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Title: A Global Environmental Crisis 42,000 Years Ago

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Abstract: Geological archives record multiple reversals of Earth's magnetic poles but the global impacts of these events, if any, remain unclear. Environmental and archaeological shifts do occur around the last major magnetic inversion, known as the Laschamps Excursion (41-42ka), but uncertain radiocarbon calibration has prevented precise dating to examine any associations. Here we use ancient New Zealand kauri trees (*Agathis australis*) to develop a detailed record of atmospheric radiocarbon levels across the Laschamps. We precisely characterize the geomagnetic reversal and perform global climate modelling and detailed radiocarbon-dating of paleoenvironmental records to investigate impacts. We find that geomagnetic field minima ~42ka caused substantial changes in atmospheric ozone concentration and circulation, driving synchronous global climate shifts that caused major environmental changes, extinction events, and transformations in the archaeological record. **[126 words]**

One Sentence Summary: The Earth's last magnetic field reversal, the Laschamps Excursion 41-42,000 years ago, caused global environmental change including multiple extinctions.

Main Text: Over the recent past, the Earth's magnetic field has steadily weakened (~9% in the last 170 years) and this, along with the current rapid movement of the magnetic North Pole, has increased speculation that a field reversal may be imminent (*1, 2*). The estimated economic impacts of such a reversal have focused on the increased exposure to extreme solar storms, with estimates of daily losses on the order of multi-billion dollars (*3*) likely to be conservative. Arguably, one of the best opportunities to study the impacts of extreme changes in the Earth's geomagnetic field is the Laschamps Excursion (hereafter 'Laschamps'), a relatively short (<1,000 year) duration reversal around 41ka (*4*). Sedimentary and volcanic deposits indicate a weakening of the magnetic field intensity to 25% of current levels during the reversed phase of the Laschamps, and importantly, as little as 6% during the preceding transition as polarity switched (Fig. 1; see Supplementary Materials) (*1, 5*).

Studies of Greenland ice cores have failed to reveal marked impacts in high latitude paleoclimate associated with Laschamps (*5, 6*), and this observation has underpinned the current view that there is no relationship between geomagnetic reversals and climate or environmental changes. However, the markedly increased levels of solar and cosmic radiation reaching the Earth's atmosphere due to the weakened geomagnetic field are likely to have decreased stratospheric ozone levels, potentially generating regional climatic impacts, particularly in lower latitudes (*7-9*). In this regard, it is notable that many environmental records around the Pacific Basin appear to detail a major (and often sustained) change in behavior around 40-42ka, including local glacial maxima in Australasia and the Andes (*7, 10*), long-term shifts in atmospheric circulation patterns (*11, 12*), and continental-wide aridification and megafaunal extinction in Australia (*4, 13-16*). The same period in North America saw the dramatic and rapid expansion of the Laurentide Ice Sheet (LIS) from a local minimum close to 42ka (*17-19*). Many of these records document a long-term phase shift into a glacial state that persisted until the transition into the Holocene (~11.6ka), in direct contrast to the Atlantic Basin records of millennial-scale abrupt and extreme changes associated with stadial-interstadials.

While the Pacific Basin environmental changes appear broadly coincident with the Laschamps, the lack of knowledge about the exact timing and duration of the geomagnetic excursion has greatly limited the ability to examine whether it played any role. In addition, there are large chronological uncertainties in radiocarbon-dated terrestrial and marine records around the Laschamps due to the substantial increase in high-energy cosmic radiation reaching the upper atmosphere causing elevated production of cosmogenic radionuclides, notably radiocarbon (^{14}C) and ^{10}Be. Although the high ^{10}Be flux has been well described from Greenland and Antarctic ice core records (*6, 20, 21*), synchronous century-long interhemispheric peaks across the Laschamps suggest a series of strong Grand Solar Minima of unknown climate impact (*20, 21*) while the associated atmospheric ^{14}C changes remain poorly constrained (*22*), preventing precise calibration (*23*).

