Chronology and Correlations of High Arctic Lakes Based on Magnetic Properties

By

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Thesis Advisor's Department

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Abstract

Located at 78⁰N the island of Spitsbergen is covered by small glacal lakes. Linnévatent and Kongressvanet are two such lakes and are separated by about five kilometers along the western coast. These lakes have been part of an ongoing study to better understand the present and past climate changes. Chronology for cores recovered from these lakes is especially hard to establish, due to large amounts of detrial coal as well as the depletion of ^{14}C due to carbonate dissolution make ^{14}C-dating methods unreliable.

During the summer of 2008 three cores were recovered from Linnévatnet with lengths of 32cm, 35cm and 65cm, near mooring sites D (core L08D), F (core L08F) and G (core L08G) respectively.   In addition, one core (K08) from Kongressvatnet had a length of 67cm was collected. These were analyzed for paleomagnetic data finding that the K08 core gave a corrupted record, most likely due to the presence of gregite as shown by the environmental records. The Linnevatnet cores gave reliable records, with the longer record (L08G) having a sudden drop in declination at 33cm. This drop was the basis of the two age models. Age Model I based on the record given and dates the core to be 3500 years old. Age Model II involves a rotation of the declination data an dates the core to be ~350 years old. Based on grain size changes indicated by the environmental magnetic data as well as varve analysis of a similar core Age Model II is determined to be more valid, dating L08G to ~350 years BP. In addition L08D and L08F did not show enough variation to be compared to longer time scale, thus were only dated using Age Model II; giving ages of ~140 years BP for both cores.

Introduction

Spitsbergen is the largest of 150 islands in the high Arctic Archipelago, Svalbard, located at 78⁰ 12' N, 15⁰ 40' E (Fig. 1). The island has a rugged landscape with many ice caps, deep valleys and fjords (Werner, 2008). The western coast of Spitsbergen, between the largest fjord, Isfjord, and the North Atlantic Ocean, contains the study area for this paper, the two lakes Linnévatnet and Kongressvatnet.

My objectives in this study were to better understand the magnetic properties of the sediments of Linnévatnet and Kongressvatnet and explore their value for correlation and paleoclimate studies. Due to the large amount of detrital coal input into both lakes ^{14}C dating has proven difficult. In addition, the karst surrounding both lakes (Salvigsen and Elgarsma) gives them a pH of 7.4-7.7 (Bøyum, 1980), which dissolves or damage

the few biological markers produced in the lake that might have helped with dating.

These difficulties dating are basis for this study. Through paleomagnetics and matching

these with known records of polar wander (Jackson et al, 2000 and Korte and

Constable,2005) an age model could be established. Furthermore an investigation of

the environmental magnetics of the sediments may reveal a signal of past climate

change.   Also, by measuring these properties I hoped to be able to develop correlations

between these lakes as well as within Linnévatnet itself. Only one previous study has

been done on the paleomagnetic record in Linnévatnet (Lovlie et al, 1990) and no data

has been published on the paleomagnetics of Kongressvatnet. My goal with this study

was to improve upon the methods used by Løvlie et al (discrete sampling every 5cm)

through continuous u-channel sampling with measurements every 1cm, giving a more

complete paleomagnetic record.

Geological Background

Over[S1] the course of the Phanerozoic, Spitsbergen moved from a position close

to the South Pole (around 600 Ma) to near the equator about 350-400Ma, then arriving

at its current position near the North Pole (Werner, 2008). The Caledonian Orogeny

during the Silurian deformed Cambro-Ordovician limestone deposits from Cambrian and

Ordovician. This orogenic event caused uplift and the formation of the Heckla Hoek

series granites (Werner, 2008). Carboniferous deposits in Svalbard consist of large

coal beds, overlain by Permian dolomites and evaporites. Marine deposits dominate the

Mesozoic strata of Svalbard (Werner, 2008). During the Tertiary transpressional forces

cause the fold-thrust belt of the western coast of Svalbard to form (Braathen and Bergh, 1995). The region considered in this paper is within this fold-thrust belt.

Linnédalen is a deep valley, which was incised during the last ice age by Linnébreen, the glacier at the southern end of the valley about 8km from the lake. . Three main rock types characterize the area: Precambrian metasediments to the east of the valley, Carboniferous sandstones and quartzites and Carboniferous/Permian limestones and gypsum (Fig. 3)(Hjelle, 1986). Near Linnébreen coal beds interfinger with sandstone. At the northern end of the valley Linnévatnet extends for 4.7km from north to south and is 1.3km wide. A glacial stream (Linnéelva) feeds the lake from Linnébreen glacier from the south. The lake sits at 12m above sea level and has three bathymetric basins (Fig. 4). A bedrock ridge, which forms a small island within the lake, separates the two basins proximal to the stream in the south. The basin distal to stream input to the north has a depth of about 37km, whereas the two southern basins are about 15m deep.   Linnévatnet is a monomictic lake, turning over in early with highly turbid waters not allowing for primary production in the summer months when the lake is ice free. From acoustic profiling the distal basin has 10m of sediment (Svendsen et al., 1989). These sedimentation rates vary from very low (~1mm/year) in the distal basin to much higher (~4.5 mm/year) near the inlet (Pratt, 2007; Snyder et al., 1994; Svendsen and Mangerud, 1997; Snyder et al., 2000).

Kongressvatnet is located between Linnédalen to the west and Grondfjord to the east at 94m elevation (Guilizzoni et al., 2006). Today the lake has two active influents, a sulfur spring and large alluvial fan known as the White Fan because of its light color (Fig. 5). Acoustic profiling done in the summer of 2008 showed that only about 5m of

sediment rates at the bottom of this 54m deep lake. Kongressvatnet is a meromictic lake, resulting from its dense inflow of mineral spring waters from various sources, which are rich in sulfides (Bøyem and Kjensmo, 1970). The main rock types in the lake's watershed are dolomite, anhydrite and (other?) evaporites, chert, silica-cemented shale, siltstone, sandstone, and both bioclastc and silicified limestones (Ohta *et al.*, 1992, Braathen and Bergh, 1995).

Methods

Three sediment cores were taken from Linnévatnet and one core from Kongressvatnet using a universal coring device. One core (L08D) from Linnévatnet was taken from the western basin near mooring D at 10.6m depth and measured 32cm in length. The second (L08F) was from the eastern basin near mooring F at 14.9m depth and measured 36cm. The last core (L08G) was taken from the basin distal to the inlet stream near mooring G at water depth of 37m and was 65cm in length. The Kongressvatnet core (K08) was taken near the deepest point at 52m and had a length of 67cm.

The longer cores were sampled for paleomagnetics by u-channeling at The University Center in Svalbard in Longyearbyen. One u-channel was collected from the working half of each core. The smaller cores were later u-channeled at the University of Arizona.

The u-channels were then sent to the paleomagnetics laboratory at the Institut des sciences de la mer de Rimouski (ISMER) & GEOTOP University of Québec in

Rimouski, Canada, where they were measured for natural remnant magnetization (NRM), anhysteretic remnant magnetization (ARM), isothermal remnant magnetization (IRM) and saturated IRM (SIRM) at 1T. Various demagnetization steps were taken for each u-channel (see Table 1).

Principle component analysis (PCA) was done on the resulting data using Microsoft Excel macro by Mazaud (2005) to determine maximum angular deviation (MAD) values. MAD values give a quantitative measurement of the best-fit line of the demagnetization steps. Any MAD values greater than 15 degrees are considered ill fitted and of questionable significance. Also, mean destructive field (MDF) is given by the Mazaud macro, which provides information on the mean coercivity state of the sample, which is a reflection of its grain size and mineralogy (Stoner and St. Onge, 2007)

ARM measurements at the demagnetization step of 20mT was examined for each sample to greater understand the changes in mineralogy and grain size. ARM/SIRM ratios were calculated and examined to indicate changes in grain size of magnetic carriers specifically the higher the ratio the smaller the grain size. Furthermore, Pseudo S-ratio (IRM/SIRM) was calculated and analyzed to indicate the concentration of ferromagnetic minerals (ratio values close to 1 indicate high concentrations of ferromagnetic minerals) (Opdyke and Channell, 1996). Then the data was matched to known secular variation records using AnalySeries 2.0.4.2 © to form age models.

Results

Core L08D

Two u-channels were taken from L08D and analyzed for their magnetic properties. In the NRM measurements both u-channels show a decrease in both declination and inclination down core and have relatively steady MDF values indicating a fairly constant grain size and magnetic mineralogy (Fig. 5). Low MAD values (2 to 5.8 degrees), allow this record to be considered reliable.

The ARM shows little variation ranging between 0.00102 and 0.00274mT as does the ARM /SIRM ratios (0.0047-0.00591) and the pseudo S-ratio hovers around 0.5. (Fig. 7) indicating nearly constant magnetic mineralogy and grain size through out the core.

Core L08F

The u-channels taken from L08F had NRM measurements showing a decrease again in both inclination and declination down core. This was accompanied by low MAD values, again showing the record's validity as the multiple measurements at each demagnetization step support each other. Relatively constant MDF values again suggest little change in mineralogy and grain size (Fig. 8). Low MAD values give this record credibility, in that its demagnetization steps all align.

The environmental magnetic measurements show similar results to that of L08D with ARM varying between 0.00105 to 0.00384 with ARM/SIRM between 0.00584 to 0.00696 The pseudo S-ratio hovers around 0.5, indicating a low concentration of ferromagnetic minerals and a relatively constant grain size and mineralogy through out the core (Fig. 9).

Core L08G

The NRM measurements of inclination from this core show more variability than the shorter cores. There is marked increase in declination above 33cm, this becomes the basis for the different age models investigated in this study (Fig. 10). There is also a decrease in MDF up core, which indicates an decrease in coercivity up core, which is further investigated by the environmental magnetics. L08G also has low MAD values meaning that the demagnetization steps are consistent with each other, giving a reliable record.

