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Abstract. Recent studies of the solar-terrestrial environment for the past 500 years have necessitated the use of a variety of historical databases: nitrates in ice cores, knowledge of large volcanic eruptions, sunspot numbers, mid-latitude aurora and geomagnetic records. The nitrate data are being used to identify large solar proton fluence events. The volcanic record helps to provide time markers for the ice core. The records of major geomagnetic storms and mid-latitude aurora have been used for additional identification. We also know that the Earth's magnetic field is evolving with a present rapid decrease in magnitude. In addition the wandering magnetic pole must be considered in ascertaining what was "mid latitude" in historic times versus "mid latitude" in 2000. We illustrate how these databases are being used in recent studies of historic solar proton events.

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THE USE OF GEOPHYSICAL DATA IN STUDIES OF THE HISTORICAL SOLAR-TERRESTRIAL ENVIRONMENT

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Abstract. Recent studies of the solar-terrestrial environment for the past 500 years have necessitated the use of a variety of historical databases: nitrates in ice cores, knowledge of large volcanic eruptions, sunspot numbers, mid-latitude aurora and geomagnetic records. The nitrate data are being used to identify large solar proton fluence events. The volcanic record helps to provide time markers for the ice core. The records of major geomagnetic storms and mid-latitude aurora have been used for additional identification. We also know that the Earth's magnetic field is evolving with a present rapid decrease in magnitude. In addition the wandering magnetic pole must be considered in ascertaining what was "mid latitude" in historic times versus "mid latitude" in 2000. We illustrate how these databases are being used in recent studies of historic solar proton events.

1. Introduction

Solar-geophysical databases are frequently used in the analyses of solar-terrestrial phenomena. Some of the more commonly used databases include interplanetary plasma data (e.g. solar wind and interplanetary magnetic field), solar particles, cosmic radiation, solar activity (e.g. solar flares, coronal mass ejections, coronal green line, disappearing filaments, solar radio bursts, sunspot numbers), and geomagnetic variations (e.g. magnetometer recordings and derived indices such as *Kp*, *aa*, and *Dst*). These data are typically used to obtain a comprehensive picture of the time period being studied, but most of these data are limited to the past century.

Over the past decade there has been increased interest in the subject of "space weather" – an understanding of what and how various solar-terrestrial phenomena can affect the near-earth space environment. In addition to improving our basic understanding of these processes, there is the underlying desire to be able to predict the space environment similar to the way meteorologists predict terrestrial weather. While meteorological forecasting has greatly improved over the past half century, space weather forecasting is in its infancy.

One of the concerns with space weather forecasting is related to the extremes of specific phenomena such as solar proton events or geomagnetic disturbances. The question of "How large can it be?" or "How long will it last?" are questions that need to be addressed. Besides improving our basic understanding of these events, there is the practical matter that many technological systems upon which we now rely, can be adversely affected by unexpected or unusual solar-terrestrial events.

For these reasons scientists have been delving into historic solar, geophysical and climatic records to better understand the solar-terrestrial climate over the past several millennia. To gain an insight into time periods in the distant past, it has been necessary to utilize some rather unexpected and unusual databases in the quest to understand the historical space and meteorological climate.

2. Solar Proton Events in Polar Ice

Large solar proton events can seriously affect space operations such as single event upsets in electronic circuits, solar cell degradation, and even complete failure of some spacecraft. Major geomagnetic disturbances frequently follow large solar proton events, typically within 20–30 h of the onset of a fast coronal mass ejection and/or significant solar flare, and the additional energy transferred through the magnetosphere can affect communications, navigation and satellite drag. The induced electric currents from these geomagnetic disturbances can also affect electrical power grids and oil pipeline operations (Thompson, *et al.*, 1990; Hruska *et al.*, 1993; Heckman *et al.*, 1997; Shea and Smart, 1998). We now know that major solar activity near the central meridian of the Sun (as viewed from the Earth) gives rise to the largest solar proton fluence events (Shea and Smart, 1996; Smart and Shea, 2003). Energetic particles are continually accelerated by fast coronal mass ejections as the fast interplanetary shock travels from the sun to the Earth. If the interplanetary magnetic field has a southward component at the time of the shock arrival at Earth, a major geomagnetic storm is likely to occur.

