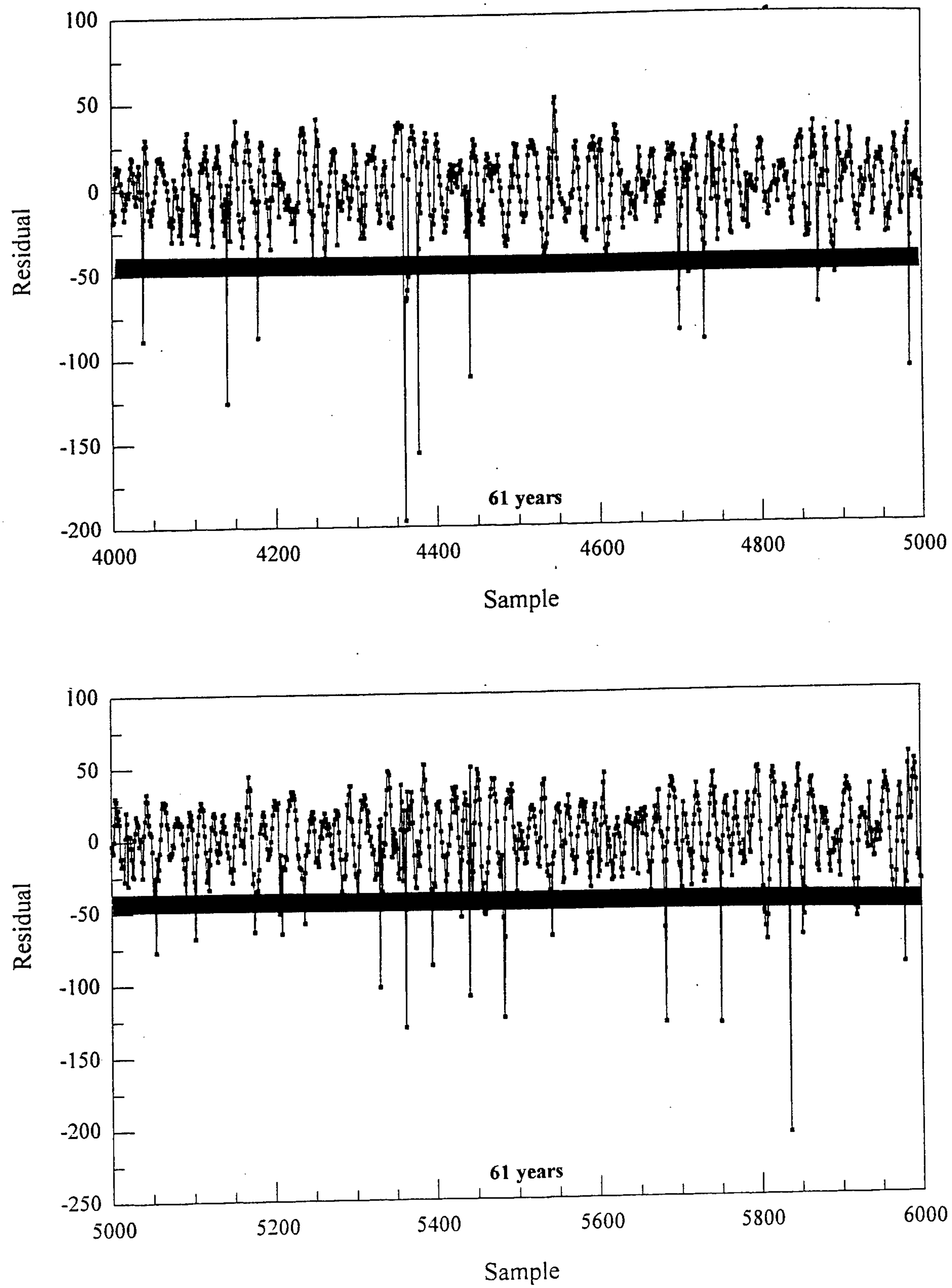
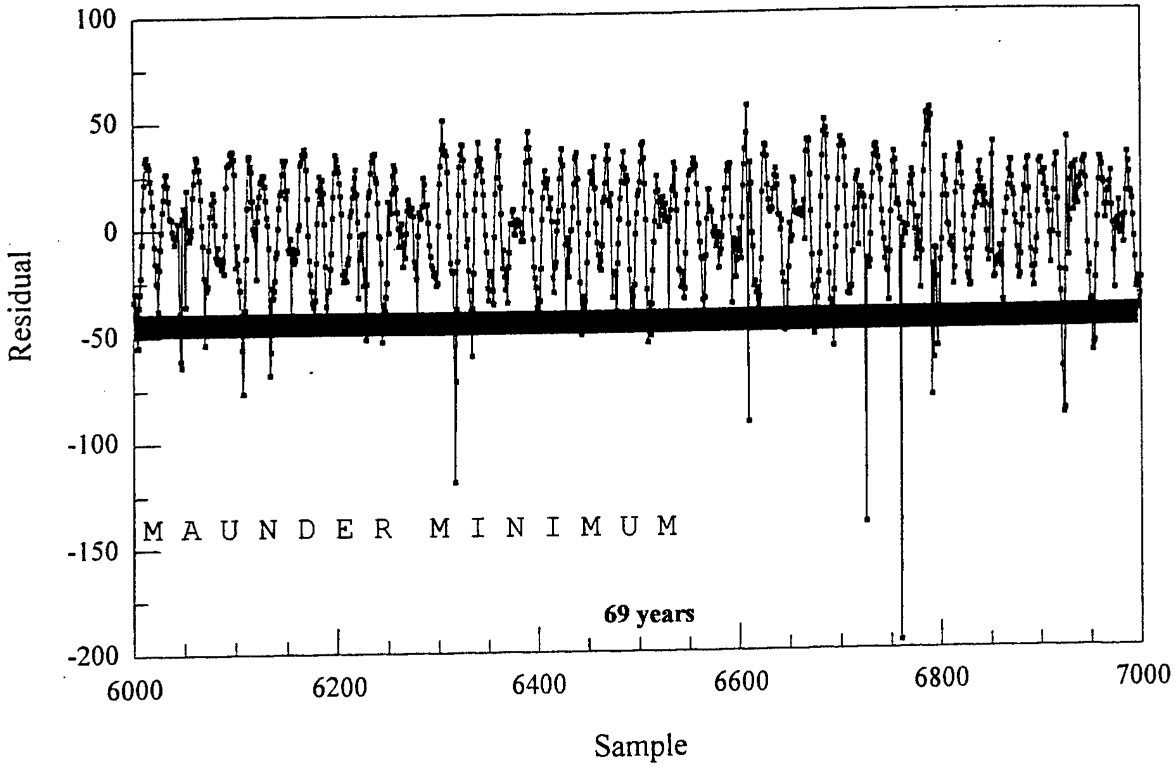


Figure 9. (9.3) Same as Figure 9.1, except the two sections range from data point 4000 – 6000.



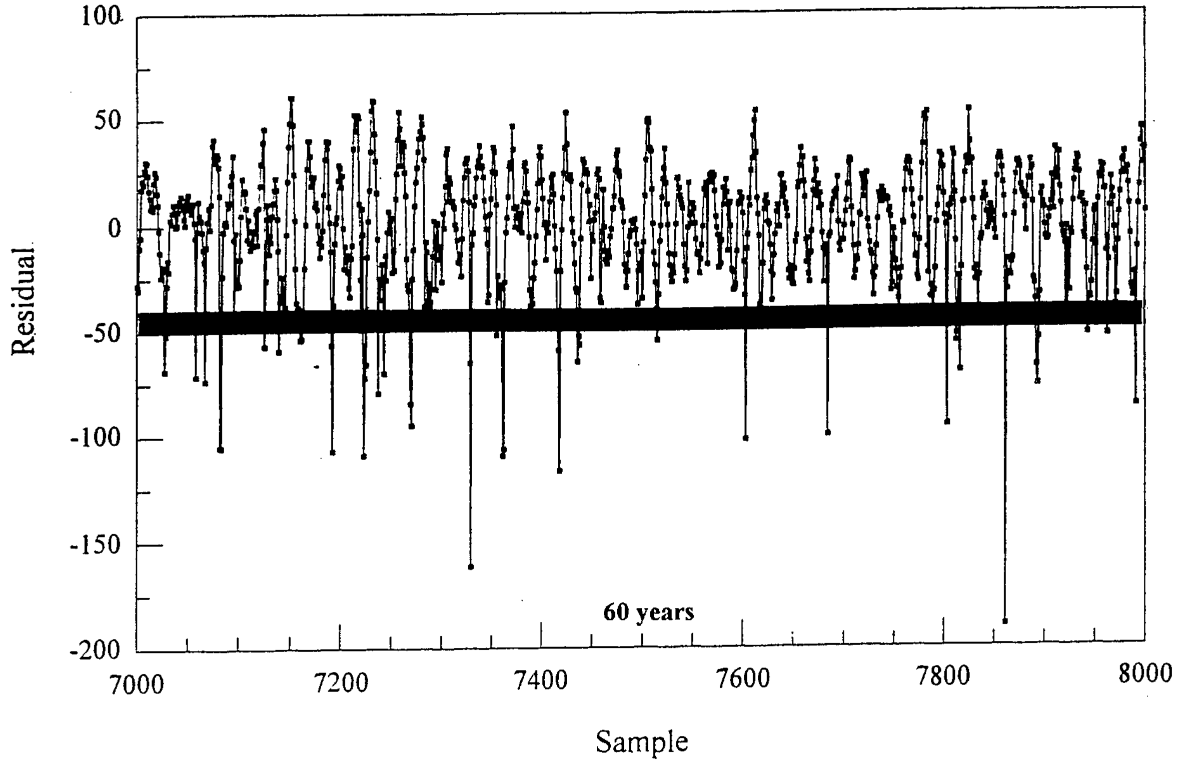


Figure 9. (9.4) Same as Figure 9.1, except the two sections range from data point 6000 – 8000.