The change increase in coercivity is seen again in the ARM measurement (0.00115-0.00744) as this decrease up core as well. From this initial measurement further investigation through the ARM/SIRM ratio (0.00686-0.01228), which also shows the increase (0.00686-0.01228), meaning a decrease in grain size. The Pseudo S-ratio shows little variation hovering around 0.5, indicating neither a large concentration of ferromagnetic or anti-ferromagnetic minerals (Fig. 11).

Core K08

The NRM data for K08 show a sudden fall in inclination above 11cm, this is accompanies by a rise in declination as wells as a change in MDF (Fig.12). The MAD values increase up core to 15 degrees at 20cm, with a spike of 23 degrees at 11cm coinciding with the changes in declination and inclination making these measurements questionable and suggesting the whole record is unreliable.

The ARM measurement indicates a decrease in coercivity up core (0.0313 to 0.0045). The ARM/SIRM shows large variations (0.0047-0.0292) whereas the pseudo S-ratio shows a direct correlation with the ARM (0.76-1.03). The pseudo S-ratio is very high, indicating a high concentration of ferromagnetic minerals in this core (Fig. 13).

Age Models

Two age models were constructed for the cores investigated in this study. Age Model 1 was based on the geomagnetic model developed by Korte and Constable in 2005 covers the past 7000 years (Fig. 14), and was used to date the longer records of K08 and L08G. The shorter records of L08D and L08F did not show sufficient variation to be matched to the longer time scale model. For these cores Age Model II (covering the AD 1572-1990 interval) was used, based on maritime records of polar wander (Jackson et al, 2000) (Fig. 14). To match the longer records of L08G and K08 to this known record the top 33cm and 11cm, respectively were rotated (discussed further below). This is commonly done when dealing with unoriented cores and involves a

rotation of the declination by 180 degrees. Though this is usually done on entire cores or whole u-channel samples taken from a longer core, it may be justified in this study as rotation may have occurred during removal of the core from the sediments or during transport.

Age Model I

The main tie point when matching the record from L08Gand K08 was the sudden drop in declination in both records.   This was matched to a drop in declination in the Korte and Constable model at about 2300 years BP. Using this and other variations in both the inclination and declination the core-bottom ages for L08G and K08 were inferred to be ~3500 years BP and ~4800 years BP, respectively (Fig 16). The L08G record matches the Korte and Constable chronology fairly well, whereas the K08 record does not show a strong correlation. When the age model is applied to the environmental magnetism records of K08 and L08G, the changes in the records do not corresponded to the ages of known glacial events

With this a fairly constant sedimentation rate of ~0.18 mm/yr is inferred for L08G (Fig. 18).   The sedimentation rates for K08 show a dramatic increase in sedimentation from 12cm to 59 cm of almost a factor of ten (0.039mm/yr to 0.35mm/yr) and dropping again at 59cm to 0.016cm/year (Fig. 19).

Age Model II

For Age Model II the upper portions of L08G and K08 were rotated by 180 degrees (Fig. 17). This eliminates the drop in declination in the records and allows them to be matched to the historical records presented by Jackson et al. Using this record minimum ages for the on L08D and L08F were found to be ~140 years BP (Fig. 19) and L08G was ~350 years BP (Fig. 20). When applied to the ARM/SIRM record the increase in grain size is consistent with having occurred at the end of the Little Ice Age (Fig. 21).   This could signal a change at that time from the deposition of more fine-grained glacial flour to coarser grained fluvial sediments starting about in the early 19th Century. In addition, this age on the L08G core matches almost exactly with a varve-counting chronology obtained from two cores taken from the same location, as well as estimates of the termination of the Little Ice Age base on varve thickness (Pompeani, 2008).   The age for K08 using Jackson et al for comparison comes out to be ~370 years BP (Fig. 20), but the records do not match well.

Using the Jackson et al. age model sedimentation rates for L08D and L08F are inferred to be nearly constant, at about 0.229cm/year (Fig. 22). Sedimentation for L08G shows changes at 20cm, 30cm and 40cm, with sedimentation rates of 0.068 cm/yr until 40cm, 0.16cm/yr from 40cm-30cm, 0.087 cm/yr from 30cm-20cm, and 0.35cm/yr above 20cm. The K08 record shows a change in sedimentation at about 18cm and 37cm with rates of 0.25 cm/yr until 37cm, 0.08cm/yr from 37cm to 18cm, and 0.41cm/yr above 18cm (Fig. 22).

Conclusions

The difficulties in dating the sediments of Linnévatnet and Kongressvatnet have posed a challenge to all the studies that have been done on these lake sediments. This study tries to resolves these issues. The cores from Linnévatnet (L08D, L08F, L08G) show records that have consistent measurements as shown by the low MAD values for all three cores. In contrast, the record observed in the core recovered from Kongressvatnet (K08) has extremely high MAD value calling the quality of the record into question as well as any age model based on the paleomagnetic record. The evidence of high concentration of ferromagnetic minerals (high pseudo S-ratios) is most likely the cause of the high MAD values as these are easily re-magnetized. Also, the ferromagnetic mineral gregite (Fe_2S_2), a biogenic mineral that often corrupts paleomagnetic records, has been previously observed as an authigenic mineral in the sediments of Kongressvatnet (Guilizzoni et al, 2006),. Additional evidence for the presence of gregite comes from XRF analysis of another core taken at the same site taken in 2008, which showed a large amount of iron and sulfur throughout the core, with an increase downcore near the same depth that the increase in pseudo S-ratio is observed in K08 (Wei-haas et al, 2008). Thus, the formation of gregite in this lake could account for the poor correlation of either age model with the K08 data, suggesting that the core from that site is unsuitable for paleomagnetic dating and making any correlations based on the paleomagnetic data from K08 to the cores in Linnévatnet impossible.

Since the records of the cores recovered from Linnévatnet are reliable paleomagnetic data is possible on these cores. From the two age models presented in this study it appears that Age Model II is more likely to be correct. Though this model

does involve a rotation of a portion of the L08G record the dating alligns well with a prior varve-based chronology, as both suggest plausible and simultaneous sedimentary signals of the ending of the Little Ice Age (increase in ARM/SIRM at ~150 years BP). Since this age model as been established for the L08D, L08F and L08G it would be possible to do similar correlations between the three basins within Linnévatnet.

Acknowledgments

Figures
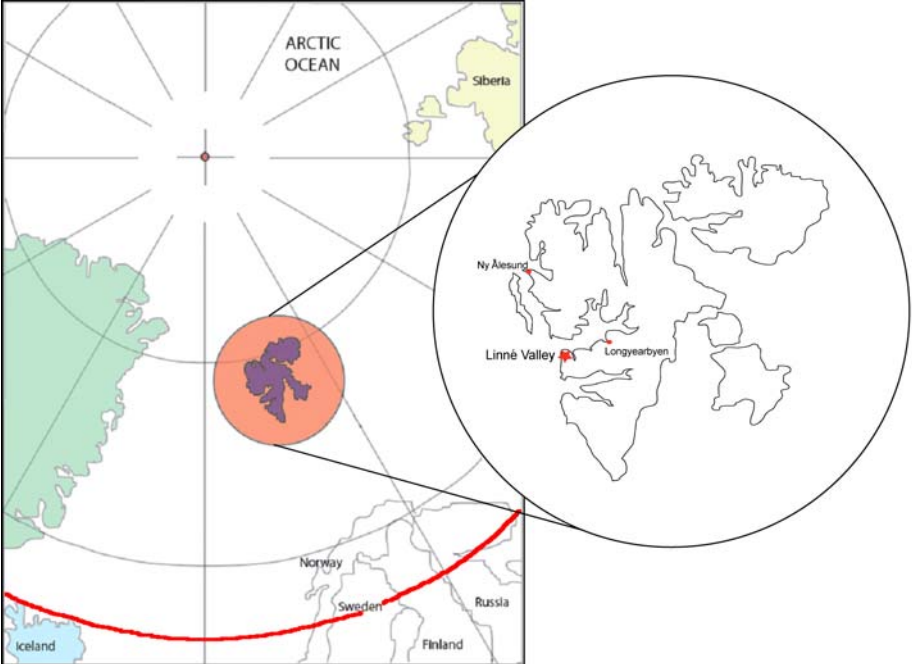
Figure 1: Map of the location of Svalbard and the Linné valley