Our knowledge of solar proton events is relatively limited. Ionization chambers have measured very high-energy (>4 GeV) solar proton events since 1935. Two decades later, high latitude neutron monitors started recording those events with protons >500 MeV. At the same time ionospheric perturbations and riometer measurements were used as a proxy for solar proton events. From the mid 1960s we have an almost continuous record of proton events measured by a variety of space-borne detectors (Shea and Smart, 1990).

Just as ionospheric perturbations and riometer measurements were used as a proxy for 10 MeV solar proton events during the period 1955–1965 (Švestka and Simon, 1975), impulsive nitrate enhancements in polar ice can be used as a proxy for large solar proton events in the distant past (McCracken *et al.*, 2001a, b). When analyzing the nitrate measurements from an ice core drilled at Windless Bight, Antactica, in the Antarctic summer of 1988/1989, Dreschhoff and Zeller (1990) and Dreschhoff *et al.* (1993) noted unusual impulsive spikes in the nitrate concentrations. They tentatively identified the years of the spikes as shown in Figure 1. The initial verification that these were years in which there were large solar proton events was made by using a variety of solar-terrestrial-geophysical databases as listed in Table I. The three most recent major spikes were associated with the historic and exceptional solar proton events of August 1972, July 1959 and July

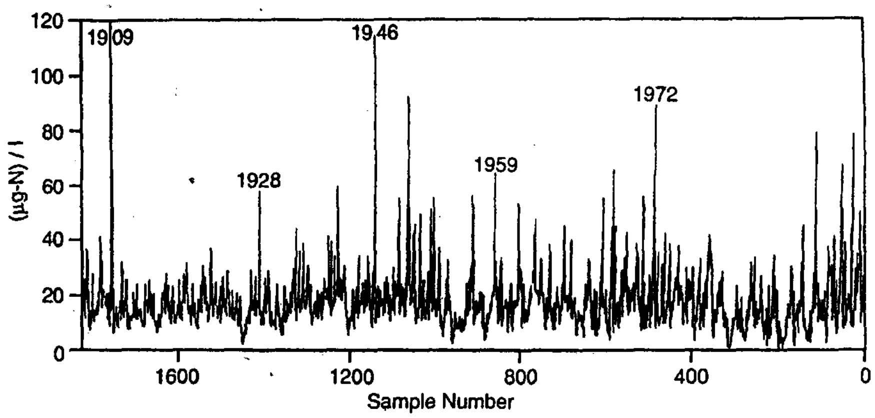

Figure 1. Measurements of nitrate concentration from an ice core drilled at Windless Bight, Antarctica. The years of the highest nitrate increases are labeled. The x-axis represents sample numbers; the y-axis the nitrate concentration in micrograms of nitrate per liter.

1946. Using the geomagnetic AA* value[1] (Allen, 1982; National Geophysical Data Center, 2004) of 325 on 7 and 8 July together with sunspot drawings of a massive region just east of central meridian on 7 July, Shea, Smart, and Dreschhoff (1999) identified the probable event that contributed to the 1928 nitrate increase. For the 1909 enhancement, these same authors identified an event on 24 September 1909 as a probable proton event. A solar flare was observed on 24 September 1909 located at 8°W with a subsequent major geomagnetic storm having an AA* value of 333 on 25–26 September. Note that the further back in time, the less data are available for correlative analyses.

Based upon these initial and promising results a 125.6-meter core (named GISP-H) was drilled at Summit, Greenland in 1992. Dating of this core established that the precipitation was deposited in the years between 1561 and 1992. The initial analysis resulted in the identification of 125 impulsive nitrate enhancements in the ice core for the period 1561–1950. Next the excess nitrate deposition for each impulsive increase in the ice core between 1950–1989 was calibrated to the solar proton fluence measured by spacecraft and ground-based detectors during the same period. Finally, using the derived calibration between nitrate concentration and solar proton events, these 125 impulsive nitrate enhancements were determined to have a >30 MeV omni-directional solar proton fluence $> 10^9$ cm^{-2} (McCracken *et al.*, 2001a,b).

In the initial GISP-H core analysis, the core was sliced into 15 mm lengths giving ~18–20 samples per year. A total of 8002 contiguous samples were taken from this 125.6-meter core, and the nitrate concentrations and electrical conductivity in each sample were measured. Since the recent meteorological data acquired in

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[1] The AA* value is derived from running means to determine the most disturbed 24-hour period rather than using a 24-hour period defined by the UT day.