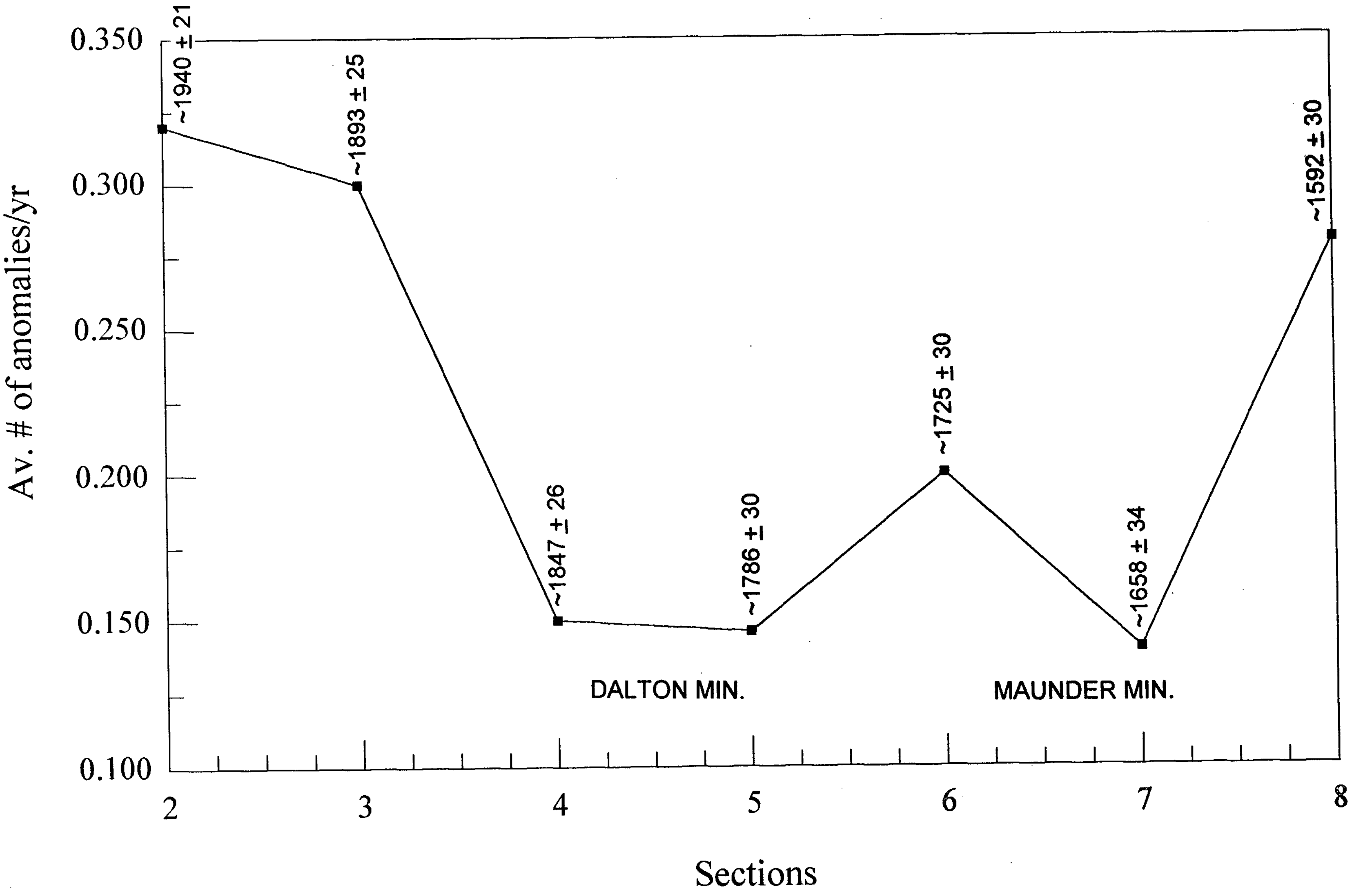


Figure 10. Average number of nitrate anomalies per year per section of core shown in Figure 9.1 to 9.4.

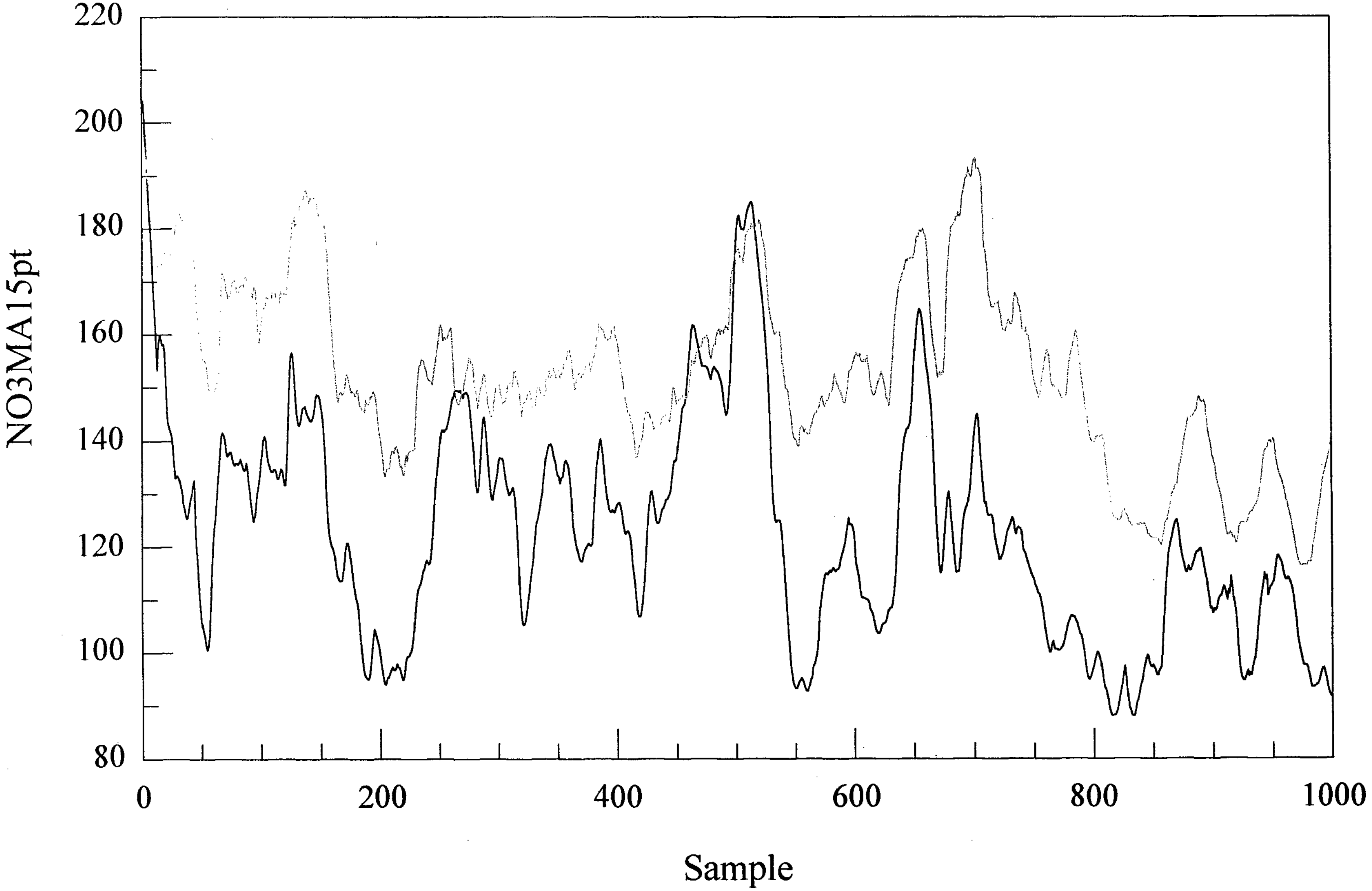


Figure 11. Upper portion of the Greenland ice core showing the trends in nitrate and conductivity, both plotted as a 15 – point moving average.

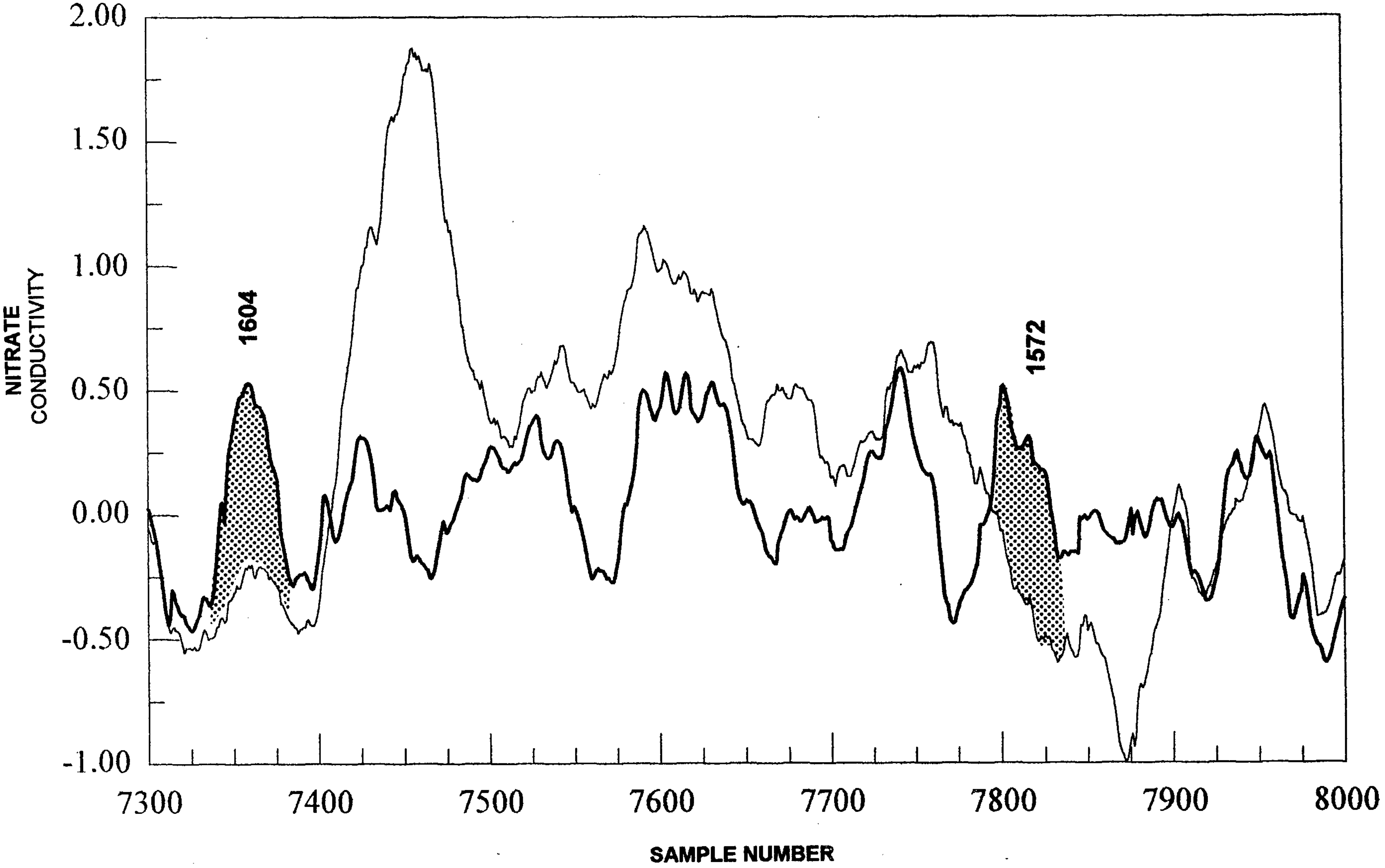


Figure 12. Lower portion of the Greenland ice core showing the trends in nitrate and conductivity, both plotted as a 15 – point moving average. In addition, both sequences have been normalized, clearly showing the deviations from the otherwise similar trend. The nitrate deviations occurring around the time periods of 1604 (SN Kepler) and 1570 (SN Tycho) are indicated by the shaded areas.

