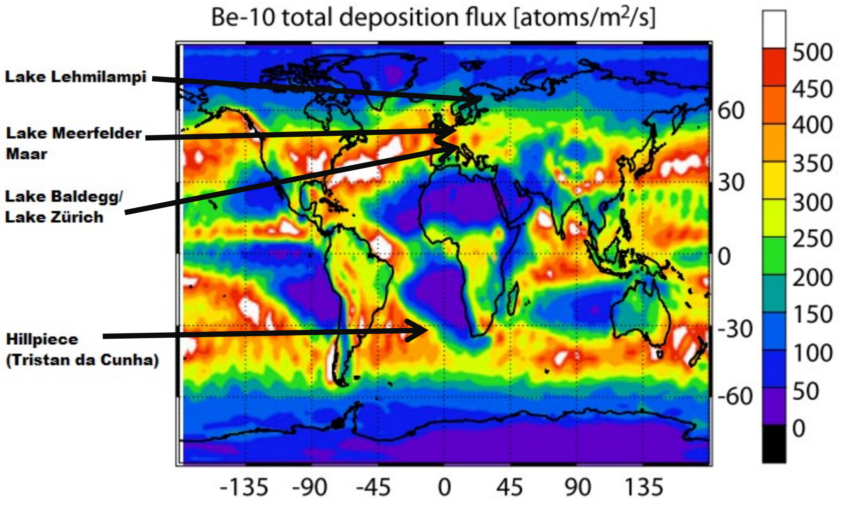
The dynamics of Beryllium 10 transport and deposition in lake sediments

Oskar Henriksson

Bachelor thesis in Geology at Lund University
no 488
(15 hp/ECTS credits)



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Lund University
2016

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Henriksson, O., 2016: The dynamics of Beryllium 10 transport and deposition in lake sediments. *Bachelor thesis in Geology at Lund University*, No. 488, 12pp. 15 hp (15 ECTS credits)

Abstract: Lake sediments have lately been explored as a ^{10}Be archive, complementing previous research on ice cores and marine sediments. ^{10}Be is an important proxy as it can be used to study past solar activity, a factor which affects the climate. Where other methods studying solar activity only cover a brief period of history, ^{10}Be has the potential to go further back in time. The concentrations of 10Be studied in lake sediments is however potentially influenced by other processes than solar activity. Despite this, the solar signal has successfully been identified with a resolution which in some studies is sufficient to show the 11-year (Schwabe) cycle. This paper aims to improve the understanding of processes affecting the ^{10}Be in lake sediments in order to identify weather measured ^{10}Be concentrations reflect changes in atmospheric production or environmental processes related to transport and deposition. By reviewing previous research, it has been found that influences from the surrounding environment are present in the preserved ^{10}Be concentrations in lake sediments and have to be accounted for in order to obtain a reliable solar signal. However, when these influencing factors are corrected for, a solar signal with annual resolution can be obtained. This leads to the conclusion that ^{10}Be in lake sediments could be comparable to other archives such as ice cores, with the benefit of reaching further into the past.

Keywords: Lake sediment, ^{10}Be, Beryllium-10, solar activity, solar cycle

Supervisors: Markus Czymzik and Raimund Muscheler

Subject: Quaternary Geology

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Dynamiken rörande transport och deposition av beryllium 10 i sjö sediment

OSKAR HENRIKSSON

Henriksson, O., 2016: The dynamics of Beryllium 10 transport and deposition in lake sediments. Examensarbete i geologi vid Lunds universitet, No. 488, 12pp. 15 hp (15 ECTS credits)