TABLE I

Identification of solar-terrestrial events associated with the impulsive nitrate spikes from the ice core drilled at Windless Bight, Antarctica.

Date (year)	Solar and/or geophysical phenomena	Database used for identification
1972	Sequence of solar flares near central meridian	Solar flare reports
	Solar proton event	Spacecraft data
		Cosmic ray data (neutron monitors)
	Geomagnetic storm	Cosmic ray data (neutron monitors) (i.e. Forbush decrease)
		Geomagnetic data
1959	Sequence of solar flares near central meridian	Solar flare reports
	Solar proton event	Cosmic ray data (neutron monitors)
	Geomagnetic storm	Cosmic ray data (neutron monitors) (i.e. Forbush decrease)
		Geomagnetic data
1946	Solar flare near central meridian	Solar flare report
		Short wave fade
	Solar proton event	Cosmic ray data (ionization chambers)
	Geomagnetic storm	Geomagnetic data
1928	Sunspots near central meridian	Sunspot data
	Geomagnetic storm	Geomagnetic data
1909	Solar flare near central meridian	Solar flare observation
	Geomagnetic storm	Geomagnetic data

Central Greenland show an approximate uniform precipitation rate throughout the year for the last decade (Bromwich, Chen, and Cullather, 1999), a uniform annual precipitation rate was assumed to persist throughout the period of the ice core.

2.1. VOLCANO RECORDS FOR ICE CORE DATING

A problem in analyzing ice cores is the determination of the date during which the snow layer was deposited. It is well known that nitrates are sequested in polar ice as the result of atmospheric convection from lower latitudes to the polar regions (Jackman, Fleming and Vitt, 2000). Because of sublimation in the Arctic summer period, there is a normal annual pattern with a maximum of nitrates in the summer and a minimum in the winter. This "summer high, winter low" pattern is shown

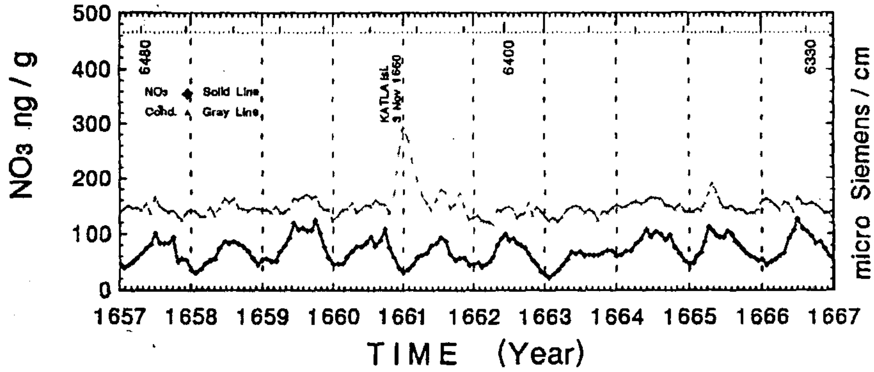


Figure 2. The high-resolution nitrate (nanograms per gram) and electrical conductivity data (μS cm^{-1}) for the interval 1657–1667 illustrating the annual variation in nitrate concentration. The bottom (*dark*) curve represents the nitrate concentration; the upper (*light*) curve represents the conductivity. The increase in conductivity at the end of 1660 is attributed to the eruption of the Katla, Iceland volcano on 3 November 1660. The numbers at the top of the figure are sample numbers.

The dates of major volcanic activity are well known throughout the period covered by the GISP-H ice core. Of particular importance are major volcano eruptions in nearby Iceland. When volcanoes erupt, sulfates are injected in the atmosphere, and the sulfates deposited in the polar snows generate an additional increase in the electrical conductivity in that particular layer of snow. Thus the records of major volcano eruptions were used to identify fiducial dates in the ice cores. Figure 2 illustrates that the large increase in conductivity at the end of 1660 could be associated with the eruption of the Katla, Iceland volcano on 3 November 1660. Dreschhoff and Zeller (1994) describe the dating of the GISP-H ice core.