Figure 2:
Simplified Geologic map of Spitsbergen, the main island in Svalbard (taken from Alden, 2006)
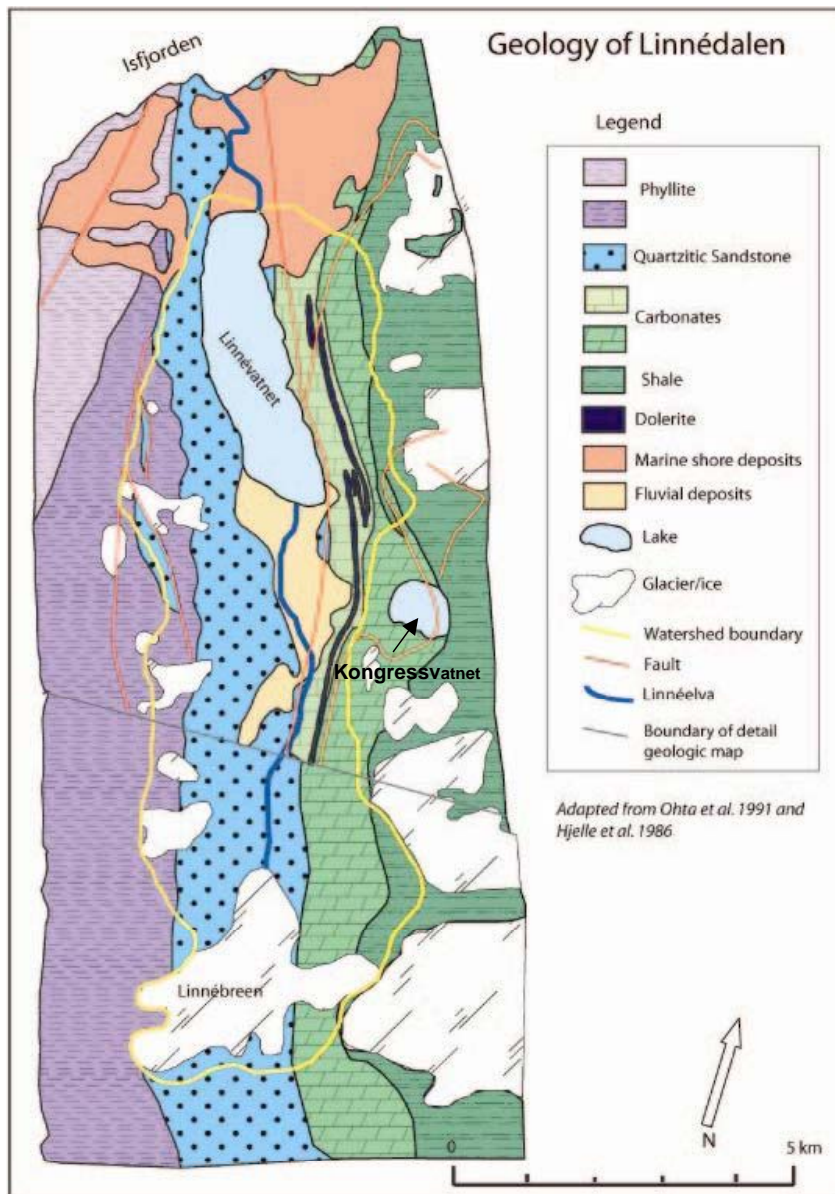
Figure 3. The geology of Linnédalen. From Perrealt, 2006.
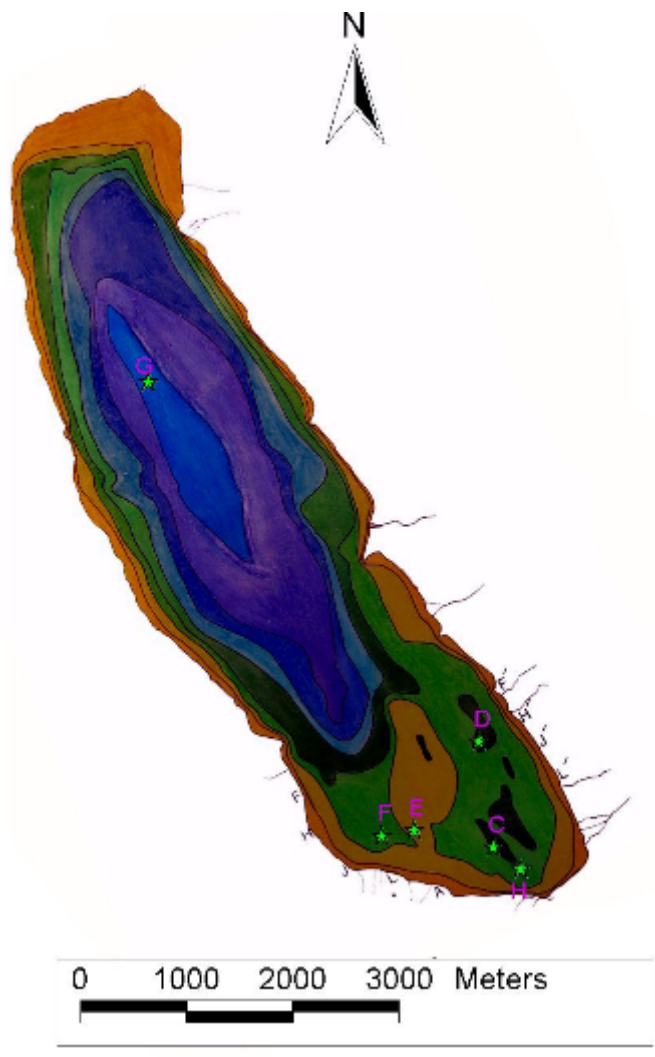
Figure 4: Bathymetric Map of Linnévatnet with mooring sites
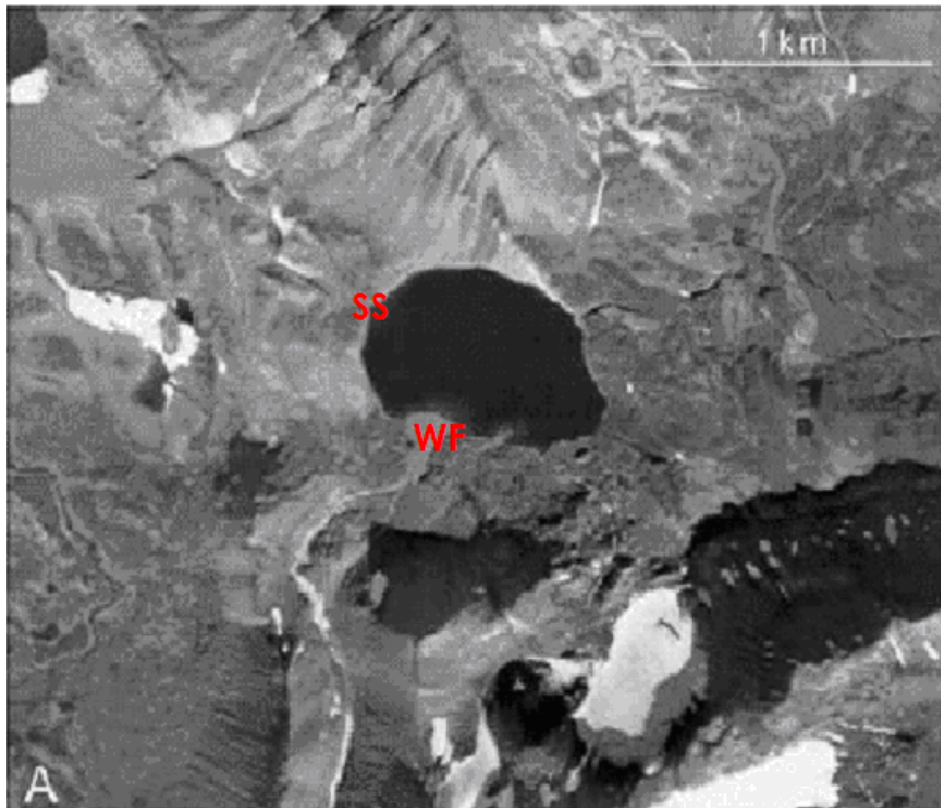
Figure 5. August 1969 aerial photo of Kongressdalen and Kongressvatnet, taken by Norwegian Polar Institute. Up-direction is North. SS and WF is location of the sulfur spring and white fan respectively.

Sample	NRM Demagnetization Steps(mT)	ARM Demagnetization Step	IRM Demagnetization Steps	SIRM Demagnetization Steps
L08D	0,5,10,15,20,25,30,35, 40,45,50,55,60,65,70, 75,80,90,100,110	0,5,10,15,20,25, 30,35,40,45,50,55, 60,65,70,75	0,5,10,15,20,25, 30,35,40,45,50,5 5,60,65,70,75,80	0,5,10,15,20,25,30, 35,40,45,50,55,60, 65,70,75,80
L08F	0,5,10,15,20,25,30,35, 40,45,50,55,60,65,70, 75,80,90,100,110,120	0,5,10,15,20,25, 30,35,40,45,50,55, 60,65,70,75,80,90	0,5,10,15,20,25, 30,35,40,45,50,5 5,60,65,70,75,80	0,5,10,15,20,25,30, 35,40,45,50,55,60, 65,70,75,80
L08G	0,5,10,15,20,25,30,35, 40,45,50,55,60,65,70, 75,80,90,100,110,120, 130,140,150	0,5,10,15,20,25, 30,35,40,45,50,55, 60,65,70,75,80	0,5,10,15,20,25, 30,35,40,45,50,5 5,60,65,70,75,80	0,5,10,15,20,25,30, 35,40,45,50,55,60, 65,70,75,80
K08	0,5,10,15,20,25,30,35, 40,45,50,55,60,65,70, 75,80	0,5,10,15,20,25, 30,35,40,45,50,55, 60,65,70	0,5,10,15,20,25, 30,35,40,45,50,5 5,60,65,70,75,80	0,5,10,15,20,25,30, 35,40,45,50,55,60, 65,70,75,80