Sammanfattning: Sjösediment har på senare tid studerats som arkiv för Beryllium-10 (^{10}Be) en isotop som härrör från kosmisk strålning. Isotopen ^{10}Be är mycket intressant då den kan användas för att studera historisk solaktivitet, en faktor som påverkar klimatet. Sjösedimenten anses komplimentera tidigare forskning rörande ^{10}Be, då med fokus på isborrkärnor och marina sediment. Solens aktivitet har identifierats framgångsrikt med en upplösning som i vissa fall är god nog för att identifiera den 11-åriga solcykeln. Syftet med denna artikel är att öka förståelsen för processer som påverkar ^{10}Be koncentrationen i sjösediment, genom att avgöra huruvida uppmätta ^{10}Be koncentrationer speglar produktion i atmosfären eller om indirekta störningar under transport och deposition påverkar resultatet. Genom att granska tidigare publikationer inom området, har det varit möjligt att identifiera faktorer i sjön och i dess närhet, som påverkar koncentrationen av ^{10}Be i sedimenten. När dessa påverkande faktorer tas i beaktande är det möjligt att återskapa historiska signaler från solen, i vissa fall med årlig upplösning. Detta leder till slutsatsen att sjösediment kan vara jämförbara med andra klimatarkiv så som isborrkärnor, med den fördelen att sjösediment opåverkat sträcker sig längre tillbaka i tiden.

Nyckelord: Sjö sediment, ^{10}Be, Beryllium-10, solcykel

Handledare: Markus Czymzik och Raimund Muscheler

Ämnesinriktning: Kvartärgeologi

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1 Introduction

Beryllium-10 (^{10}Be) is a cosmogenic radionuclide formed in the Earth's atmosphere when protons and neutrons (formed when galactic cosmic rays collide with atmospheric atoms) spallate oxygen and nitrogen atoms. (Kaste & Baskaran 2012). The production rate is influenced by the deflection of galactic cosmic rays as an affect of magnetic shielding. Strong geomagnetic and solar magnetic fields, cause stronger deflection of the galactic cosmic rays (Ljung et al. 2007). Hence, a weaker solar activity means that more cosmogenic radionuclides such as ^{10}Be will be produced in the atmosphere. From the troposphere ^{10}Be is scavenged by rain, snow or dust particles, bringing ^{10}Be to the Earth´s surface after residing in the atmosphere for 1-2 years (most of this time is spent in the stratosphere) (Berggren et al. 2010). The processes behind the production are well understood making the radionuclides useful proxies when studying past solar activity variations, which has been successfully done using ice cores in polar regions (Berggren et al. 2009). Ice cores do however, loose temporal resolution through lateral ice flow and thinning (Mann et al. 2012). Since ^{10}Be is long lived with a half-life of 1.388 ± 0.012 Ma (Korschinek et al. 2010), it has the potential to be used on longer time scales than ice cores can accommodate (Fink & Smith 2007). Recently, ^{10}Be measurements in annually laminated lake sediments have proven to be an attractive optional research area for solar activity reconstructions. Annually laminated lake sediments have the benefit of a temporal resolution independent of the age of the sediment (Mann et al. 2012). However, ^{10}Be measurements in lake sediments are more difficult to interpret as an array of factors affect the transport and deposition within the catchment and lake (Berggren et al. 2013). In order to interpret solar activity signals from these sensitive paleoenvironmental records further research has to be conducted on the dynamics of ^{10}Be deposition in lake sediments (annually laminated or not).

The production rates of ^{10}Be have been found to vary naturally by about 25 % within the 11-year solar cycle (Schwabe cycle) and even greater variations are expected on centennial timescales (Kaste & Baskaran 2012). The 11-year cycle which is often referred to when studying solar activity can be identified in a multitude of records. The last 400 years are covered by the recently revised data on sunspot numbers (Clette et al. 2015), which have been visually observed and counted using telescopic instruments. Other records such as the solar modulation potential, which focuses on the cosmic rays rather than the solar activity, also show similar results (Mann et al. 2012). The variations in ^{10}Be are of great interest for researchers studying solar cycles and climatic variability on longer time scales (Martin-Puertas et al. 2012). The measurable trends of ^{10}Be variations in lake sediments, are as mentioned, sensitive to influences from the surrounding environment. Since some work has already been done on the topic, a literature review should form a good platform for a better understanding of the dynamics behind ^{10}Be transport and deposition in lake sediments which can be used to improve the understanding of solar influences on the climate.

The aim of this paper is therefore to study the dynamics of ^{10}Be transport and deposition in lake sediments, as a means to further develop and understand the potentially useful archive with regards to solar activity reconstruction. This will be accomplished by reviewing previous research and comparing ^{10}Be in lake sediments with other known archives.