2.2. GEOMAGNETIC AND AURORAL DATA

McCracken *et al.* (2001b) identified 125 impulsive nitrate enhancements having a >30 MeV omni-directional fluence $>10^9$ cm^{-2} in the GISP-H core. Since seven of the eight large solar proton fluence events between 1954 and 1992 (Shea and Smart, 1990, 1994) were followed by major geomagnetic disturbances, it appeared reasonable to assume that a majority of the proton events identified from the nitrate measurements also would have been followed by a significant geomagnetic disturbance. The data records show that the precipitation of nitrates into the polar ice begins ~4–8 weeks after the initiating proton event; thus a search was made for significant geomagnetic disturbances within 2–3 months prior to the maximum of the impulsive nitrate increase.

Historical records and the work of Cliver, Feynman and Garrett (1990a, b) con-

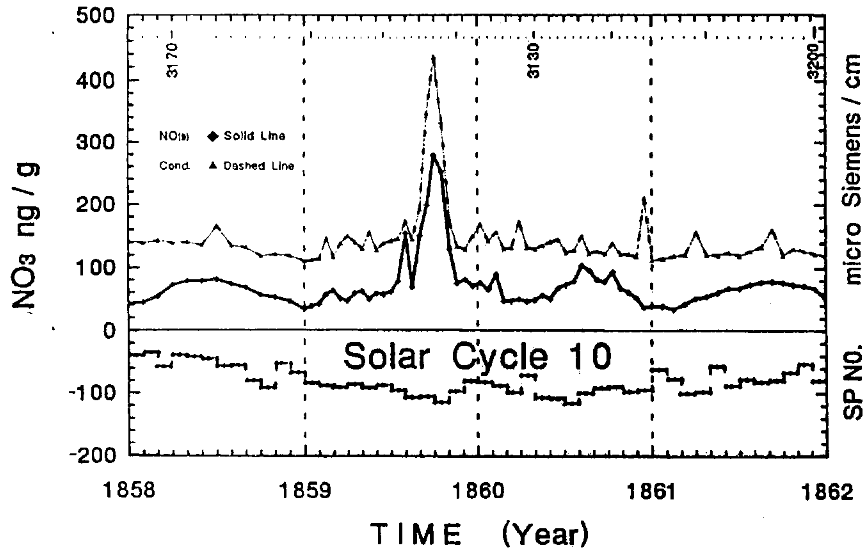


Figure 3. The nitrate concentration from the GISP-H ice core for the period 1858–1862. The large increase in both nitrates and conductivity is associated with the "white-light" flare on 1 September 1859.

1858 to 1862, shown in Figure 3, illustrate the major impulsive increase in late 1859; this increase is associated with the Carrington flare of 1 September 1859 (McCracken *et al.*, 2001a). While not all impulsive nitrate events can be associated with a preceding significant geomagnetic disturbance, the use of the geomagnetic records has assisted in verifying some of the dates.

Geomagnetic data are readily available from ~1840 (Royal Greenwich Observatory, 1955; Nevanlinna and Kataja, 1993; Nevanlinna *et al.*, 1993) to the present time. For earlier time periods, records of mid and low latitude aurora as a proxy for major geomagnetic storms have been used. Sightings of aurora at mid and low latitudes are indicative of major geomagnetic disturbances, but not always indicative of a major solar proton fluence event. Records of high latitude aurora were not utilized since they are a common occurrence.

Lists of mid-latitude aurora are available in various publications (e.g., Křivský and Pejml, 1988) and from data repositories (National Space Sciences Data Center, 2004). Figure 4 illustrates the correspondence between the dates of our nitrate enhancements and low latitude aurora from China, Korea and Japan (Yau, Stephenson, and Willis, 1995). In this figure we have included only those aurora that occurred within 90 days prior to the assigned date of our major nitrate enhancements. Since not every major solar proton event is followed by a major geomagnetic storm, we