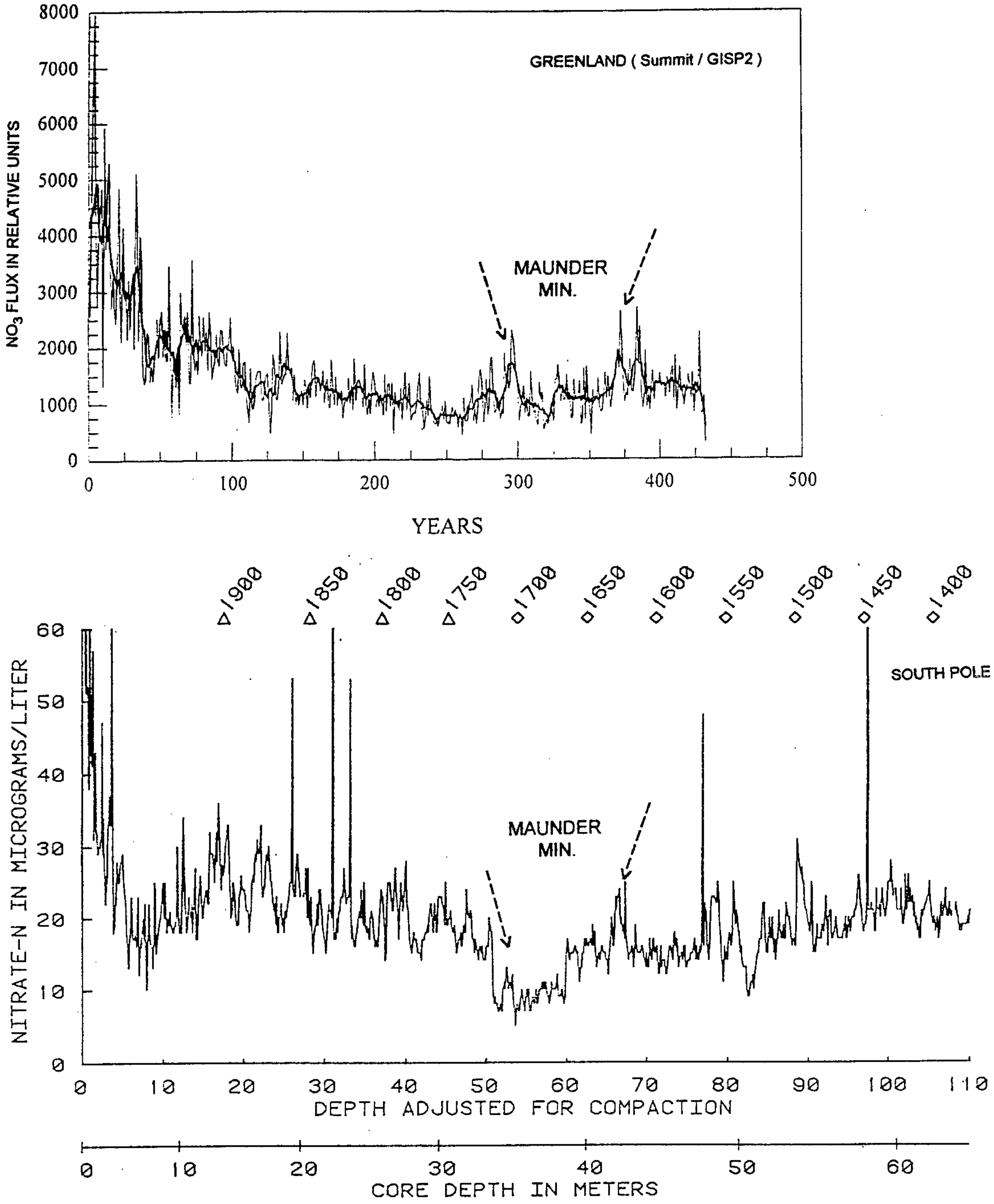
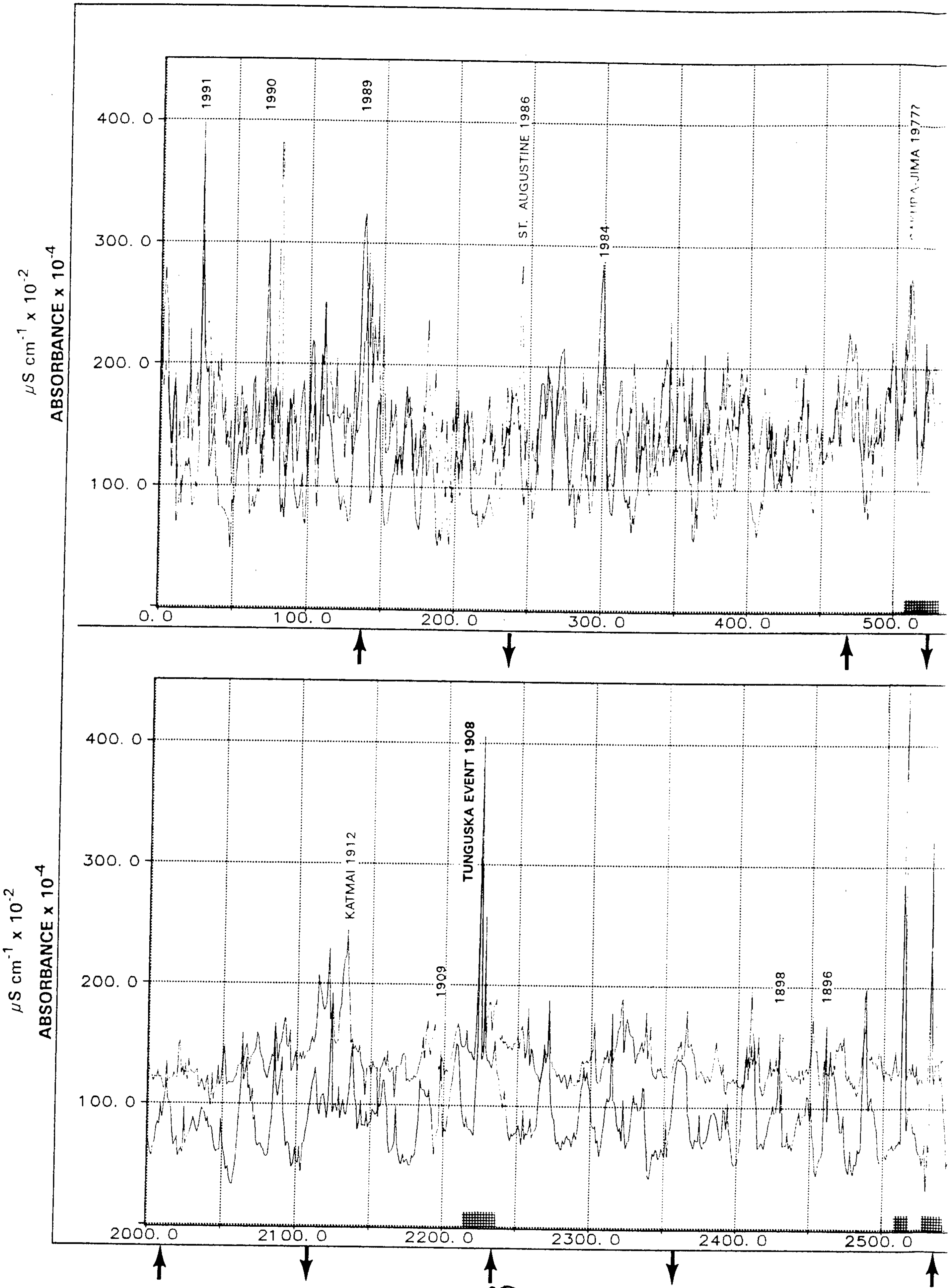