Radiocarbon changes across the Laschamps Excursion

Here we perform detailed radiocarbon analyses of ancient New Zealand kauri (*Agathis australis*) trees preserved in swamps (*24*) to generate the first contiguous reconstruction of atmospheric ^{14}C across the Laschamps (see Supplementary Materials). We compare series of radiocarbon measurements across multiple kauri trunk cross-sections to identify variations in atmospheric radiocarbon at a highly-resolved level. A 1700-year record from a tree recovered from Ngāwhā, Northland, is particularly important as it spans the period of greatest change in ^{14}C, including an apparent weakening of the magnetic field prior to the Laschamps. The growth of the Ngāwhā tree is relatively suppressed compared to modern kauri, and there is a marked decrease in tree-ring width commencing with the weakest phase of the geomagnetic field (Fig. 1 and S4, Supplementary Materials). We spliced the kauri tree ^{14}C series into the radiocarbon dataset reported from the ^{230}Th-dated Hulu Cave speleothem (*22*) to provide an absolute (calendar) timescale (Fig. 1). Our 40-year resolved reconstruction (Fig. 1) shows major changes in atmospheric radiocarbon prior to and during the Laschamps (*23*), closely matching reconstructions of the virtual geomagnetic pole (positions and geomagnetic intensity (*1, 5*)). Comparison of the kauri-Hulu ^{14}C to the paleomagnetic intensity data indicates the reversed phase of the geomagnetic field (and associated partial recovery) defining the Laschamps *sensu stricto* occurred at 41.56-41.05ka (Supplementary Materials).

By modelling ^{14}C-production rates from our kauri $\Delta^{14}C$ record it is possible to precisely align to the ice core timescale using ^{10}Be-records (*21*). Across this period, we infer that the Greenland ice core timescale GICC05 is 265 years younger than the Hulu Cave timescale (95.4% range: 160-310 years; Figs 1 and S15), which is considerably more precise than previous comparisons (*21*). Notably, the steep rise in $\Delta^{14}C$ commences at 42.35ka, with a peak value of 782‰ occurring at 41.8ka, three hundred years before the full Laschamps reversal, and is the highest yet-reported atmospheric concentration of the pre-Anthropogenic radiocarbon timescale (*22, 23, 25*) (see Supplementary Material). The peak $\Delta^{14}C$ value reported here occur during the most weakened phase of the geomagnetic field (*5*) and is associated with a prominent solar Grand Minima recorded by ^{10}Be flux (*20*) (Fig. 1; Supplementary Materials), when the weakened interplanetary magnetic field allows enhanced input of Galactic Cosmic Rays (GCRs) into the upper atmosphere. This new kauri-Hulu record provides the first precise radiocarbon calibration curve for this period, permitting a detailed recalibration of wider environmental changes to test synchrony between events, whilst also enabling us to investigate the potential climate drivers during the Laschamps for the first time.

Global chemistry climate modelling

To explore the impacts of a dramatically weakened geomagnetic field on atmospheric ionization, chemistry, and dynamics, we undertook a series of simulations using a global chemistry-climate model, SOCOL-MPIOM (*8*) (see Supplementary Materials). Firstly, the conditions prior to the Laschamps were modelled using a geomagnetic dipole moment (M) of 100% modern value and high solar activity (providing a modulation potential (ϕ) for GCR equal to modern, 800 MV rigidity cutoff). After a 400-year spin-up, three simulations were branched off. One model run was used to study the impacts of Laschamps (M=0% current, ϕ=800), along with two additional solar states likely to heavily influence atmospheric ionization: Laschamps plus Grand Solar Minima (M=0%, ϕ=0), when the decreased solar magnetic field greatly lowers the GCR modulation potential, consistent with the multiple ^{10}Be peaks recorded in polar ice sheets (*20*); and Laschamps plus Solar Energetic Particle (SEP) events (M10 ϕ 800SEP), when energetic cosmic rays are produced by large solar flares. For the latter, we used the ionizing spectrum values from the 1956 SEP event (Supplementary Information, Fig. 2). Importantly, all these models are likely to provide conservative estimates of the impacts of a weakened magnetic field (Supplementary Information).