Table 1. Demagnetization steps for all u-channel samples for NRM,ARM ,IRM and SIRM.
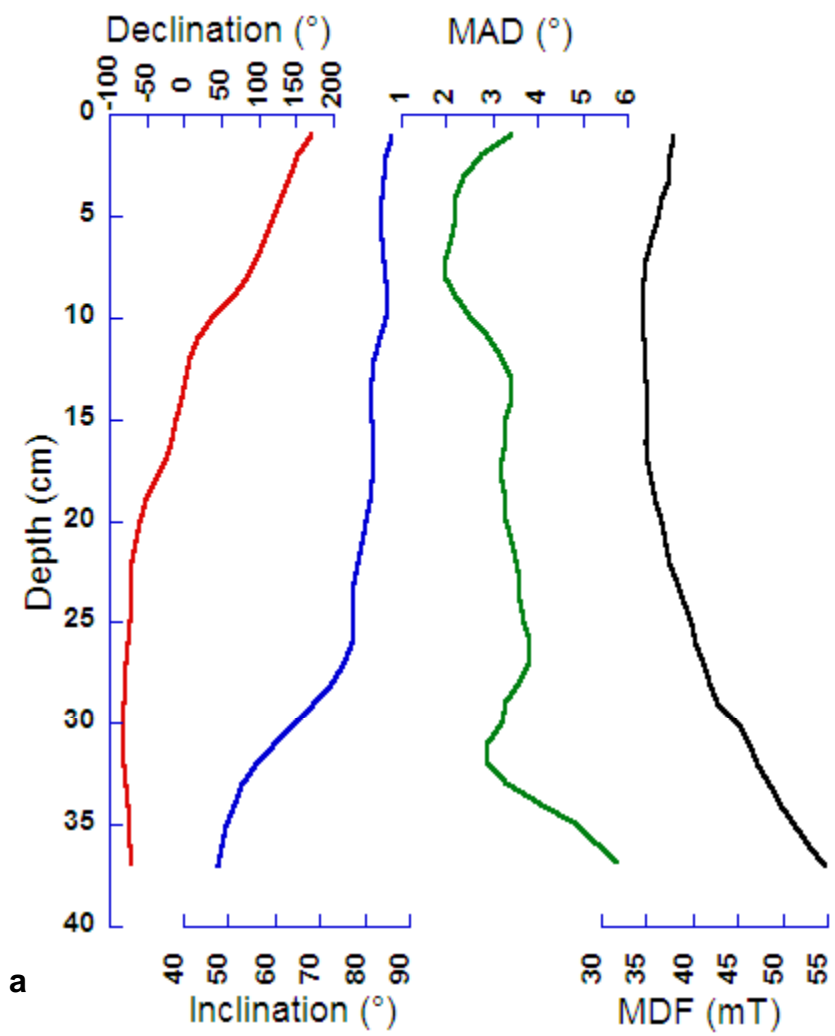
Figure 6. NRM record for L08D. Declination, Inclination, MAD and MDF vs Depth (down-core). Low MAD values indicate a reliable record and little variation in MDF indicates little change in mineralogy or grain size.
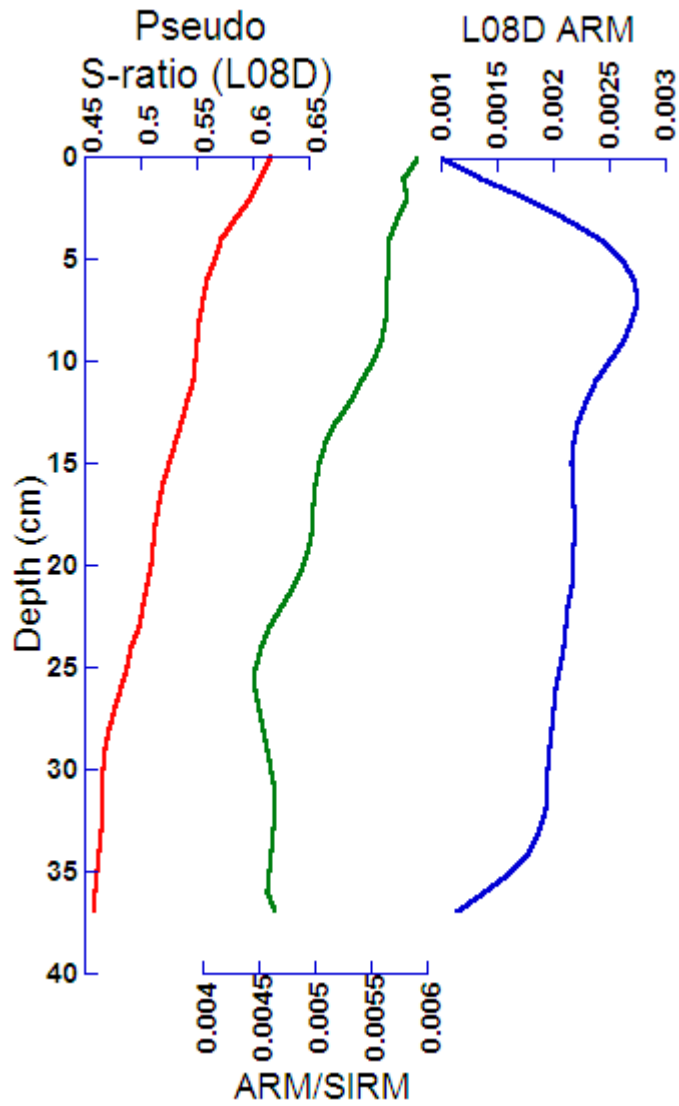
Figure 7. Environmental magnetism record for L08D Pseudo S-ratio, ARM/SIRM ratio and ARM vs Depth (down-core). Little variations in this record indicate constant magnetic mineralogy and grain size though out the core.
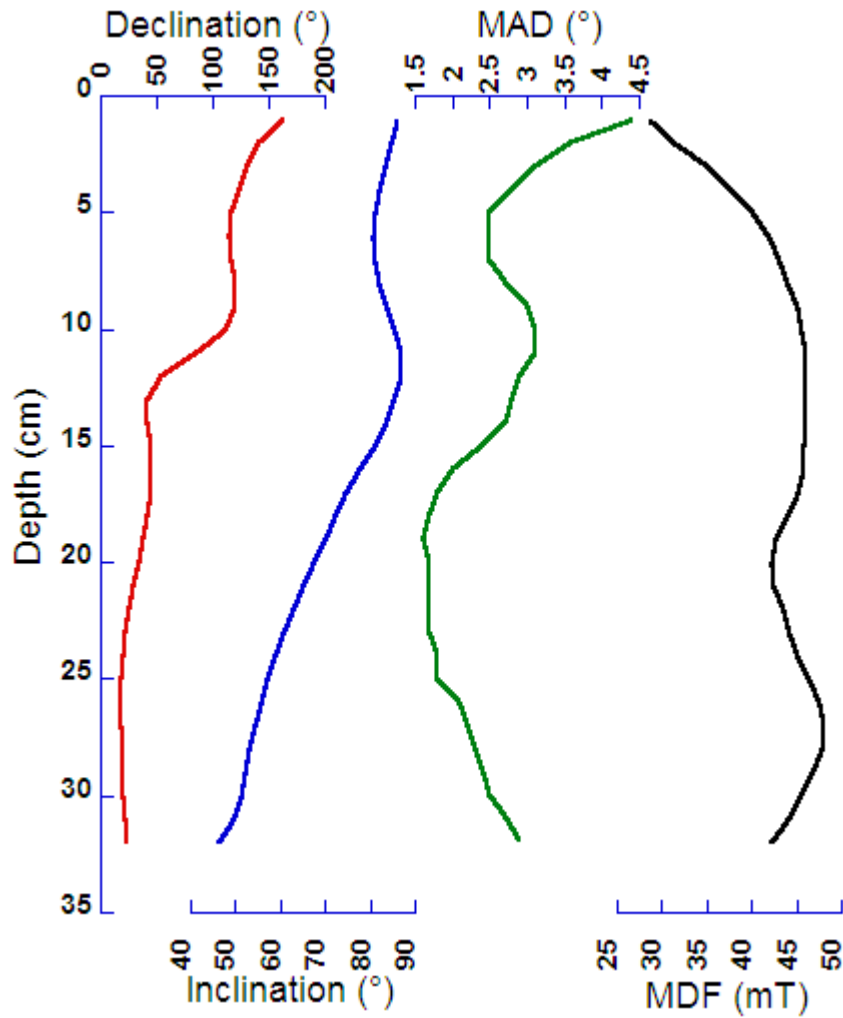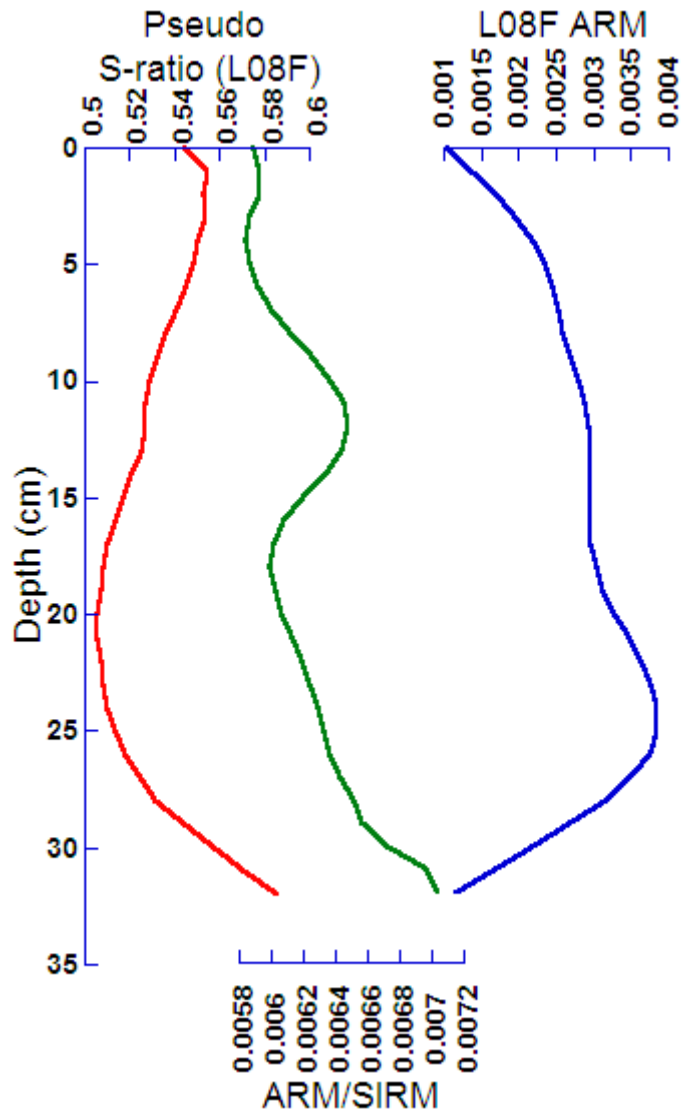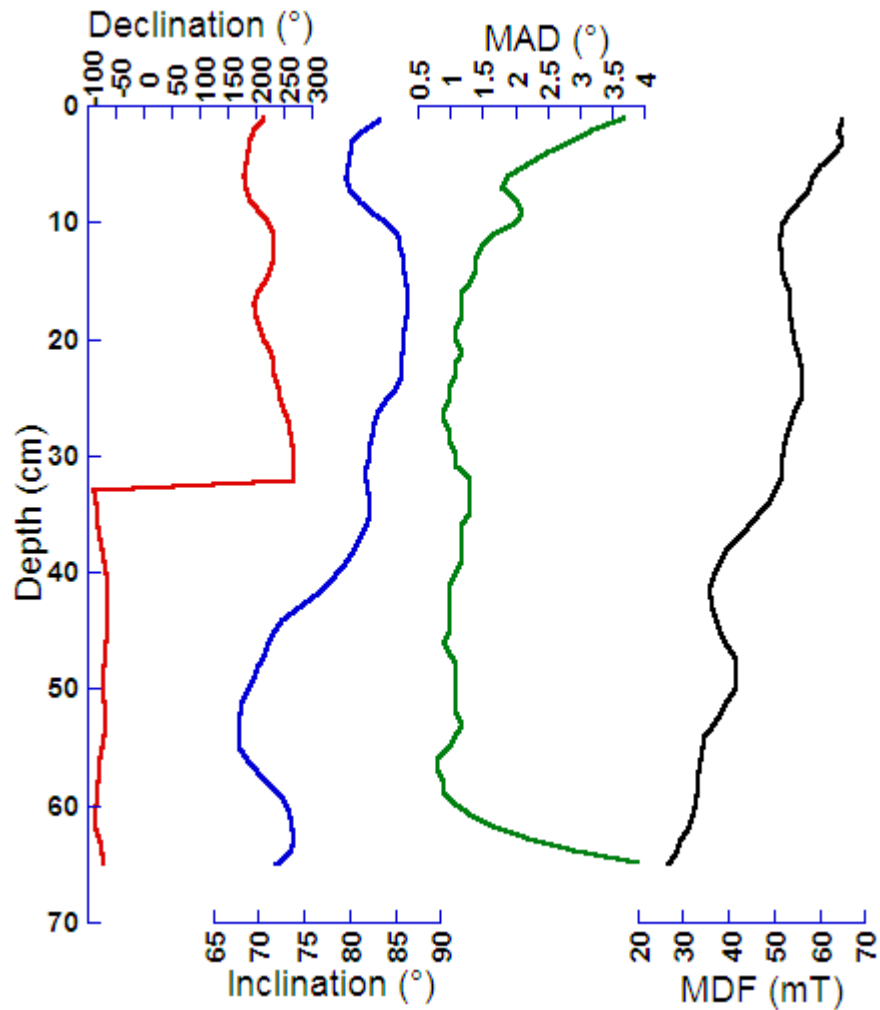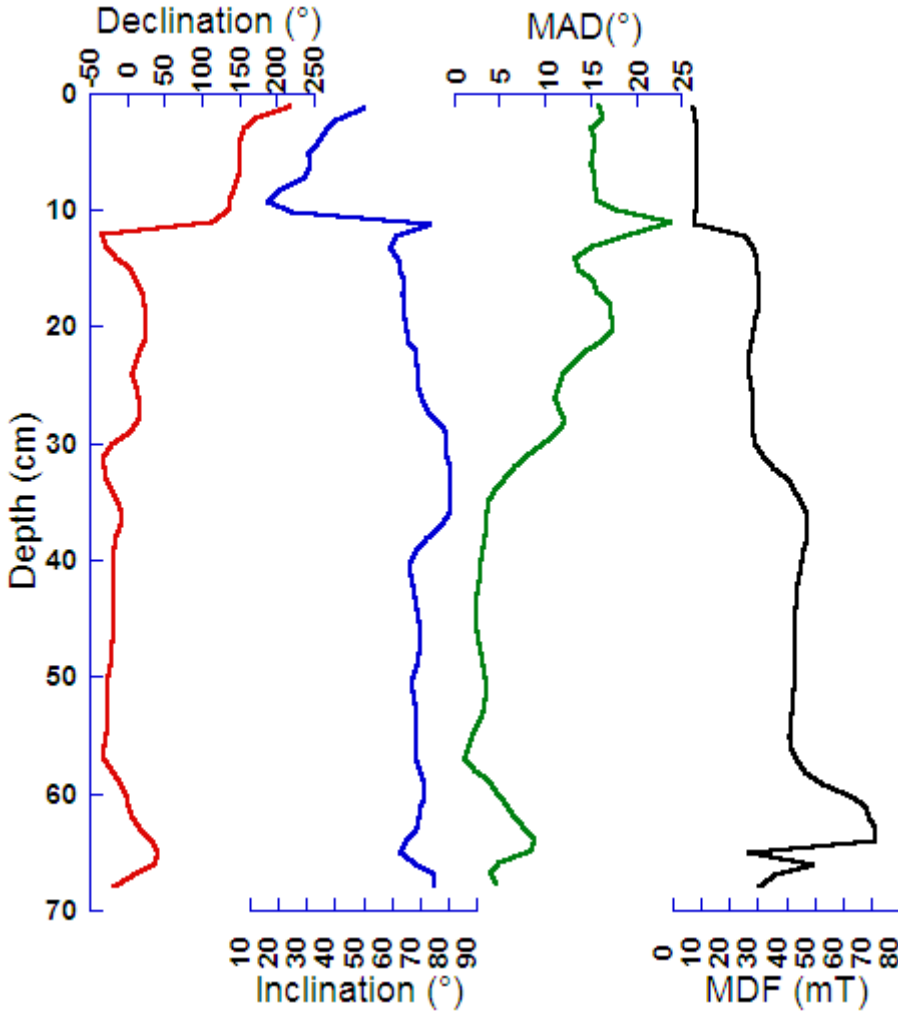
Figure 8. NRM record for L08F. Declination, Inclination, MAD and MDF vs Depth (down-core). Low MAD values indicate a reliable record and little variation in MDF indicates little change in mineralogy or grain size.