2 Methods

Six studies on lake sediments have been chosen for their contributions to the field. These have been studied and reviewed in detail in order to give a comprehensive answer to the dynamics of ^{10}Be transport and deposition in lake sediments. Firstly, chapter 5 from Handbook of environmental isotope geochemistry gives an overview of ^{10}Be as an environmental tracer (Kaste & Baskaran 2012). Two of the sources deal with data from the small Lake Lehmilampi in Finland, the first covering the period 1900-2006 (Berggren et al. 2010) and the second 1468- 1980 (Berggren et al. 2013). Further, a paper dealing with ^{10}Be concentrations from two lakes in Switzerland covering the period 1901-2010 where studied (Mann et al. 2012). ^{10}Be analysis from a small bog (previously a lake) on the isolated island of Tristan da Cunha (Ljung et al. 2007) was another source of information. Finally, a paper covering research from Lake Meerfelder Maar was also reviewed (Martin-Puertas et al. 2012).

3 Results

The main results from the investigated papers can be summarized as follows:

- All reviewed articles agree that ^{10}Be can be used as a proxy for solar activity, under suitable conditions.
- All reviewed articles highlight the need to rework the raw ^{10}Be data in order to study solar related trends successfully.
- Most articles advocate smaller catchment areas for improved assessment of solar variability
- All reviewed articles acknowledge the need to compare the ^{10}Be data with other locations or other proxies for improved credibility.
- All reviewed articles emphasize the difficulty to fully understand the dynamics of ^{10}Be transport in lake sediments.

4 Discussion

4.1 Processes affecting ^{10}Be concentrations in lake sediments

4.1.1 Scavenging from the atmosphere

Scavenging is a term widely used to describe to process where ^{10}Be, or any other smaller constituent adsorbs to a larger body and gets removed from its previous place of residence. In the case of ^{10}Be deposition this is the mode of transport by which ^{10}Be is removed from the atmosphere. The scavenging of ^{10}Be takes many different forms, e.g. through wet deposition in rain and through dry deposition with suspended aerosols Kaste & Baskaran (2012). Reports have emphasized the fact that the amount of ^{10}Be deposited at a certain locality is also affected by its geographical position, as atmospheric ^{10}Be concentrations vary with latitude.

Precipitation is a major carrier phase of ^{10}Be. The effects of local weather patterns on ^{10}Be have been modeled by Heikkilä et al. (2013) and further studied by Berggren et al. (2010) showing that as well as affecting sediment transport after heavy downpour, rain is a direct carrier of ^{10}Be from the atmosphere to earth (wet deposition). Kaste & Baskaran (2012) add that during storm events the ^{10}Be concentration in the rainfall is affected by amount of precipitation, as the ^{10}Be is scavenged in the initial stages of the storm. A larger storm with more rainfall therefore dilutes the concentration of ^{10}Be reaching the lake. Precipitation also comes in other forms than rain. Berggren et al. (2010) found evidence which shows a lower ^{10}Be concentration in sediment during periods of extensive snow cover, and speculate whether this is due to lower temperatures giving less precipitation. Kaste & Baskaran (2012) on the other hand claim that the snow itself has a higher ^{10}Be concentration compared to rain due to a larger surface area, therefore being a more efficient scavenger.

The geomagnetic shielding varies with latitude and higher atmospheric concentrations of ^{10}Be are present at high latitudes in absence of shielding (Masarik & Beer 1999). Berggren et al. (2010), also states that ^{10}Be is deposited in a predictable manner with regards to latitude, as shown in *Fig. 1* (Heikkilä (Heikkilä et al. 2013). Berggren et al. (2010) also adds that there are variations that are likely due to atmospheric circulation. *Fig. 1* (Heikkilä et al. 2013), clearly shows a correlation between amount of precipitation and ^{10}Be deposition with well defined latitudinal zones. Kaske & Baskaran (2012) claim that precipitation has a stronger correlation to ^{10}Be flux compared to latitude. This can be observed in *Fig. 1*, where areas that get a lot of precipitation such as the west coast of the Americas also get high values for ^{10}Be deposition. This in turn means that sediment on an island such as Tristan da Cunha with a high annual precipitation (Ljung et al. 2007), would get higher ^{10}Be concentrations in the sediment simply due to amount of precipitation compared to an inland site at the same latitude e.g. South Africa or central Australia. Altogether it is clear that the location of the studied site does have an impact on the concentrations of ^{10}Be in lake sediments, through a combination of precipitation, atmospheric circulation and latitude.