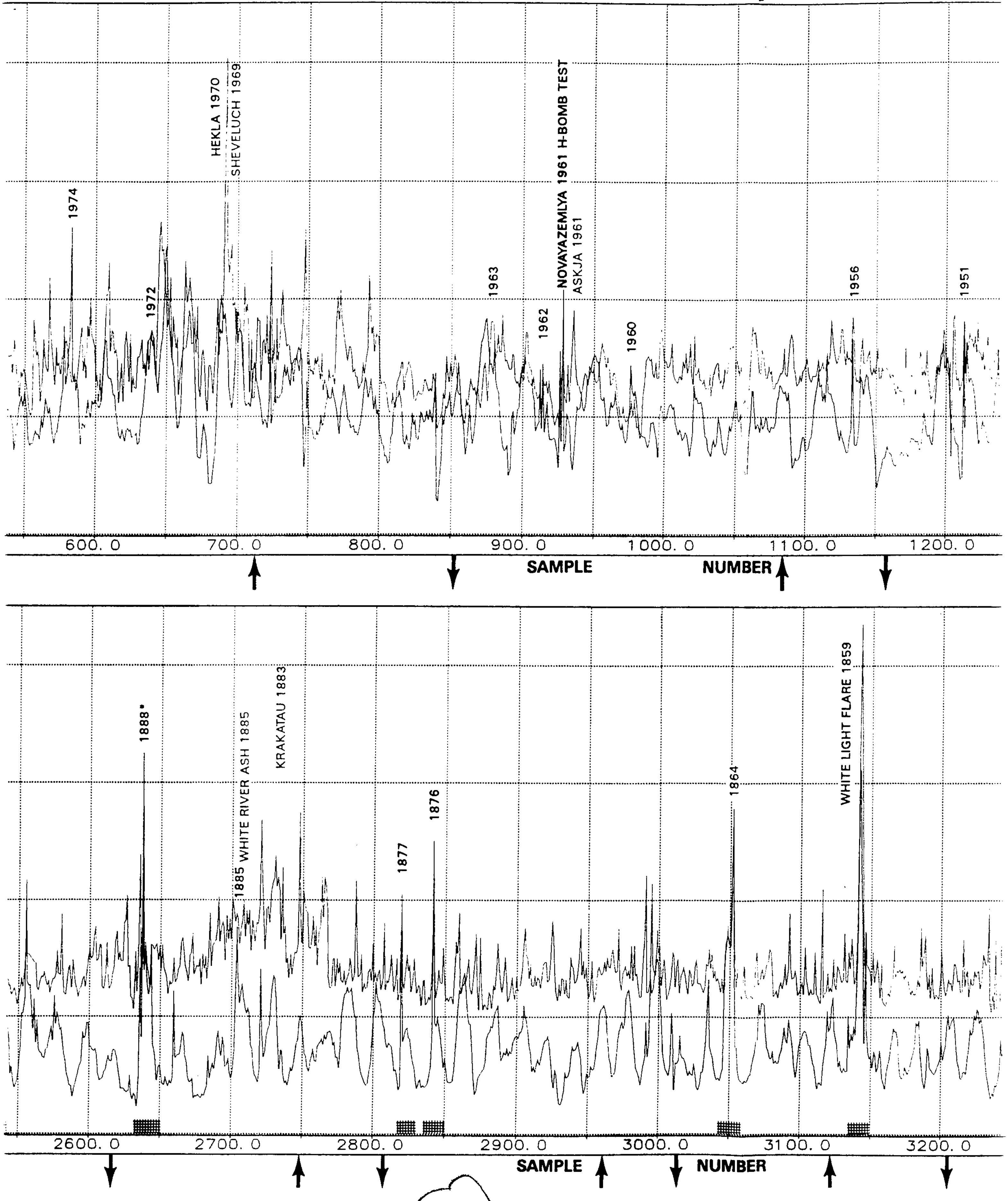
Figure 13. Two nitrate sequences from both polar regions, and both plotted with a similar resolution of about one year, display a similar background signal *representative of the prolonged period of low solar activity, called the Maunder Minimum.*



μS cm⁻¹ x 10⁻²
ABSORBANCE x 10⁻⁴
400. 0
300. 0
200. 0
100. 0
0. 0
100. 0
200. 0
300. 0
400. 0
500. 0
1991
1990
1989
ST. AUGUSTINE 1986
1984
SAKURA-JIMA 1977?
μS cm⁻¹ x 10⁻²
ABSORBANCE x 10⁻⁴
400. 0
300. 0
200. 0
100. 0
2000. 0
2100. 0
2200. 0
2300. 0
2400. 0
2500. 0
KATMAI 1912
1909
TUNGUSKA EVENT 1908
1898
1896

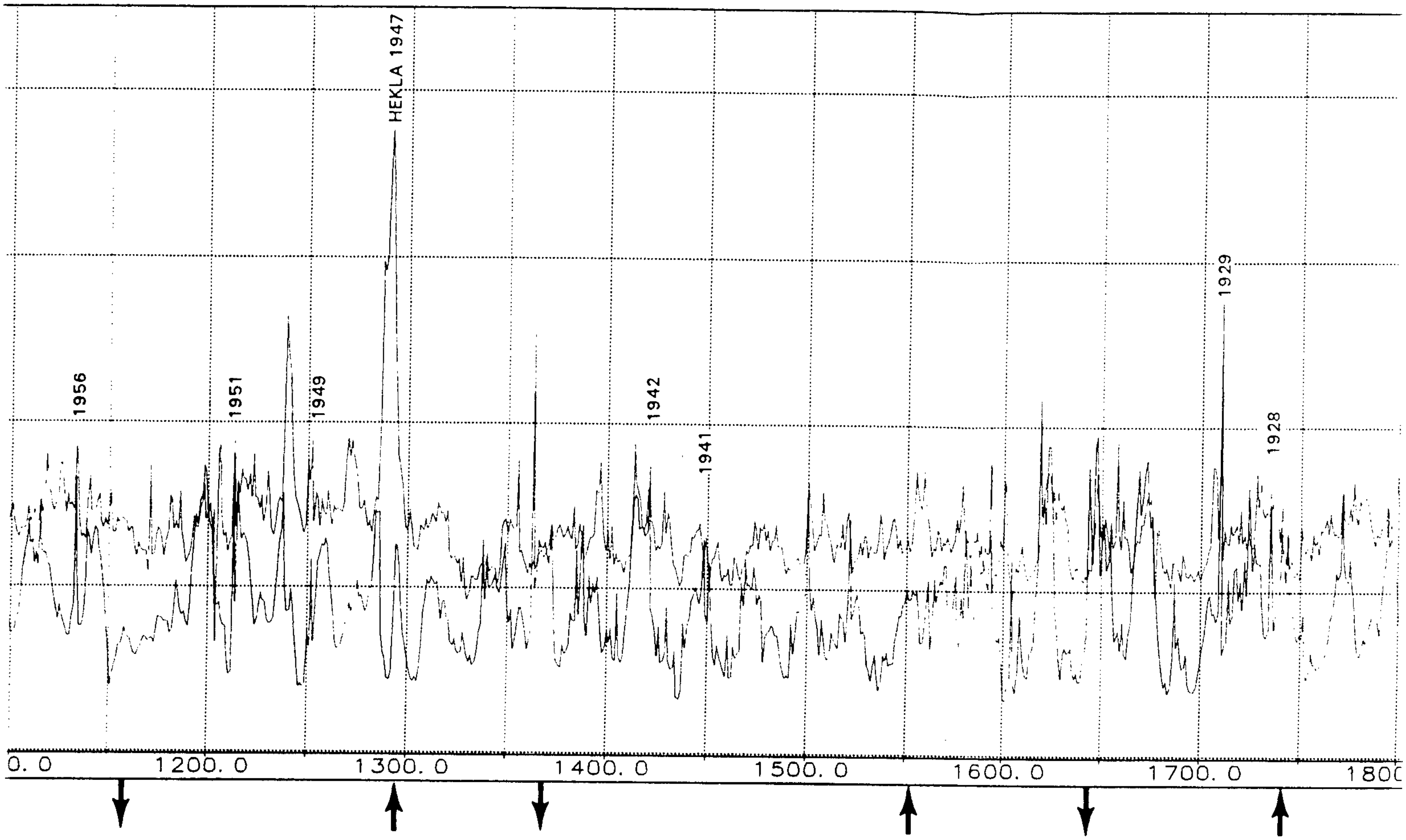
①

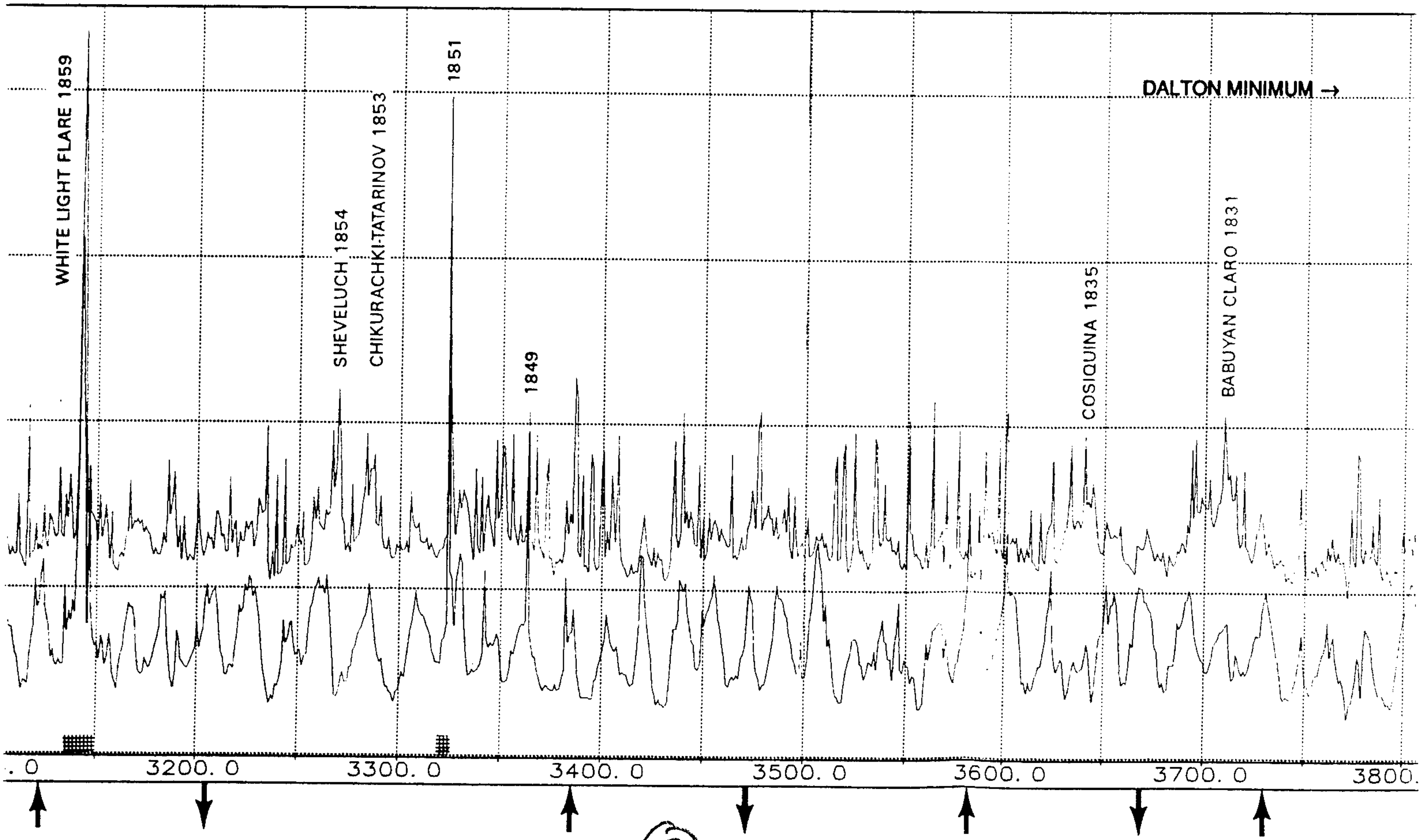
Plate 1a Nitrate and Conductivity Record, GISP2