Figure 9. Environmental magnetism record for L08F Pseudo S-ratio, ARM/SIRM ratio and ARM vs Depth (down-core). Little variations in this record indicate constant magnetic mineralogy and grain size though out the core.

Figure 10. NRM record for L08G. Declination, Inclination, MAD and MDF vs Depth (down-core). Low MAD values indicate a reliable record and the drop in MDF indicates a change in mineralogy. The sudden drop in declination becomes the basis of the two age models presented in this study.
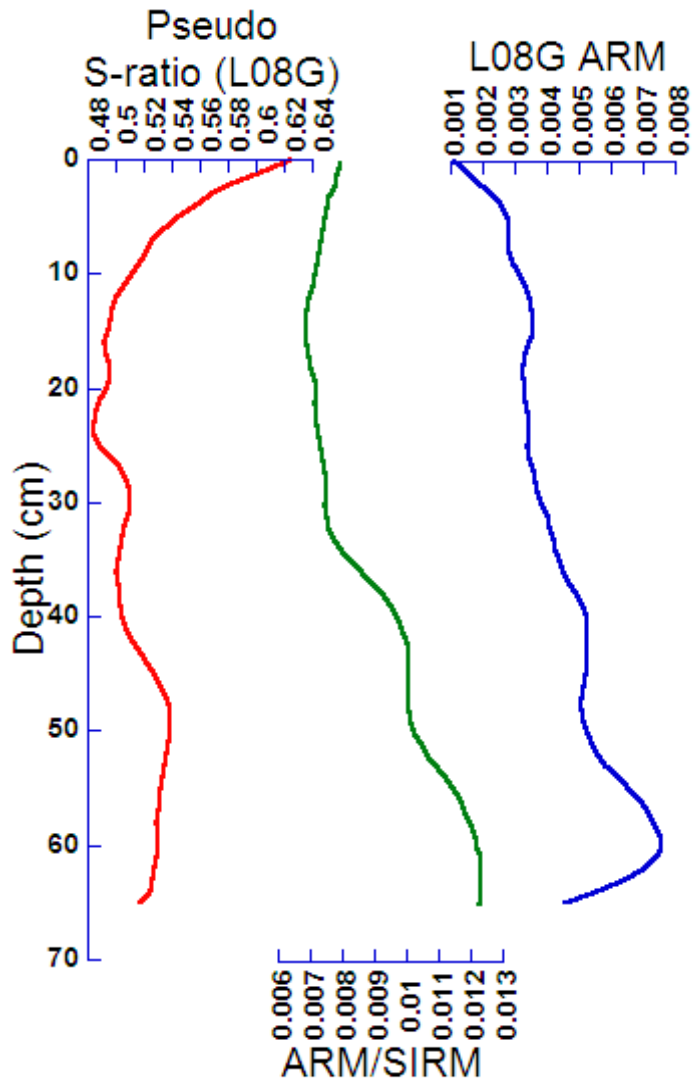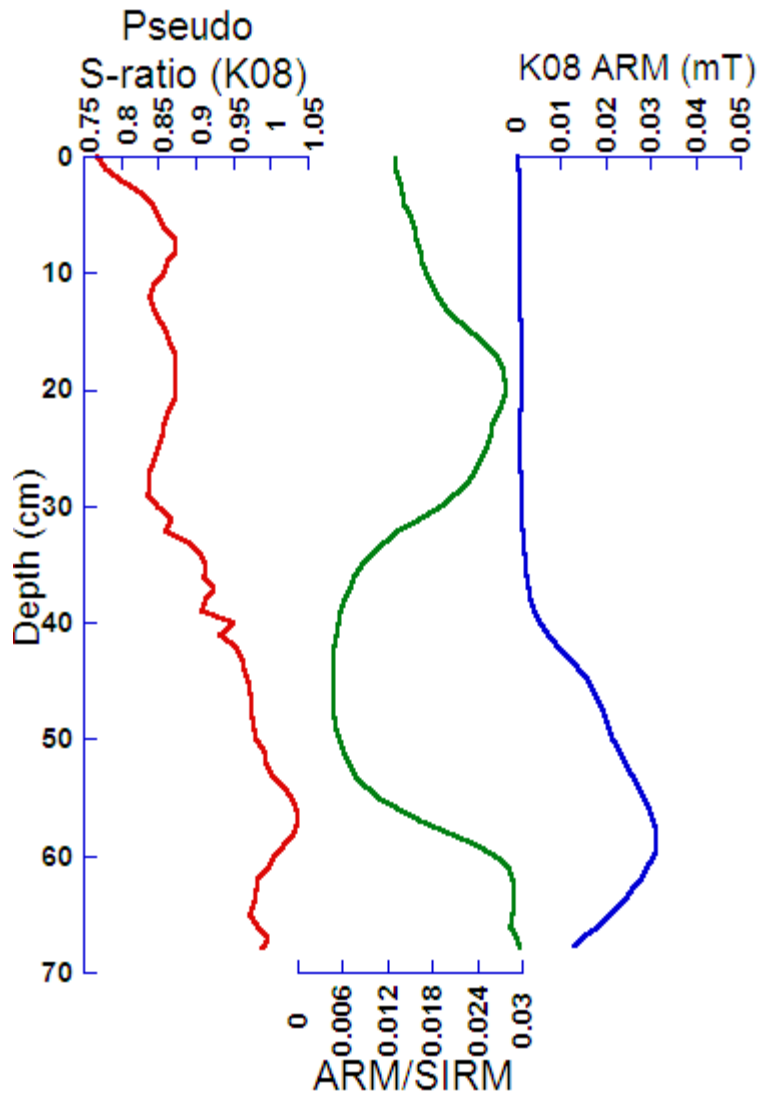
Figure 11. Environmental magnetism record for L08G Pseudo S-ratio, ARM/SIRM ratio and ARM vs Depth (down-core). The coincidental increase in ARM and ARM/SIRM indicates that a decrease in grain size is the driver of the changes in environmental magnetics down-core.