Wet deposition or scavenging of ^{10}Be through precipitation accounts for the larger part of the ^{10}Be deposition for the lakes studied in this paper. However, in other locations as is clear from *Fig. 1* precipitation is low. In such locations it is reasonable to assume that dry deposition accounts for the main influx of ^{10}Be. For the Lake Lehmilampi site it is estimated that dry deposition is responsible for roughly 20% of the ^{10}Be deposition when comparing wet and dry deposi-

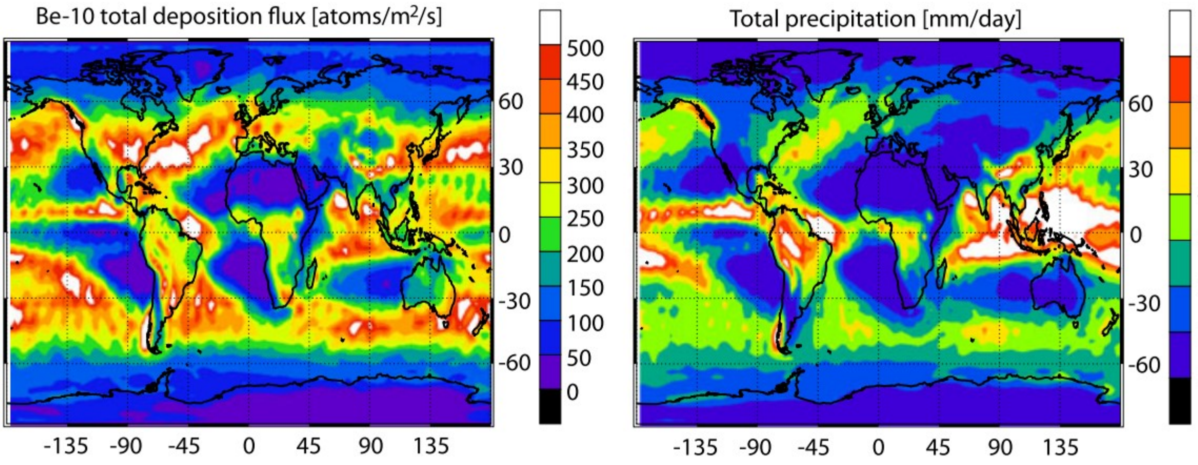

Fig. 1. The map on the left shows the deposition flux of 10Be (atoms/m^2/s) which has been modelled using a climate model averaged over years 1986- 1990. On the right the precipitation rate for the same period is shown. Figure from Heikkilä et al. (2011).

tion (Berggren et al. 2010). Dry deposition is considered to be of “lesser importance” according to Kaske & Baskaran (2012). This statement is however, unlikely to be true for areas such as those with very low precipitation. It has also been shown that the rapid settling of volcanic ash, following stratospheric volcanic eruptions such as Agung (1963) and Pinatubo (1991) cause significant peaks in ^{10}Be deposition in polar regions as ^{10}Be is scavenged from the atmosphere by settling aerosols (Baroni et al. 2011).

4.1.2 Transport to lake catchment

Once the ^{10}Be has reached Earth through either wet or dry deposition it will continue to move with the sediments through redeposition before it settles. The catchment area of the lake is a factor which many researchers consider a main source of uncertainty. A larger catchment area has a greater variability when it comes to sediment transport following heavy rain and flooding.

Most of the reviewed papers have chosen localities with a small lake and catchment area in order to limit uncertainties to do with sediment redeposition. The studied bog on Tristan da Cunha measured 220 m^2 and had a catchment area of 4500m^2 which together with the barren surrounding landscape was considered a good locality for limiting the uncertainties on ^{10}Be concentration within the lake sediment (Ljung et al. 2007). Lake Lehmilampi (Finland), has an even smaller surface area of 150m^2 and a catchment area of 1000 m^2 (Berggren et al. 2010) which means that less environmental influences are expected. The Swiss lakes (Mann et al. 2012) on the other hand have seemingly not been chosen for their small size. The larger of the two, Lake Zurich, has a surface area of roughly 89 000 m^2 while Lake Baldegg has a surface area of 5 200 m^2. Mann et al. (2012) do however acknowledge this fact that large and eroding catchment areas are less suitable for investigating changes in ^{10}Be concentration as ^{10}Be attached to older eroded sediments could elevate the concentrations in core samples. Methods to limit the effect of “old” ^{10}Be transported to the lake sediments during events of sediment redisposition have been investigated. Potassium is an element which indicates the presence of detrital catchment material, peaks of the element in the data set could therefore be used to correct the data for sediment redeposition (Czymzik et al. 2015).