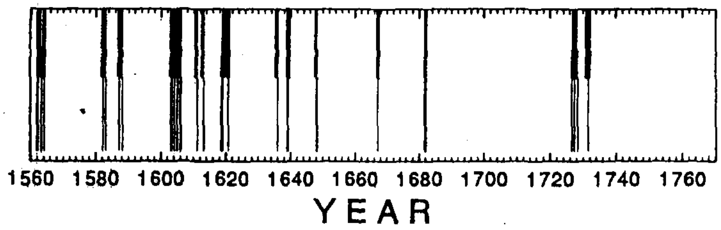
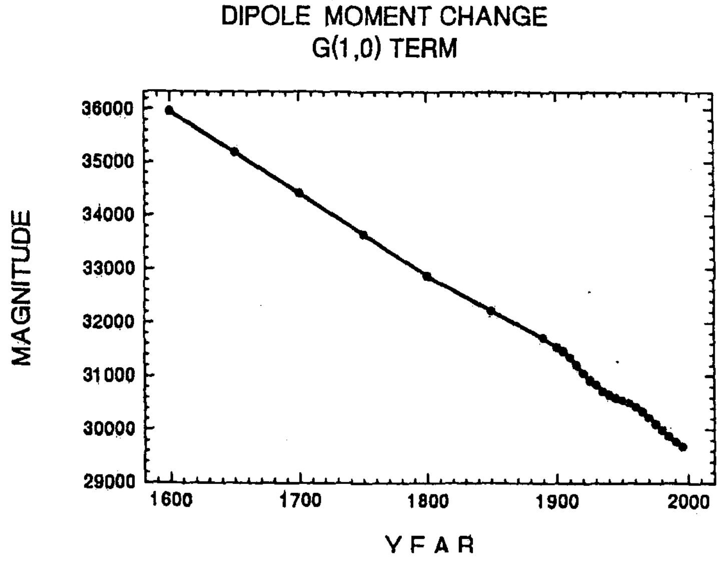


Figure 4. A comparison of the dates of impulsive nitrate enhancements with the dates of low-latitude aurora. The *thick lines* at the top of the figure are nitrate events; the *thinner lines* extending below the thick lines represent the dates of associated aurora within a three-month period prior to the maximum of the nitrate enhancement.