Figure 12. NRM record for K08. Declination, Inclination, MAD and MDF vs Depth (down-core). High MAD values indicate that the record is highly unreliable. The spike in MAD values that accompanies the drop in declination makes the event questionable.

Figure 13. Environmental magnetism record for L08G Pseudo S-ratio, ARM/SIRM ratio and ARM vs. Depth (down-core). The coincidental increase in ARM and pseudo S-ratio indicates that an increase the ferromagnetic minerals is the main driver of the changes in environmental magnetics down-core.
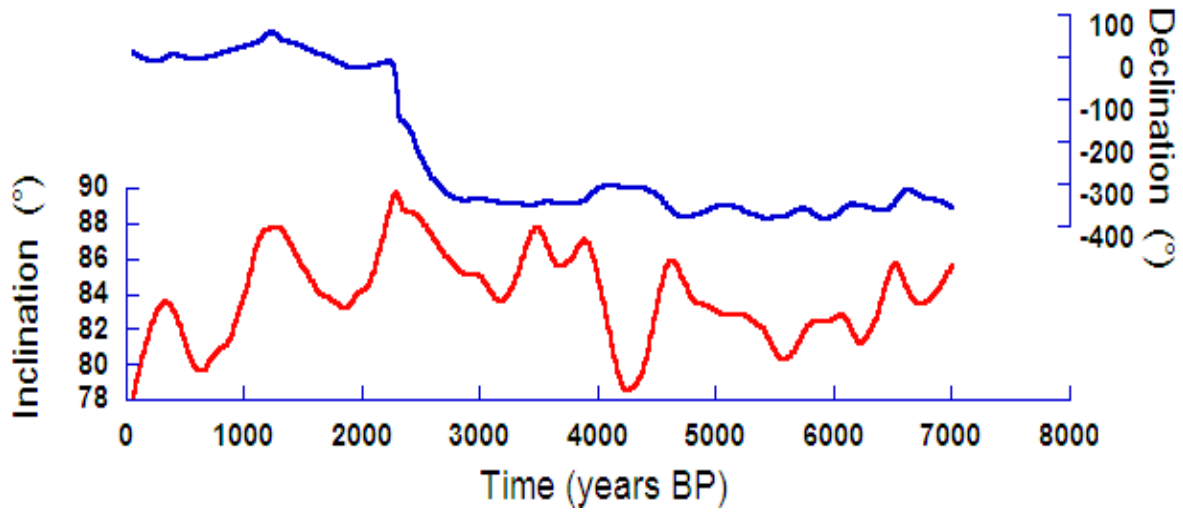
Figure 14. The declination and inclination record from Korte and Constable, 2005
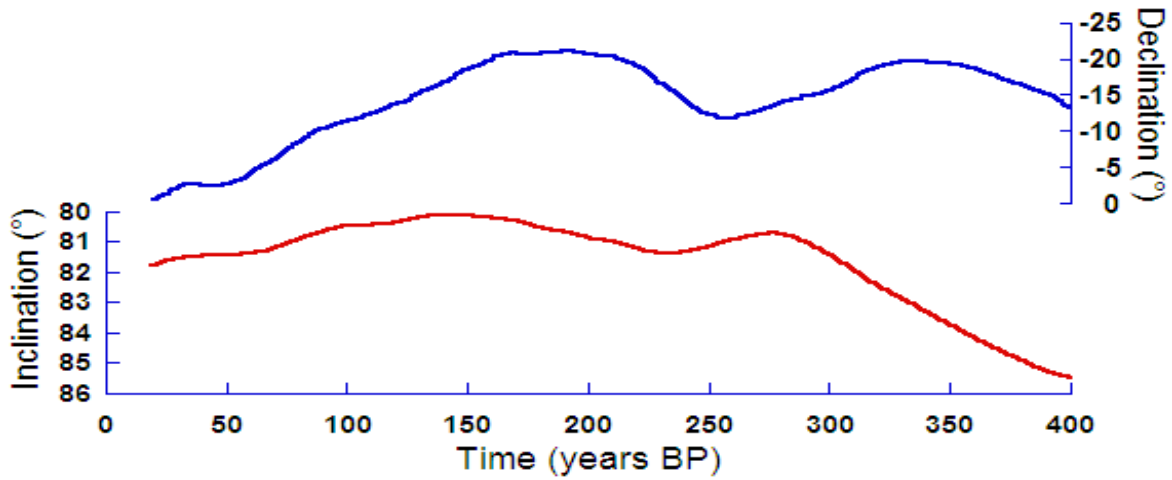
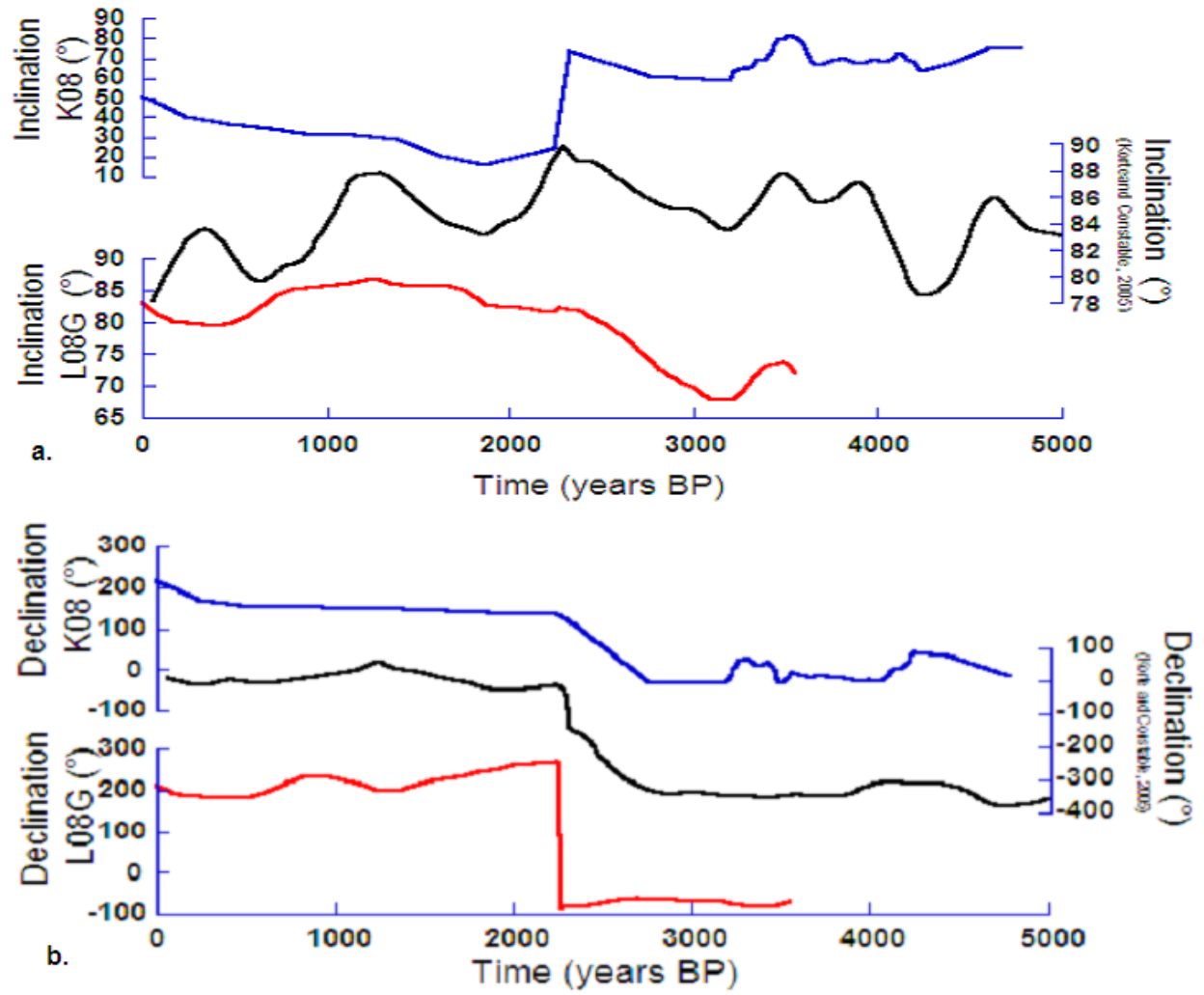Figure 15. The Declination and Inclination record from Jackson et al, 2000.