Whilst our simulation for the weakened magnetic field during the Laschamps (M=0%, ϕ=800) showed modest but significant changes in atmospheric chemistry and climate (see Supplementary Information), the scenario for Laschamps plus Grand Solar Minima (M=0%, ϕ=0) showed greatly amplified impacts, most notably during the boreal winter (December-February; Fig. 2). Our results yield a large increase in ionization potential from GCRs, resulting in an enhanced production of nitrogen oxides (NOx) and hydrogen oxides (HOx) (*8*). We postulate that these positive anomalies may be explained by an increase in the Brewer-Dobson-Circulation, which would have increased transport of ozone-rich air from the equatorial stratosphere to the ozone-depleted air over the poles (*26*). The modelling shows that NOx- and HOx-catalyzed destruction leads to decreased stratospheric ozone concentrations of ~5% over the mid- to low-latitudes (Fig. 2C). At the same time, a 5% increase is also seen in the northern lower stratosphere and troposphere. These factors result in marked changes in atmospheric heating rates, especially expressed in the tropical stratosphere (cooling of over 1˚K) and the lower stratospheric Arctic (heating of over 1˚K), with far-reaching impacts. Most notably, as a consequence of the decreased equator-to-pole temperature gradient, we observe a weakening of the polar vortex and an increase in sea-level pressure over the Arctic and North America and decreases over western Europe, with parallel changes in surface temperature and zonal air flow. These changes resemble a negative phase of the Arctic Oscillation (AO) and/or a positive North Atlantic Oscillation-like pattern (NAO), consistent with reanalysis studies (*27*).

In spite of the seasonal bias towards summer precipitation over Greenland, the model predictions of pronounced boreal winter Arctic surface cooling are potentially important in the context of the Greenland ice core records spanning this period: the two weakest phases of geomagnetic field strength during the Laschamps closely coincide with the cold Greenland Stadials 11 (GS-11) and GS-10 (Fig. 1). Furthermore, GS-10 and the following brief interstadial GI-9 have a number of atypical features that have led to suggestions they might represent the interruption of a single long warm interstadial (composed of GI-10 and GI-9) by an abrupt cold phase which changed the climatic gradient between the mid-latitudes and Greenland (*28, 29*) (Supplementary Materials). As a result, the climatic impacts of the Laschamps may have been obscured by the way they are captured in the Greenland ice core records.

Pacific climate and environmental impacts

In the Northern Hemisphere it remains difficult to disentangle the similarly-timed impacts of Laschamps from Greenland stadial-interstadial events, early glacial advance, and the expansion of Anatomically Modern Humans (AMH) (*4, 30*). Therefore, in order to isolate the potential impacts of Laschamps from these confounding factors, we used the new kauri-Hulu radiocarbon calibration curve to examine a transect of stratigraphically-constrained sites in the Pacific (*i.e.* outside the Atlantic Ocean basin) from the subantarctic to the tropics.

We used high-resolution radiocarbon dating series to investigate Laschamps-aged sedimentary sequences at sites which record the behavior of both the Intertropical Convergence Zone (ITCZ)

(Lake Towuti, Sulawesi) and mid-latitude Southern Hemisphere westerlies (subantarctic Auckland Islands). On the subantarctic Auckland Islands (50˚S; see Supplementary Materials), which currently sit under Southern Hemisphere mid-latitude westerly airflow (*12*), a lignite sedimentary horizon at Pillar Rock records a warm period from 54 to 42ka within the last glaciation. Pollen records of *Dracophyllum* scrub-grassland on this exposed cliff top, and long-distance transport of lowland podocarp forest pollen from the New Zealand mainland, indicates weaker westerly winds than now and mean annual temperatures within 1-1.5 °C of today (Supplementary Materials); interpreted to represent a period when the core of the Southern Hemisphere westerlies lay relatively polewards, delivering mid-latitude air masses over this sector of the Southern Ocean (*12*). A series of 12 contiguous ^{14}C ages reveal the upper stratigraphic boundary marking a return to periglacial conditions occurred at 42.23±0.2ka, coincident with the weakening of the magnetic field during the transition phase into the Laschamps (Fig. 1). The periglacial conditions lasted until the Holocene (*12*), suggesting pervasive and widespread cold conditions across this sector of the Southern Ocean and an associated northward shift in core westerly airflow.