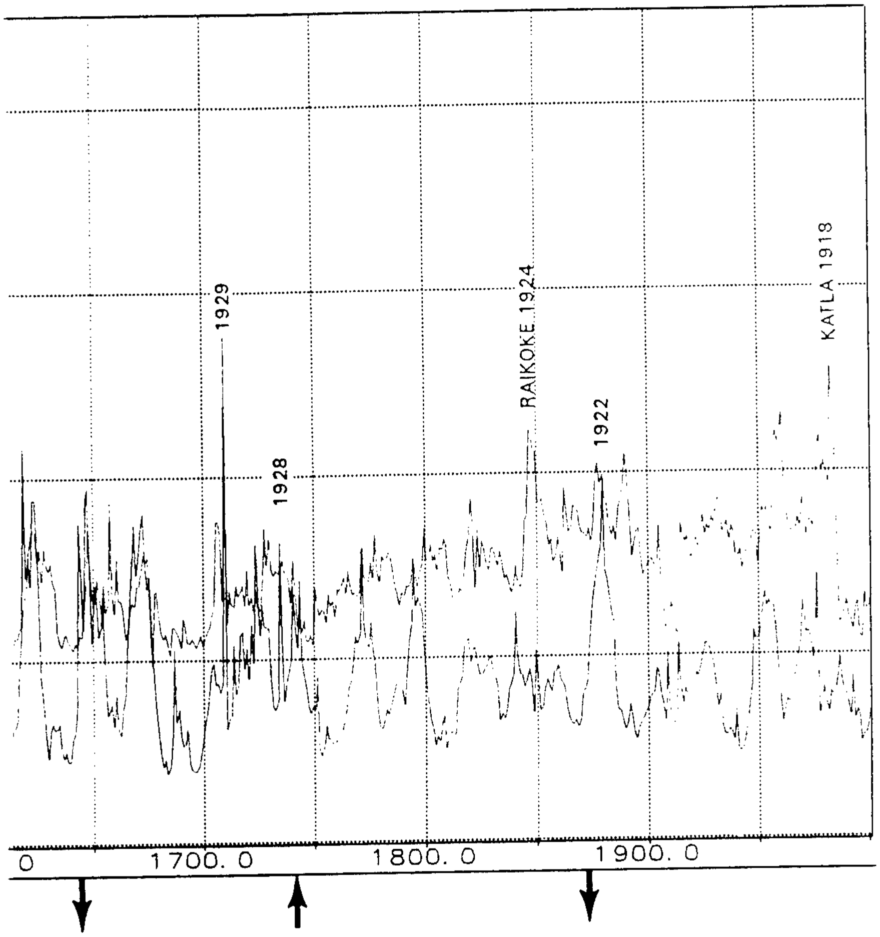


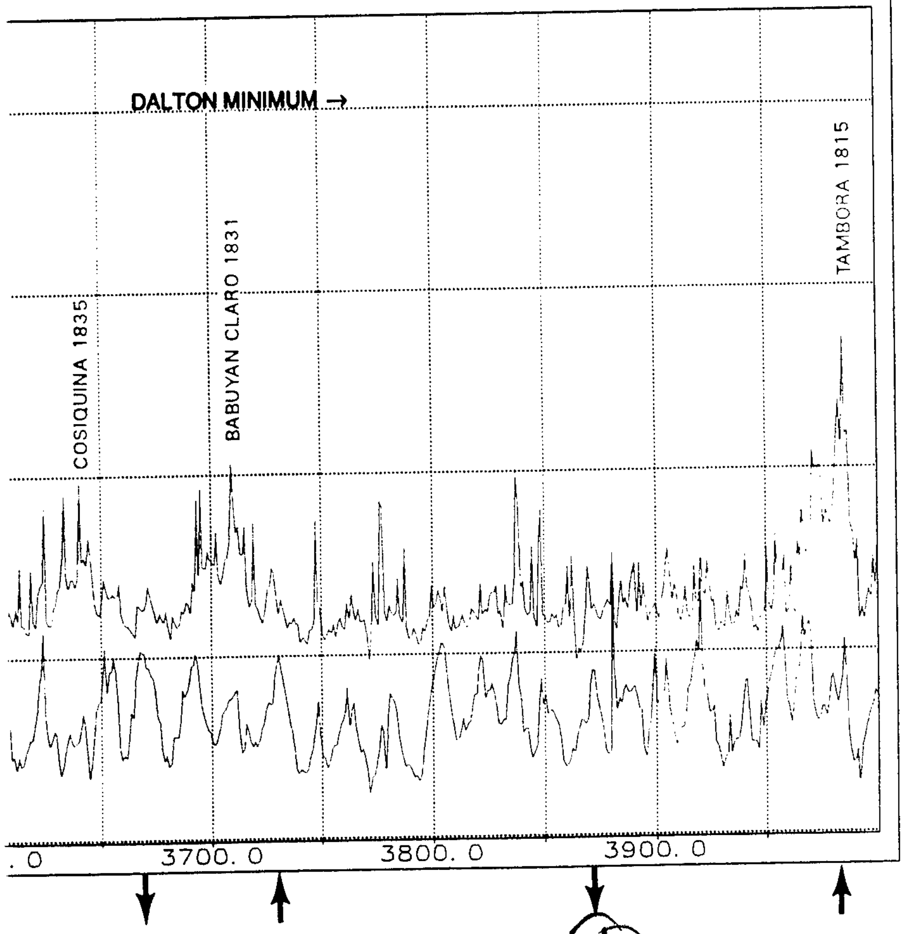
②

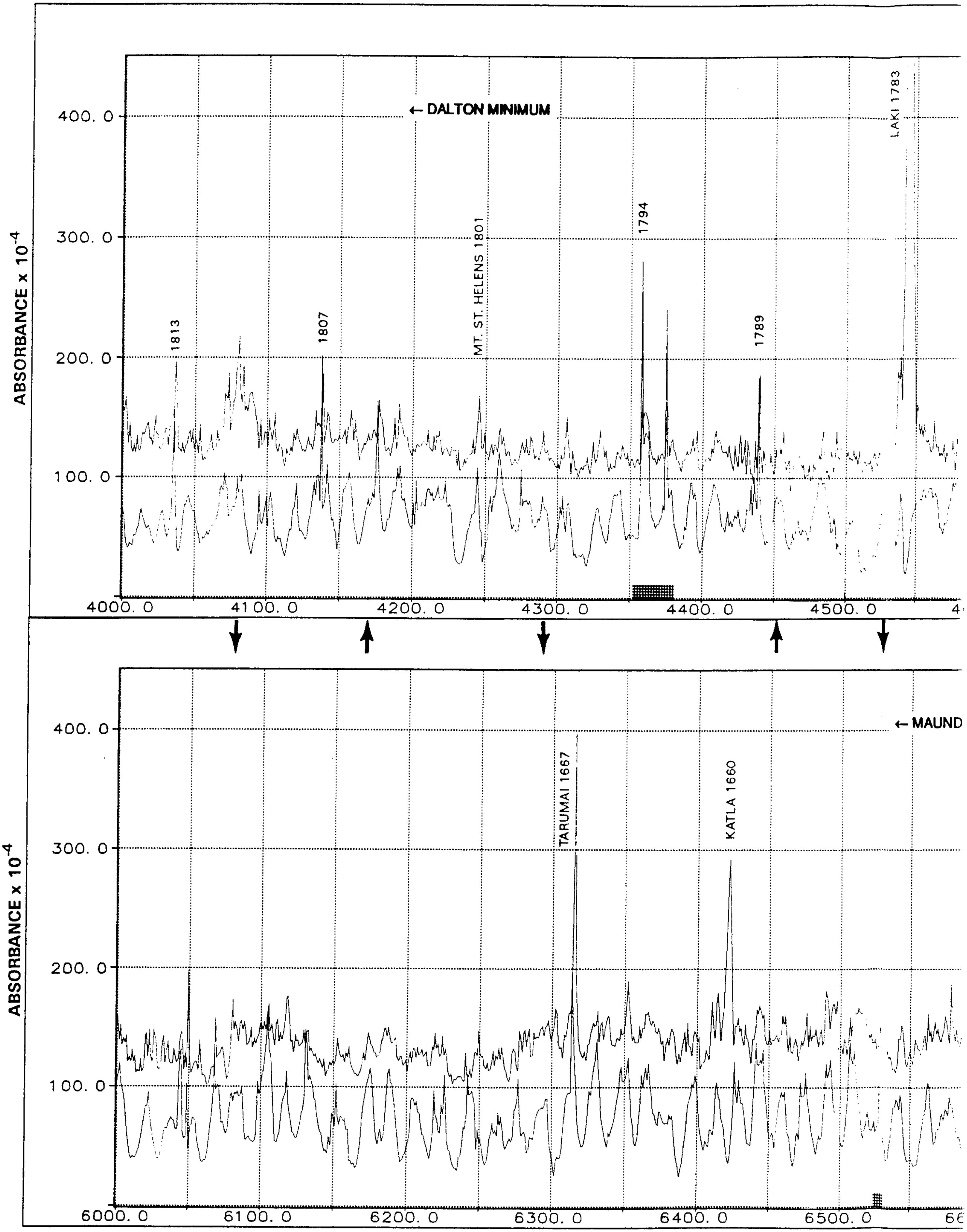
Record, GISP2-H-Part I






1929
1928
RAIKOKE 1924
1922
KATLA 1918
0
1700. 0
1800. 0
1900. 0

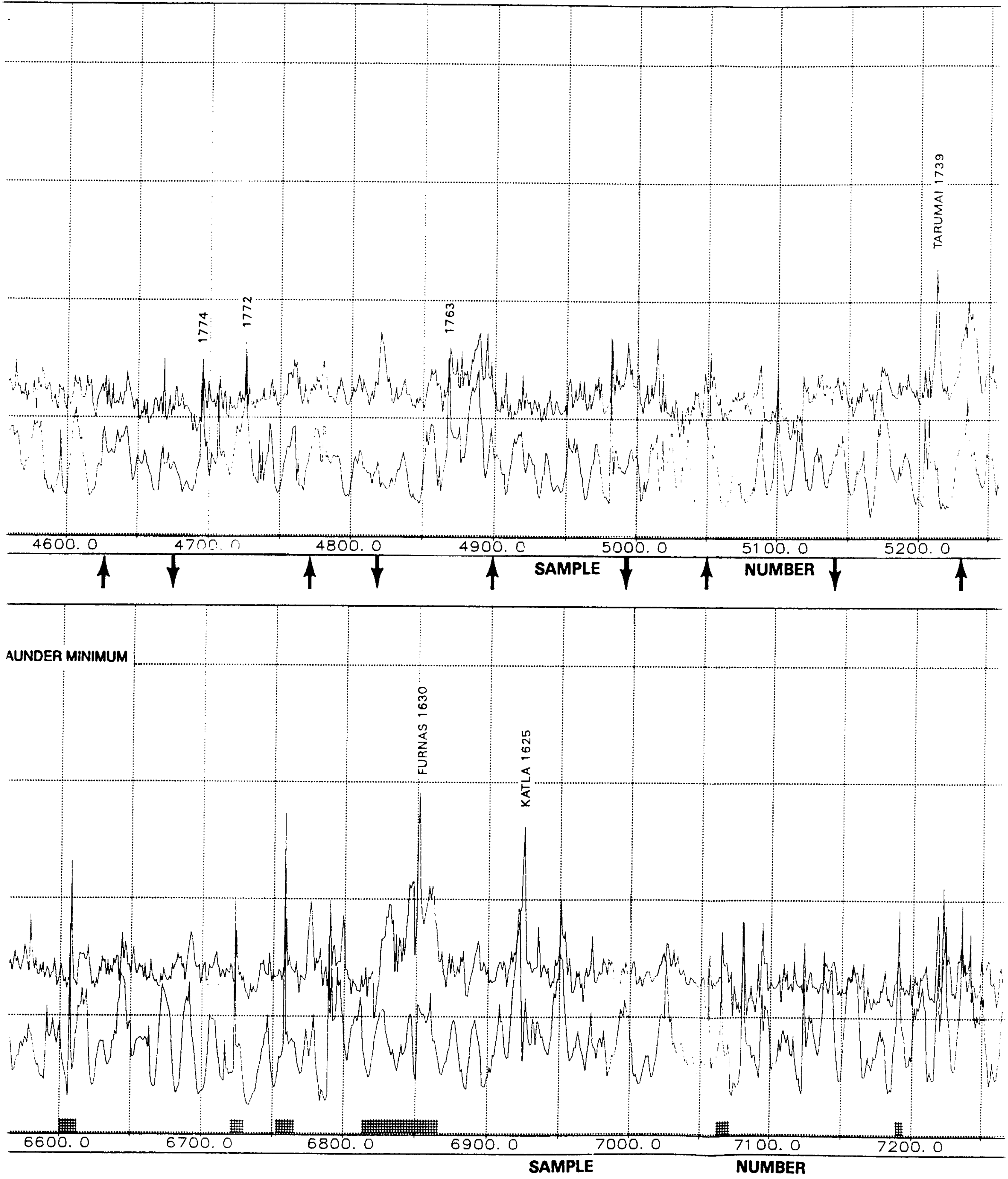

DALTON MINIMUM →
COSIQUINA 1835
BABUYAN CLARO 1831
TAMBORA 1815
. 0
3700. 0
3800. 0
3900. 0



μS cm^{-1} x 10^{-2}
ABSORBANCE x 10^{-4}