Figure 16. Best fit correlations of Inclination (a) and Declination (b) of K08 (blue) and L08G (red) compared with the Korte and Constable model (black).
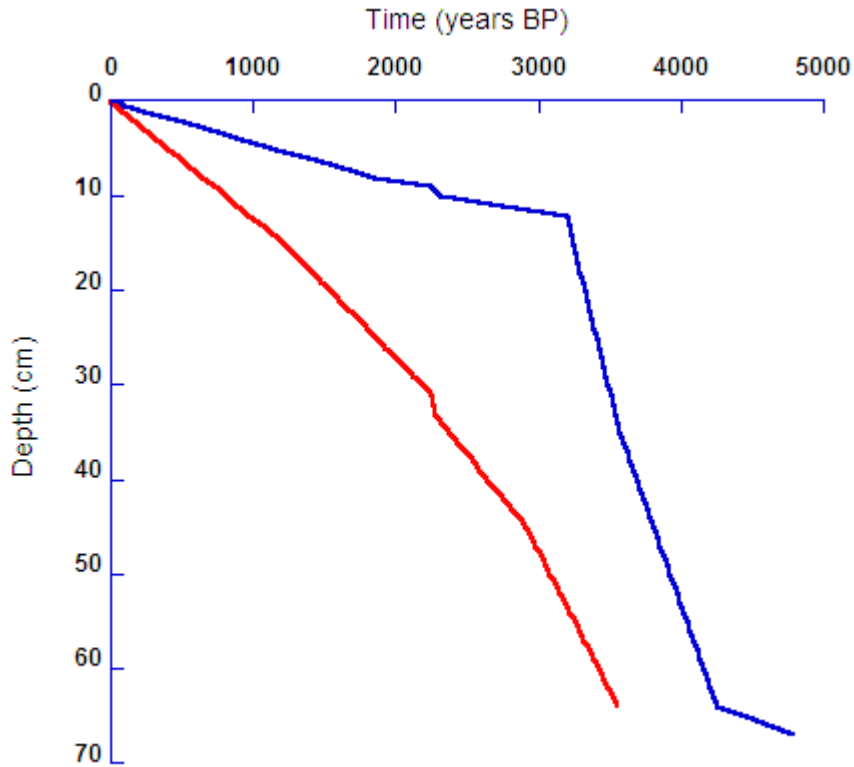
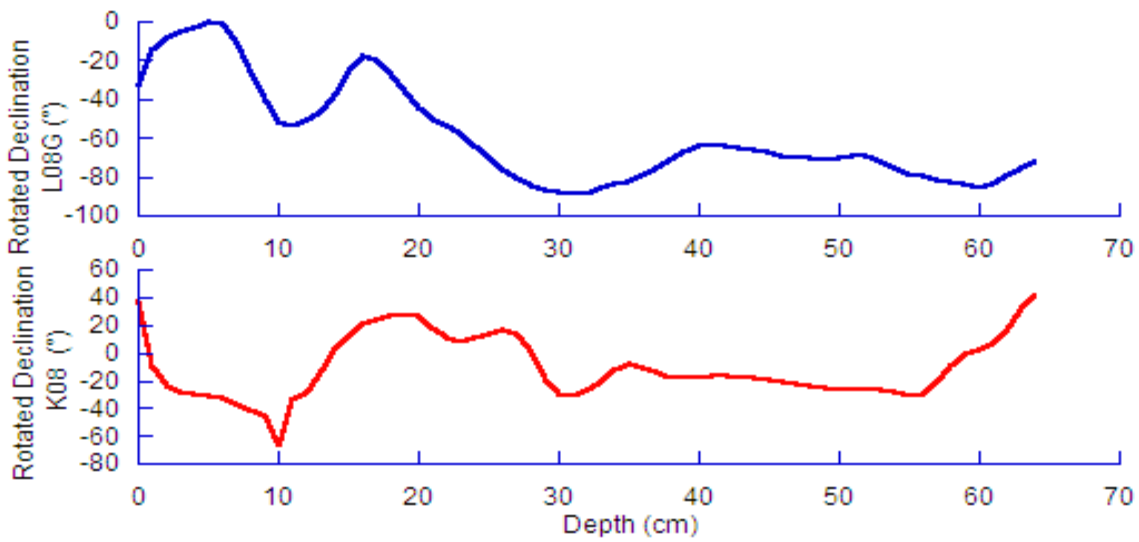Figure 17.Depth vs. Time of L08G (red) and K08 (blue)