In the equatorial west Pacific, Lake Towuti currently experiences a wet season from December to May as the ITCZ migrates southward (*11*). During the last glacial period, Lake Towuti preserves a marked and sustained shift in $\delta^{13}C_{\text{leaf wax}}$ to more positive values (more arid conditions) which persisted until the Pleistocene-Holocene boundary (Fig. 3; see Supplementary Materials) (*11*). A comprehensive series of 13 new radiocarbon dates and sediment magnetic intensity minima suggest the ITCZ shift occurred at 42.35±0.2ka, again during the geomagnetic transition phase into the Laschamps (Fig. S11), precisely aligning to the westerly airflow shift recorded at Pillar Rock. The high level of precision on the ages obtained for the major climatic boundaries recorded in Lake Towuti and Auckland Islands is only possible due to the contiguous series of radiocarbon dates from each sequence, which permit accurate alignment against the steep rise in atmospheric radiocarbon values across this period (Fig. 1).

The above changes are consistent with a wealth of observations that indicate major environmental changes around the Pacific Basin at the time of the geomagnetic transition into the Laschamps. For instance, a northward movement of the Southern Hemisphere westerlies has been proposed to explain the local peak glacial advance in arid southern central Andes sometime prior to 39ka (Fig. 3) (*7*), and tentatively related to fluxes in cosmic radiation and the Laschamps (*8*). Maximum glacial advances are also observed in New Zealand around 42ka (*10*), consistent with the climate modelling of enhanced southwesterly airflow over the mid-latitudes (Fig. 2). These broad-scale atmospheric circulation changes appear to have had far-reaching consequences. Within Australia, the peak megafaunal extinction phase is dated around 42.1ka, both in mainland and Tasmania (Fig. 3) (*14-16*), and has generally been attributed to human action, although well after the initial arrival of humans at least 50ka (*14, 16, 31*). In contrast, the megafaunal extinctions appear to be contemporaneous with a pronounced climatic phase shift to arid conditions that resulted in the loss of the large interior lakes and widespread change in vegetation patterns (*13, 15*). At Lynch's Crater in north-east Australia the shift in vegetation structure, accompanied by increased burning (*15*), has been recalibrated here at 41.91±0.4ka, overlapping with the climatic boundaries observed at Lake Towuti and the Auckland Islands. Likewise, sediments at the Lake Mungo site associate the timing of the loss of Australia's interior lakes and megafaunal extinction phase with a reported geomagnetic excursion ~42ka (locally called the 'Lake Mungo Excursion') (*13*) (Supplementary Materials). Similar signals of dramatic floral and faunal change also appear to exist on New Caledonia and as far afield as South Africa (see Supplementary Materials). Together, these records suggest that both a mid-latitude climatic shift and major extinction phases overlap with the geomagnetic transition leading into the Laschamps, implying an association between these events.

Our model simulations potentially provide important insights into the global nature of the changes observed around the time of the Laschamps. Although the immediate impacts associated with the geomagnetic transition were likely on the order of the duration (800 years), many of the above synchronous changes persisted for multi-millennia. This implies a threshold may have been passed in one or more Earth system components, effectively tipping into a different persistent state (Fig. 3). One possibility is that with the Earth's orbital configuration moving towards a glacial stage and limited global ocean ventilation (see Supplementary Materials), the climate system may have been sensitive to a relatively short but extreme forcing around the time of the Laschamps. For instance, terrestrial and marine sedimentary records have revealed that the LIS expanded rapidly from a local minimum at 42ka (*18, 19*) in association with a magnetic reversal (*17, 19*), with geological constraints and numerical models indicating some parts of the ice sheet may have expanded >1000 km by ~39-37ka (*18*). Potentially importantly, whilst our model simulations do not suggest any major change in airflow over the equatorial and southern Pacific, we do find a substantially weakened polar vortex, most notably during the boreal winter (Fig. 2 and Supplementary Materials). The greatly reduced surface temperatures akin to a negative phase of the AO could potentially have created a positive feedback for ice sheet growth, reducing global sea levels. Recent work has suggested that an expanded LIS would have reorganized atmospheric circulation across the wider Pacific Ocean (*11*). Such a hemispheric-wide response to forcing is consistent with the synchronous movement of the mid-latitude Southern Hemisphere westerlies determined from Pillar Rock, and implied from glacial behavior in New Zealand, Australia, and the central Andes.