400. 0
300. 0
200. 0
100. 0
← DALTON MINIMUM
1813
1807
MT. ST. HELENS 1801
1794
1789
LAKI 1783
4000. 0
4100. 0
4200. 0
4300. 0
4400. 0
4500. 0
μS cm^{-1} x 10^{-2}
ABSORBANCE x 10^{-4}
400. 0
300. 0
200. 0
100. 0
← MAUND
TARUMAI 1667
KATLA 1660
6000. 0
6100. 0
6200. 0
6300. 0
6400. 0
6500. 0

①

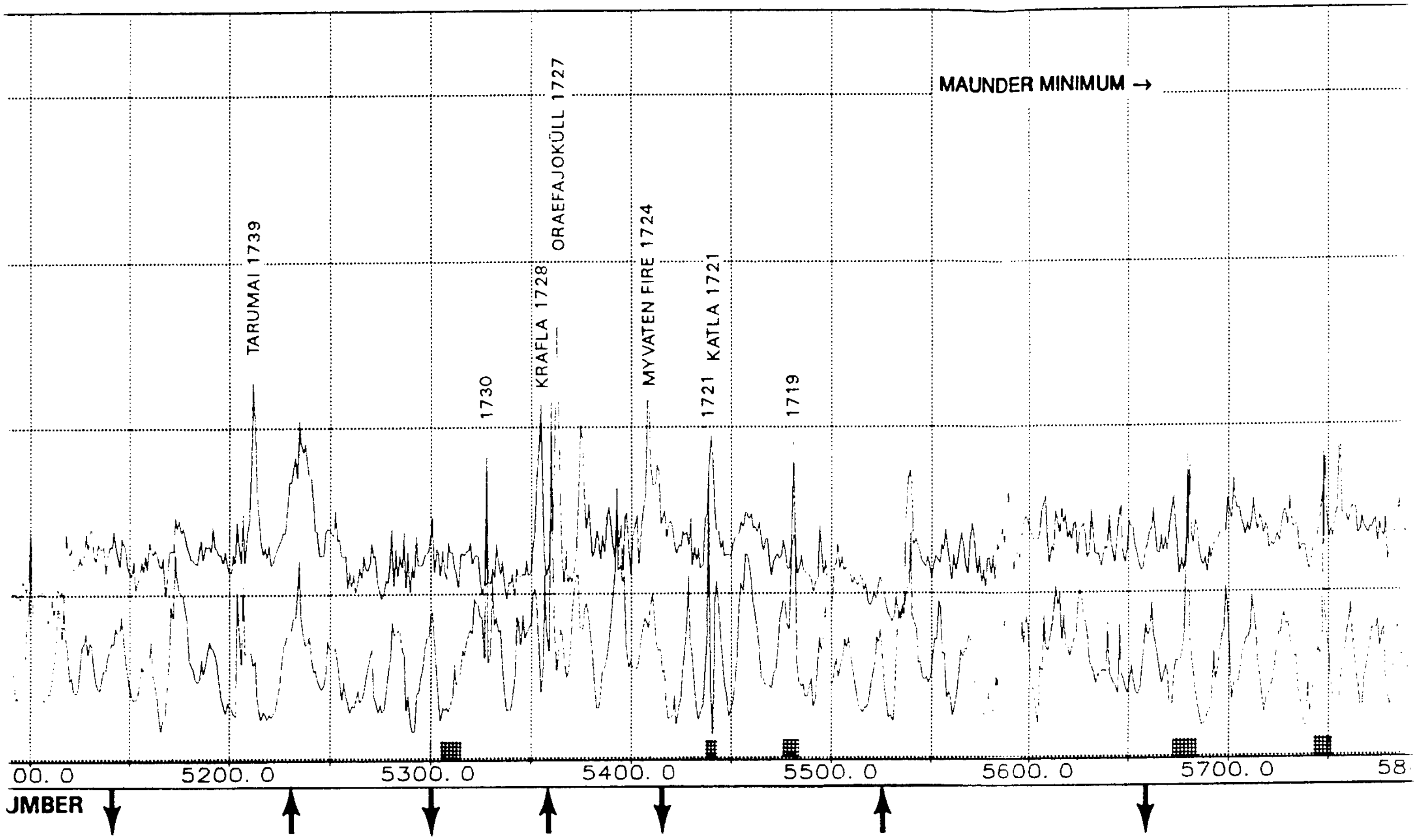
Plate 1b Nitrate and Conductivity Record, GISP2-H