Figure 18. Declination records of L08G and K08 with 0-33cm and 0-11cm rotated by 180 degrees, respectively.
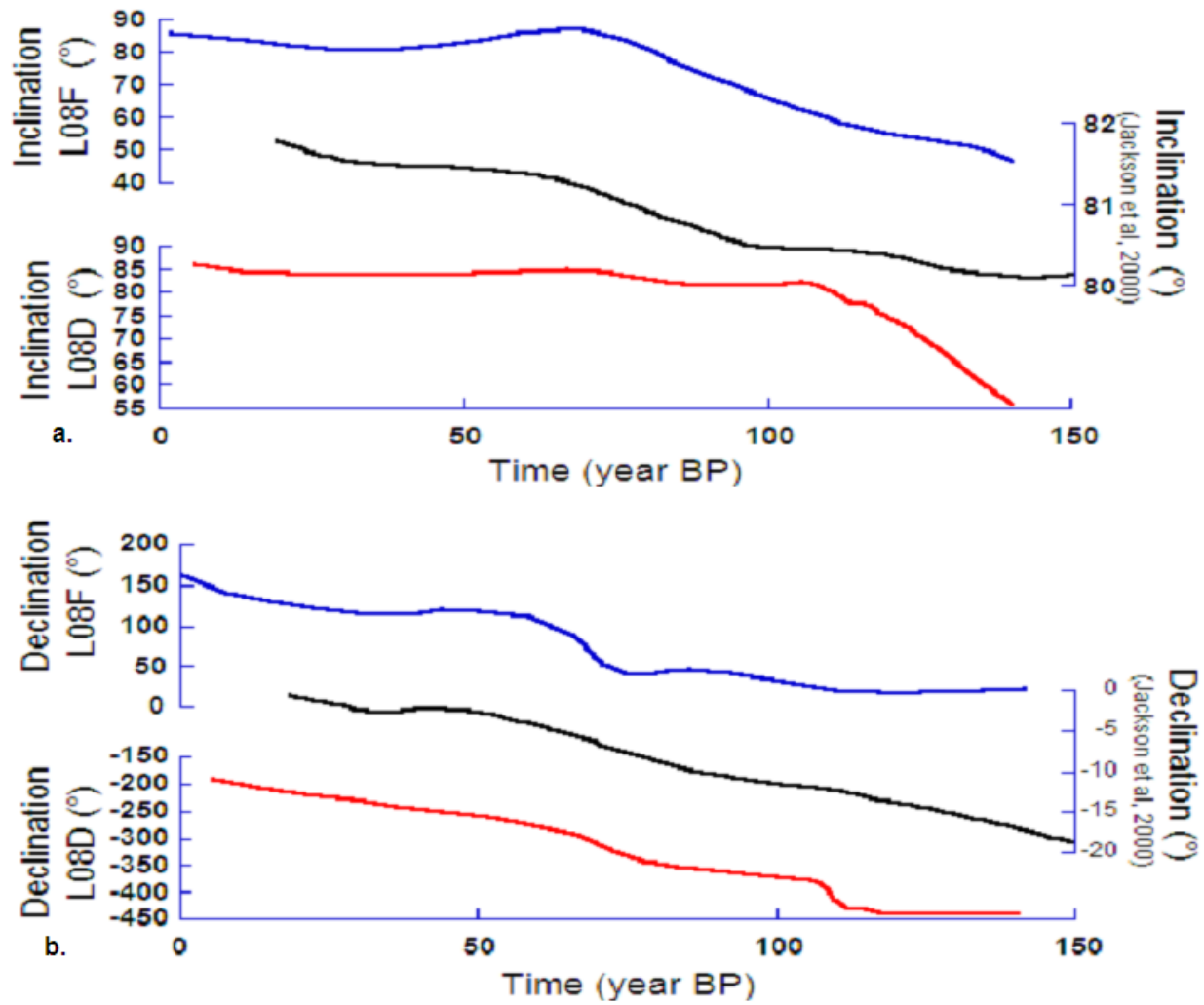
Figure 19. Best fit correlations Inclination (a) and Declination (b) of L08F (blue) and L08D (red) compared with the Jackson et al model (black).
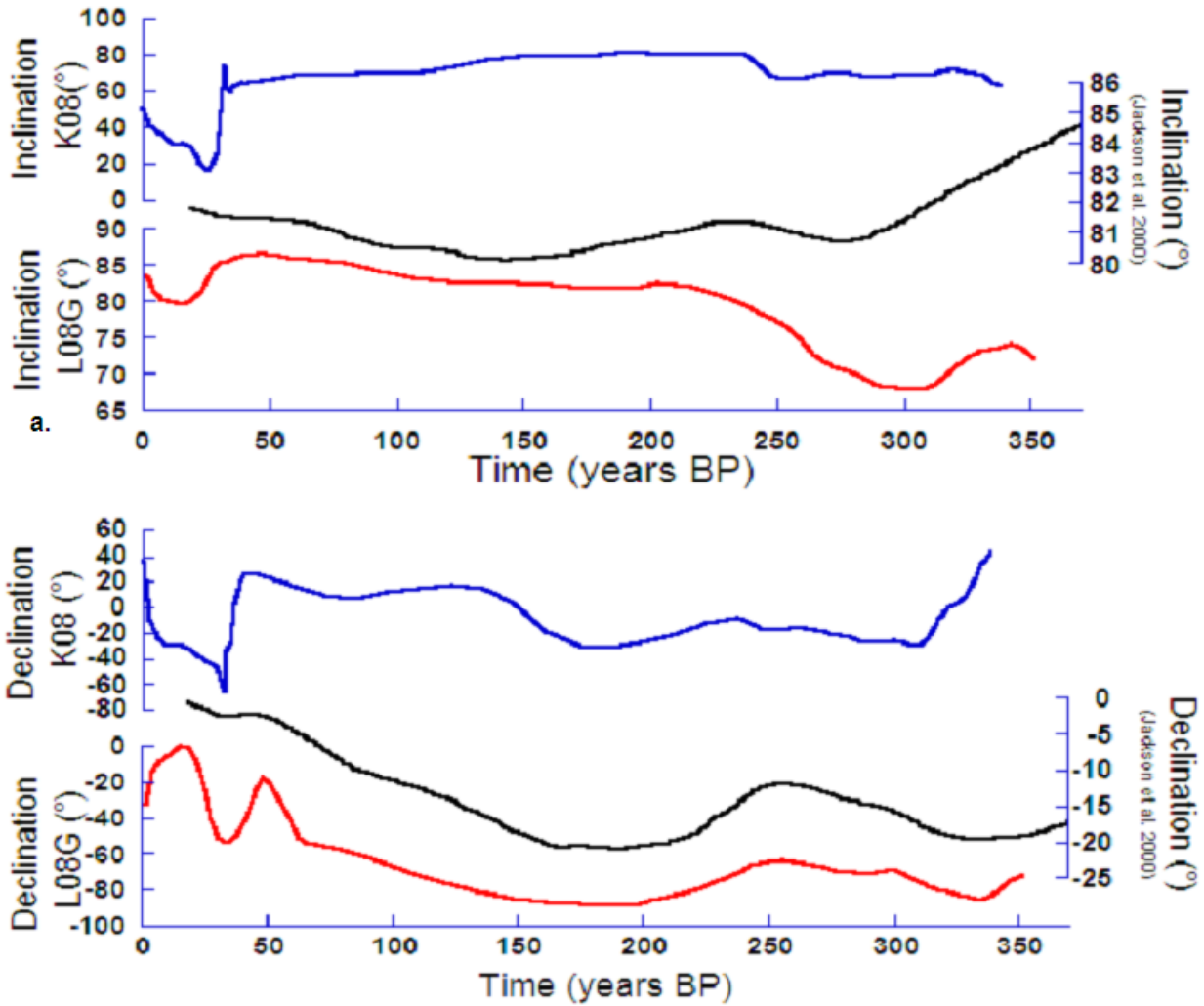
Figure 20. Best fit correlations Inclination (a) and Declination (b) of K08 (blue) and L08G (red) compared with the Jackson et al model (black).
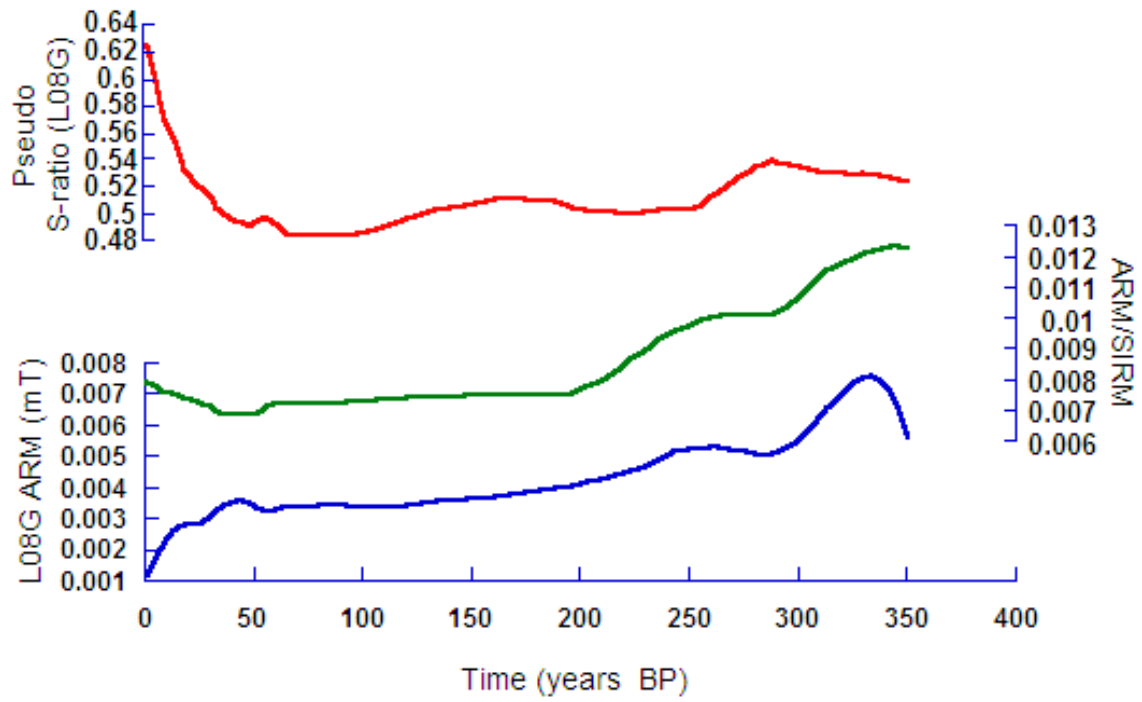
Figure 21. Environmental magnetism records for L08G vs. Time (years BP). Shows an increase in grain size at the end of the Little Ice Age.
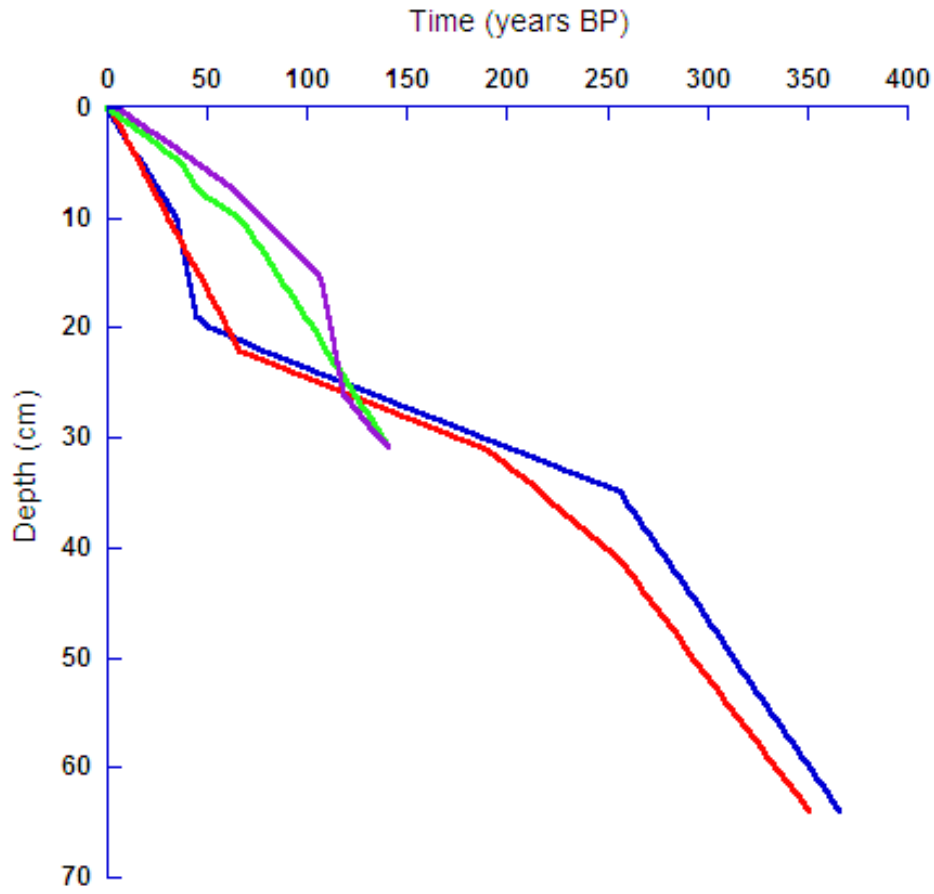
Figure 22. Time (years BP) vs. Depth (cm) of L08G (red), K08 (blue), L08F (purple) and L08D (green)

References

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