The Adams Transitional Geomagnetic Event and wider implications

Overall, the signals discussed above suggest a major climatic and environmental event occurred across the mid- to lower latitudes around 42ka, coincident with the Earth's weakened geomagnetic field immediately preceding the reversed state of the Laschamps (Fig. 3). We describe this as the 'Adams Transitional Geomagnetic Event' (hereafter 'Adams Event') after the science writer Douglas Adams, due to the timing (the number '42') and the associated range of extinctions (*32*). Previous studies may have failed to identify such a relationship between the Laschamps and climatic impacts due to the lack of temporal resolution and by focusing on the period of actual reversed geomagnetic field (41.45-41.05ka) (*5, 6*), rather than the preceding extended phase of much weaker geomagnetic field (42.35-41.45ka).

The lowered geomagnetic field intensity during the transition into the reversed state of the Laschamps would have dramatically increased levels of UV radiation (by an estimated 5-10% of current levels at higher latitudes) and also atmospheric ionization, especially in equatorial and low latitudes (<40º) due to a tenfold decrease in the cosmic ray cut-off rigidity (Fig. 4, Supplementary Materials). The ionization level would have been further heightened by a factor of two during solar Grand Minima evident in ice core records and observable in the kauri records (Fig. 1) (*20*) (Supplementary Materials). The increased atmospheric ionization may have promoted stratospheric and tropospheric cloudiness through cloud-seeding type impacts, particularly towards the lower latitudes (*9*), and potentially also-lightning strikes, explaining the increased records of charcoal observed around the Laschamps in Australia (*15*), and lack of relationship with archaeological signs of human activity (*33*).

The implications of this study are considerable. For instance, it is intriguing to note the Adams Event is very close in timing to the sudden appearance and increase in figurative cave art, red ochre handprints, and changing use of caves around the world 40-42ka *e.g.* in Europe and Island Southeast Asia (*34-36*) (Fig. S34, see Supplementary Materials). This sudden behavioral shift in very different parts of the world is consistent with an increasing, or changed, use of caves during the Adams Event, potentially as shelter from the abrupt and unprecedented increase of UVB to harmful levels, which might also explain an increased use of red ochre sunscreen (*4*). Rather than the actual advent of figurative art, early cave art would therefore appear to represent the preservation of pre-existing behaviors on a new medium (*36*) (see Supplementary Materials). Other important archaeological boundaries closely associated with the Laschamps include the extinction of the Neandertals, re-calibrated here at 40.9-40.5ka, along with some of the first European AMH cultures such as the Uluzzian in Italy (Fig. 3, Supplementary Materials) (*4, 30, 37*).

The Adams Event appears to represent a major climatic, environmental, and archaeological boundary that has previously gone largely unrecognized. Additionally, the other well-known geomagnetic excursion in the recent past, Mono Lake (34ka) (*1*), also appears to be marked by a distinct peak in the $\Delta^{14}C$ levels in the Hulu Cave stalagmite (Fig. 3) and aligns closely with a further latitudinal shift in the ITCZ as recorded in Lake Towuti as well as a cluster of megafaunal extinctions in Eurasia (*38*) (Supplementary Materials). Importantly, geomagnetic transition phases can last substantially longer than during the Laschamps; for instance the most recent full geomagnetic reversal, the Brunhes-Matuyama (at ~790ka; (*39*)) has a transition phase of around ~20ka, some 25 times longer than the Adams Event, with potentially globally-significant climatic and evolutionary effects. The discovery that geomagnetic reversals can cause orders of magnitude increases in cosmic radiation and alter ozone concentrations and temperature gradients provides a new model for sudden paleoclimate shifts. Overall, these findings raise important questions about the evolutionary impacts of geomagnetic changes recorded throughout the geological record (*4*).

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Supplementary Materials:

Materials and Methods

Figures S1-S22

Tables S1-S7

References (*1-142*)