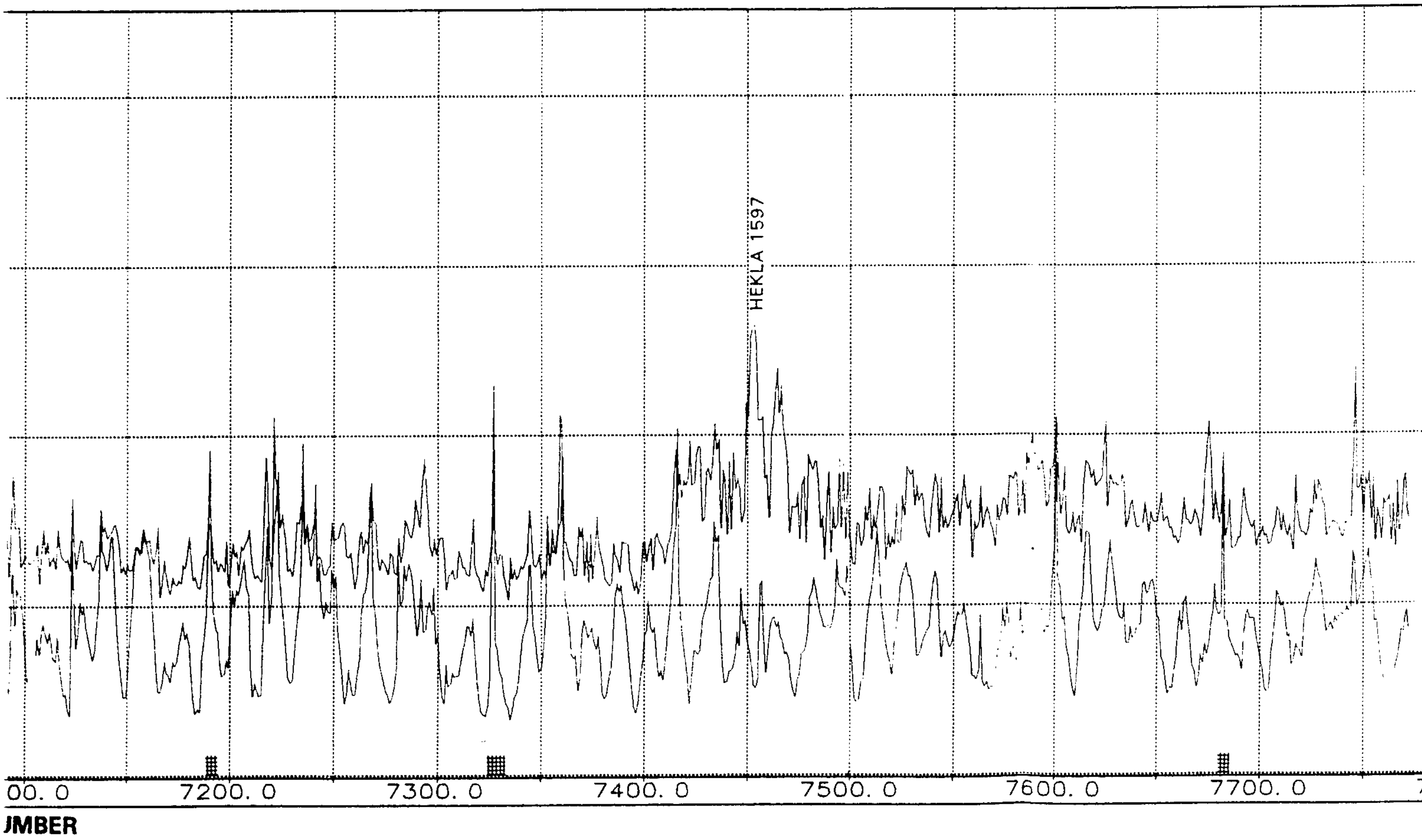


②

ecord, GISP2-H-Part II

I
T

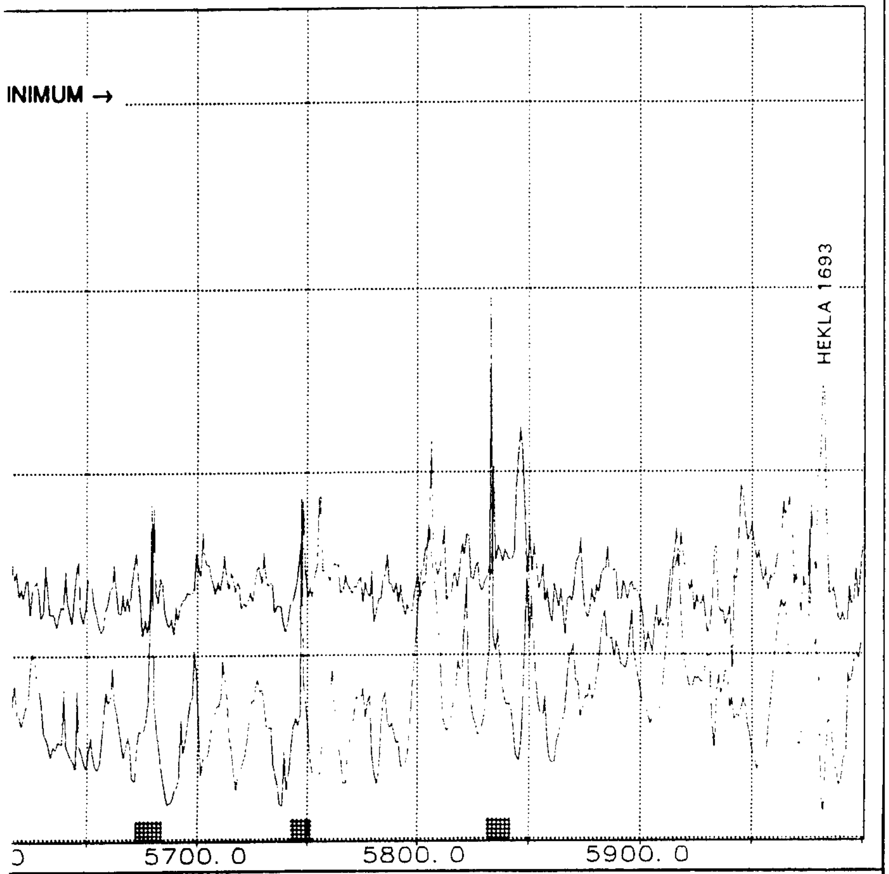


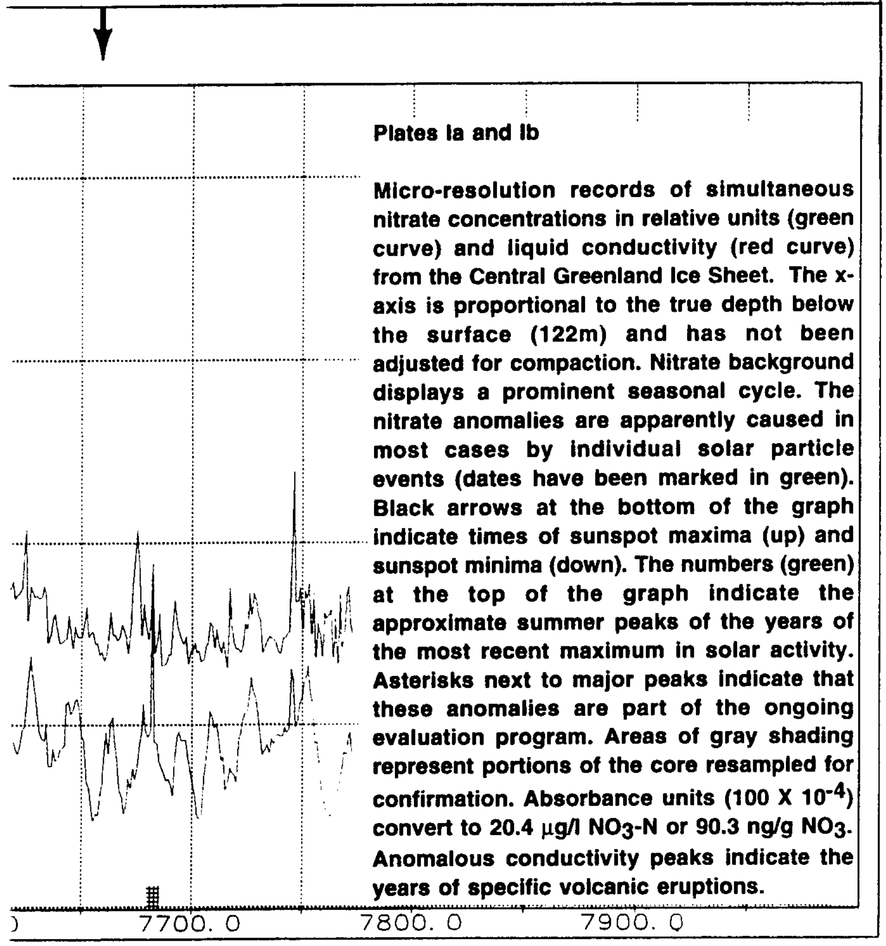


Pl

Mi
nit
cu
fro
ax
th
ad
dis
nit
mo
ev
Bl
inc
su
at
ap
th
As
th
ev
re
co
co
An
ye

③





Plates Ia and Ib

Micro-resolution records of simultaneous nitrate concentrations in relative units (green curve) and liquid conductivity (red curve) from the Central Greenland Ice Sheet. The x-axis is proportional to the true depth below the surface (122m) and has not been adjusted for compaction. Nitrate background displays a prominent seasonal cycle. The nitrate anomalies are apparently caused in most cases by individual solar particle events (dates have been marked in green). Black arrows at the bottom of the graph indicate times of sunspot maxima (up) and sunspot minima (down). The numbers (green) at the top of the graph indicate the approximate summer peaks of the years of the most recent maximum in solar activity. Asterisks next to major peaks indicate that these anomalies are part of the ongoing evaluation program. Areas of gray shading represent portions of the core resampled for confirmation. Absorbance units (100 X 10^{-4}) convert to 20.4 µg/l NO_3-N or 90.3 ng/g NO_3. Anomalous conductivity peaks indicate the years of specific volcanic eruptions.

25th International Cosmic Ray Conference
Contributed Papers, Vol.1, 89-92, 1997

SH 6.2.7

EVIDENCE FOR HISTORICAL SOLAR PROTON EVENTS FROM NO(X) PRECIPITATION IN POLAR ICE CORES

G.A.M. Dreschhoff[1], M.A. Shea[2], D.F. Smart[2], and K.G. McCracken[3]

[1]*Space Technology Center, University of Kansas, Lawrence, Kansas 66045, U.S.A.*
[2]*Space Effects Division, Geophysics Directorate/PL, Hanscom AFB, Bedford, MA 01731, U.S.A.*
[3]*Jellore Technology, Mittagong, NSW, Australia*

ABSTRACT

Evidence has been found in the nitrate concentration in polar ice cores of major solar proton events during the late 19th and early 20th centuries. A comparison made between the nitrate concentration since 1940 with known solar proton events permits the identification of possible events prior to direct solar proton measurements. The initial results of this study identifies major events in 1909 and 1859 plus a period of enhanced solar proton event activity toward the end of the last century.

THE NATURE OF THE NITRATE EVENTS

Enhanced peaks in the nitrate concentration in polar ice cores have been found in time association with major solar proton events. In this paper we extend this association considering nitrate data from polar ice cores from both the southern and northern polar regions. The drilling, sampling and analytical procedures are described by Dreschhoff and Zeller (1990) and Zeller and Dreschhoff (1995). For both locations the nitrate concentrations are sampled about 20 times per year.

At this time, there is no universal agreement regarding the sources of the nitrates that are ultimately stored in the icecore record. Sources include the nitrates transported from lower latitudes in the troposphere with source regions ranging from sea surface release, to stratosphere to troposphere exchange. The maximum in the summer also will be affected by sublimation (thereby concentrating the nitrate) and reduced precipitation. The observed concentration starts to decline in the vicinity of the autumnal equinox, as the result of enhanced precipitation and reduced sublimation. The minimum is reached in late midwinter, and the concentration commences to rise thereafter. This annual behavior of the nitrate background is well defined for 80% of the full length of the Greenland icecore, representing the time interval from 1576 to 1992.

Another source of the nitrate is in the polar stratosphere which is transported downwards by the polar vortex (Gruzdev and Sitnov, 1992). This transport is most efficient in winter and early spring, especially when there is a well established polar vortex; however, the extent to which it is effective in the presence of enhanced photo-ionization in summer is not well known. A portion of this stratospheric source has been explained in terms of ionization by electrons released from the radiation belts in magnetic storms and by ionization by galactic and solar cosmic radiation.

In this paper we examine discrete nitrate events in the icecore record estimating the time of deposition of each snow/ice sample as precisely as possible. Using well defined deposits in the ice due to known geological events and by counting the annual nitrate cycles, the time of deposition of the snow can be identified to within one year for the majority of the Greenland icecore. In about 80% of the record, the phase of the annual variation allows the commencement of an anomaly to be determined to within ± 1 month. After eliminating anomalies in the nitrate record that are possibly of geological origin there remains a class of impulsive anomalies, often of amplitude greatly in excess of the annual variation, and usually of duration of 3 months or less. For this study, we have concentrated on major nitrate anomalies.

COMPARISON WITH THE COSMIC RAY RECORD

The magnitude of any nitrate signal is dependent upon local climate conditions in the regions where the individual cores were obtained (Dreschhoff and Zeller, 1990; Zeller and Dreschhoff, 1995). In the Antarctic regions the precipitation of nitrate is most efficient during the period of the meteorological vortex (approximately the Antarctic winter). For reasons such as these it is important to utilize ice cores from both polar regions to identify time associations with geophysical phenomena. In addition, individual peaks should be evident in two separate cores drilled from the approximate same location.