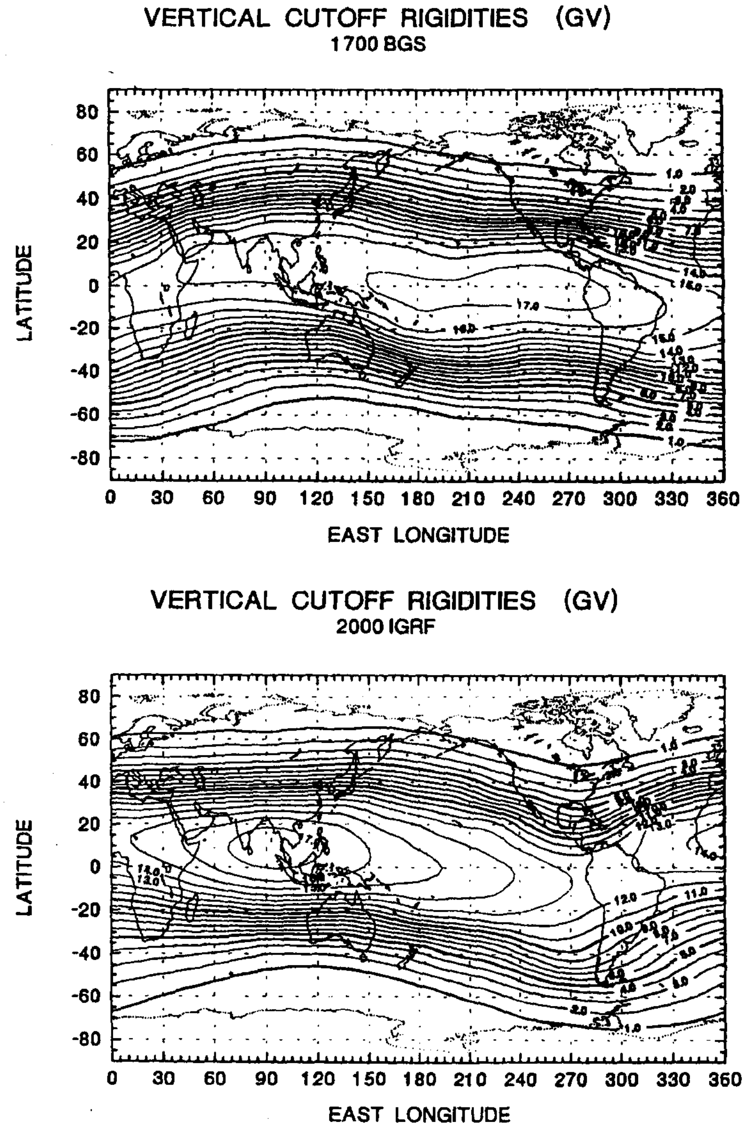
3. Geomagnetic Field Data

The previous section discussed how the sighting of mid- and low-latitude aurora has assisted in the dating of some impulsive nitrate events from the GISP-H ice core. However, since that ice core extends back to 1561, the proper geomagnetic coordinates for the years prior to 1950 must be determined.

The geomagnetic field is constantly changing and reverses polarity every ~20 000 years. At the present time, in geological terms, we are in a period of maximum change with the magnitude of the G(1,0) term rapidly decreasing from a value of ~36 000 nT in 1600 to a value of ~29 500 nT in 2000 as shown in Figure 5.



In addition to the decrease in the geomagnetic field, the position of the geomagnetic pole has moved from a location of 82.7°N, 318.2°E in 1600 (Fraser-Smith, 1987) to its location in 2000 of 79.54°N, 288.43°E (Olsen, Sabaka, and Tøffner-Clausen, 2000).


VERTICAL CUTOFF RIGIDITIES (GV)
1700 BGS

VERTICAL CUTOFF RIGIDITIES (GV)
2000 IGRF

Figure 6. Vertical cutoff rigidity contours for Epoch 1700 and Epoch 2000. The BGS field model

Utilizing geomagnetic field models appropriate for every 50 years between 1600 and 2000, we have calculated a world grid of vertical cutoff rigidity values for each Epoch. These calculations were done every 5 degrees in latitude and 15 degrees in longitude; details are given by Shea and Smart (2004). From these cutoff rigidity values, iso-rigidity contours were determined for each epoch. The iso-rigidity contours for 1700 and 2000 are plotted in Figure 6. As can be seen, there are considerable differences in the iso-rigidity contours over this 300-year period.

The cutoff rigidity values can be calculated with reasonable accuracy for the past 400 years. For periods earlier than $\sim$1500, the magnitude of the dipole is not precisely known and only approximations of geomagnetic field models are available (Merrill, McElhinny, and McFadden, 1996). On the other hand, the cutoff rigidities are a crude approximation of the geomagnetic latitude, and concentric geomagnetic latitudes can be determined for millennia from the simple knowledge of the location of the geomagnetic pole which can be computed from the dipole and quadrapole terms in the spherical coefficient expansion (Akasofu and Chapman, 1972). Locations that are considered to be mid-latitude in 2000 may have been closer to sub-auroral latitudes 400 years earlier. Aurora sighted at sub-auroral locations, as mentioned earlier, would not be an indication of a major geomagnetic storm (and possible solar proton event). In evaluating nitrates in polar ice for periods earlier than $\sim$1500, auroral data can be used in verification provided the geomagnetic latitude is sufficiently equatorward of the polar regions to be designated as "mid or low latitudes".

Finally, there has been considerable interest in the possibility that variations in cosmic radiation may be related to climate changes (Friis-Christensen and Svensmark (1997); Svensmark and Friis-Christensen, 1997; Svensmark, 2000; Kristjánsson, Kristiansen and Kaas, 2004). The amount of galactic cosmic radiation impinging at the top of the atmosphere is directly related to the cutoff rigidity above any specific location. Since there are significant changes in the cutoff rigidity in some regions of the world over the past 400 years, these changes should be considered in the evaluation of whether cosmic radiation has an appreciable effect on the climate of a specific region of the world. In addition, the changes in the galactic cosmic radiation should also be included in these studies; these data can be inferred from ^{10}Be measurements (Beer *et al.*, 1990).

4. Concluding Remarks

This paper presents a synopsis of different solar and geophysical data that are being used for historical studies of the Earth and its climate. While most present-day measurements of geophysical phenomena were not available in the distant past, fluence solar proton events is an example of utilizing an unexpected measurement to identify these events into the distant past. It is anticipated that future research will discover other proxies of geophysical phenomena thus enhancing our knowledge of Earth's geophysical climate for many millennia.

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