The top part of Figure 1 presents the nitrate data from Greenland from 1855 to 1992. The bottom part of Figure 1 presents similar data obtained from Antarctica from 1905 to 1990. In both samples there is a coincidence between the major impulsive nitrate events and known solar-terrestrial events.

The Antarctica core reveals high nitrate concentrations in the most efficient Antarctic polar NO_x collection season during 1972, 1959, and 1946. Three major solar proton fluence events occurred those same years in August 1972, July 1959 and July 1946 (Shea and Smart, 1996). The impulsive peaks in 1928 (identified in two core samples) and 1909 have been tentatively associated with exceptional solar/geomagnetic activity during July and September of those years respectively (Shea, et al., 1993).

The core from Greenland shows spikes in the nitrate records for 1991, 1990, and 1989. These are periods of major solar proton events in the 22nd solar cycle (Shea and Smart, 1994). Another spike is evident in 1984 in time association with another major event (Shea and Smart, 1990).

SEARCH FOR EVENTS DURING MINIMUM SOLAR ACTIVITY

To test the solar event association further, we have analyzed the nitrate record for the period of the Maunder minimum, 1645-1715. We can only identify two impulsive nitrate events, (which occur near the end of Maunder minimum), during the duration of the minimum. The probability of occurrence in that interval was therefore 0.032 per annum, to be compared with 0.089 for whole data record which supports the view that the impulsive solar events were less frequent during the Maunder minimum. In particular we note that there were no nitrate events at all in the 51-year period, 1650-1701. There is no other time period of this length in the nitrate record that is totally devoid of nitrate impulsive events. Thus the prolonged absence of impulsive events in the nitrate record is uniquely associated with the Maunder minimum in sunspot activity.

EVENTS PRIOR TO DIRECT SOLAR PROTON MEASUREMENTS

With the likelihood that the nitrate records can be used to identify major solar fluence events, we now consider the period prior to 1942. One of the largest impulsive events in the Greenland nitrate record is dated to be in the latter part of 1859, in good time coincidence with the observed white light flare on 1 September 1859 (Carrington, 1860). This flare was followed within a day by a major geomagnetic storm. At the present time we have not examined an Antarctic core prior to 1905; therefore it is not possible to see if this event can be identified in the nitrate measurements from Antarctica.

The value of nitrate determinations from both polar regions can be demonstrated by a careful inspection of the plots shown in Figure 1. Since local meteorological conditions play such an important role in nitrate precipitation, nitrate peaks from an Antarctic core may not correspond to the same amplitude nitrate peaks in an Arctic core. Thus cores from both hemispheres are essential to identify the peaks not only from possible proton fluence events but also from other phenomena.

The August 1972 solar proton events appear as a major peak in the Antarctic core, but only a minor peak in the Arctic core. The peak in 1928, tentatively associated with an event in July 1928, is evident in both the Arctic and Antarctic cores. The peak in 1909 from the Antarctic core tentatively associated in a major solar-terrestrial event in September 1909 is not as evident in the Arctic core. The Arctic core has a pronounced peak in 1908 which has been associated with the

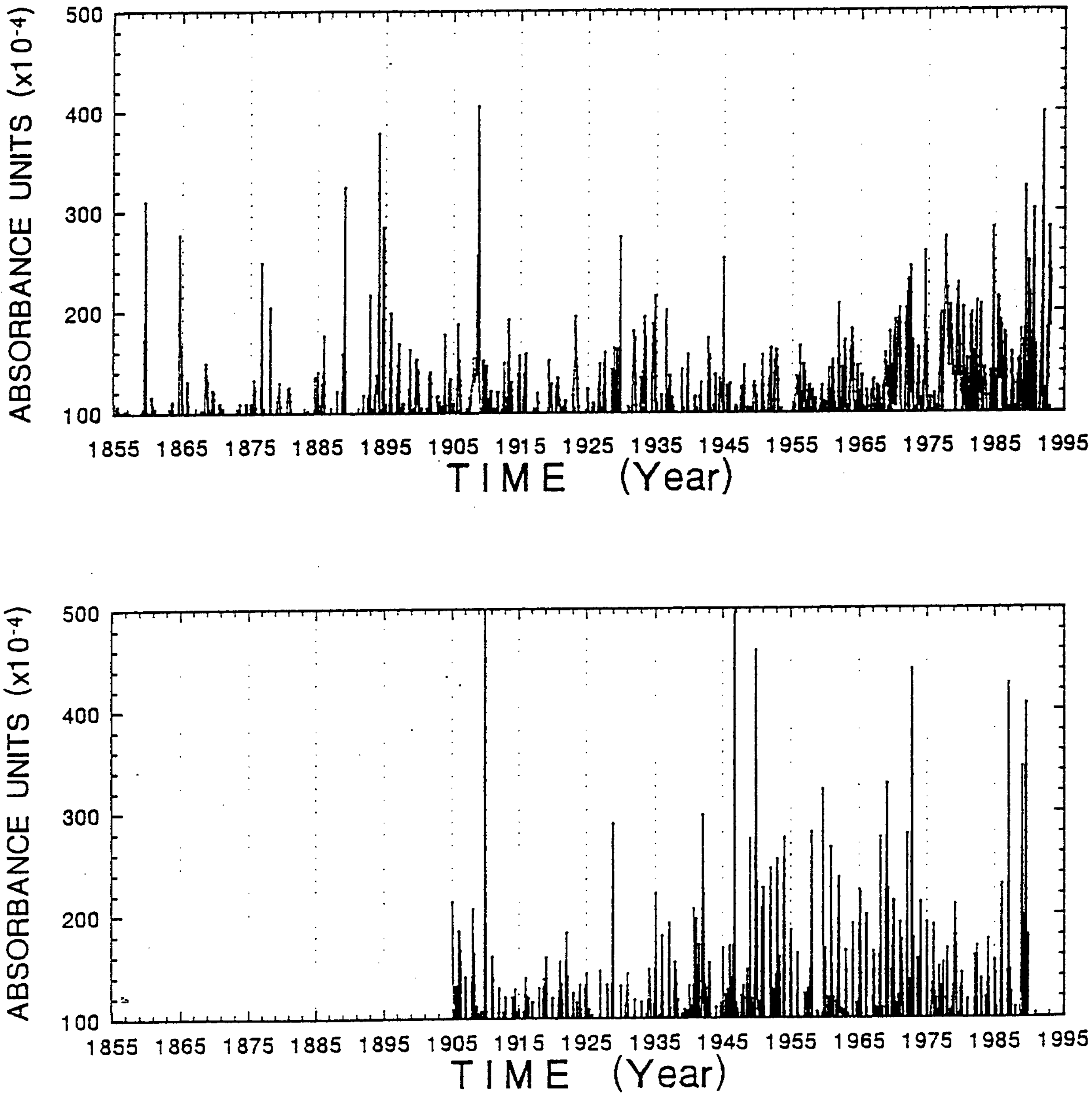


Figure 1. Nitrate concentrations in relative units (UV absorbance) in two ice cores from both polar regions, Greenland (top) and Antarctica (bottom). The background has been cut-off at the approximate series mean (100 x 10^{-1}). Some primary nitrate peaks have been associated with ionization events from solar proton events.

Tunguska meteorite. One of the two smaller peaks with an absorbance of about 140 x 10^{-4} units may be associated with the September 1909 geomagnetic disturbance. Meteorological conditions in the Arctic are not as distinct and straightforward as in the Antarctic, therefore considerable care must be taken in identifying the peaks in the Arctic core. In spite of these problems, we feel that the major peaks in either core, if not in time association with a known volcanic or other geophysical event, might be associated with a major solar proton fluence event.

Of particular interest are the eight peaks with an absorbance greater than 200 x 10^{-4} units during the last half of the 19th century. Six of these peaks occur in the period between 1875 to 1895 - i.e., from the decreasing portion of the 11th solar cycle to just after the maximum in the 13th solar cycle. From these initial evaluations it would appear that the last part of the 19th century may have been as active as the last part of the 20th century, although the sunspot numbers during that period were not comparable with the sunspot numbers of the 22nd solar cycle.

Additional ice cores from Antarctica are now available for dating. Hopefully they will encompass the entire period presently covered by the Arctic ice core and thus can be used for correlative analyses.

SUMMARY

We have shown that nitrate concentrations in polar ice cores can be used to identify major solar proton fluence events. The concentrations in the Arctic ice core indicates that there was a period with major solar proton events toward the end of the last century.

ACKNOWLEDGMENTS

The work by GAMD was supported by the U.S. Air Force (Grant AFOSR F49620-95-0003). We wish also to extend our thanks to the Office of Polar Programs of the U.S. National Science Foundation for their contribution of logistic facilities to us in Greenland and to extend our appreciation for the support received at the U.S. National Ice Core Laboratory.

REFERENCES

Carrington, R.C., Description of a Singular Appearance Seen in the Sun on September 1, 1859, *Mon. Not. Royal Astron. Soc.*, ***20***, 13-15, 1860.

Dreschhoff, G.A.M., and E.J. Zeller, Evidence of Individual Solar Proton Events in Antarctic Snow, *Solar Phys.*, ***127***, 337-346, 1990.

Gruzdev, A.N., and S.A. Sitnov, The Annual Variation of Tropospheric Ozone and Estimates of Tropospheric-Stratospheric Exchange in the Arctic and Antarctica Based on Ozone Sounding Data, *Isvestiya, Atmos. and Oceanic Phys.*, ***28***, 9, 707-714, 1992.

Shea, M.A., and D.F. Smart, A Summary of Major Solar Proton Events, *Solar Phys.*, ***127***, 297-320, 1990.

Shea, M.A., and D.F. Smart, Significant Proton Events of Solar Cycle 22 and a Comparison with Events of Previous Solar Cycles, *Adv. Space Res.*, ***14***, (10)631-(10)-638, 1994.

Shea, M.A., and D.F. Smart, Solar Proton Fluxes as a Function of the Observation Location with Respect to the Parent Solar Activity, *Adv. Space Res.*, *17*, (4/5)225-(4/5)-228, 1996.

Shea, M.A., D.F. Smart, G.A.M. Dreschhoff, and E.J. Zeller, The Flux and Fluence of Major Solar Proton Events and their Record in Antarctic Snow, *23rd International Cosmic Ray Conference, Contributed Papers*, *3*, 846-849, 1993.

Zeller, E.J., and G.A.M. Dreschhoff, Anomalous Nitrate Concentrations in Polar Ice Cores - do they Result from Solar Particle Injections in the Polar Atmosphere?, *Geophys. Res. Lett.*, ***22***, 2521-2524, 1995.