As mentioned by Ljung et al. (2007) with regards to the locality on Tristan da Cunha the vegetation cover throughout the catchment area is another factor which affects the influx of ^{10}Be. ^{10}Be is intercepted by the vegetation cover increasing the transport time and affecting the deposition. On Tristan da Cunha the volcanic bedrock with little vegetation combined with the large amount of steady precipitation which an island often gets, means that the sediment transport is short giving accurate readings of ^{10}Be concentration (Ljung et al. 2007). In a heavily vegetated environment both sediment and ^{10}Be transport will be slowed down, as vegetation prevents sediment erosion. When ^{10}Be remains and accumulates in the catchment area sediments, there is a potential for reworking during i.e. storm and flooding events thus disturbing the signal in lake sediments (Berggren et al. 2010). Berggren et al. (2010) also refers to the “detention effect” which produces a lag in the arrival of ^{10}Be as it is will not immediately reach the lake, confounding the production signal.

Another important influence on ^{10}Be in Lake sediments that should be mentioned, is the dilution of ^{10}Be concentrations through sediment input. Similarly to the dilution of ^{10}Be in rainfall through an increase in precipitation, an increased input of sediment will affect the ^{10}Be concentration in the sediment. This is a change which has nothing to do with the atmospheric production and would therefore be misleading with regards to solar activity reconstruction. Flux is a measure sometimes used as an alternative to ^{10}Be concentration as it provides a value on the ^{10}Be deposition.

4.1.3 Processes in the lake

Within the lake the last and final interactions with the environment take place. Just as with the earlier discussed catchment area sediment redeposition is a factor within the lake itself. Underwater currents and bioturbation are examples of processes which could disturb settled sediment and affect the ^{10}Be concentrations in shallow layers, hence disturbing the produced signal. Similar to the atmospheric processes scavenging occurs from the waters of the lake, where both organic and minerogenic particles are thought to affect the concentrations of ^{10}Be in sediments. According to

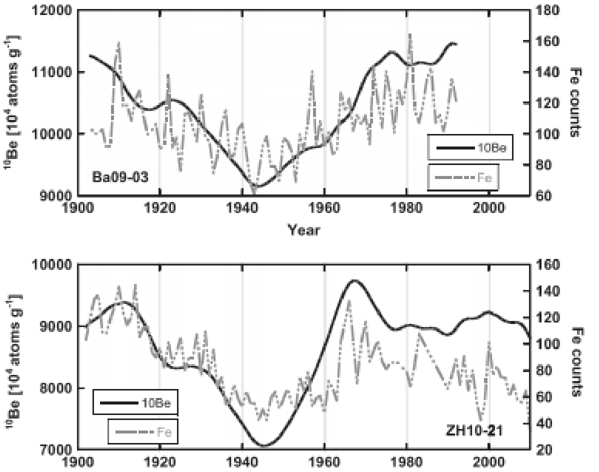

Fig. 2. Upper panel shows annual ^{10}Be concentration (grey) and iron signal (black) from Lake Baldegg (Ba09-03), lower panel similarly shows data from Lake Zurich (ZH10-21). Figures from Mann et al. (2012).

Kaste & Baskaran (2012) aluminosilicates are major carriers of ^{10}Be, highlighted by the correlation between ^{10}Be and Al in ocean margin sediments. Further, the mechanism behind the adsorption is explained by the interaction with oxygen on the mineral surface. Apart from primary and secondary silicates, iron is also mentioned as a potential scavenger in the lake. The iron correlation is investigated by Mann et al. (2012) where iron-oxy-hydroxides are found to be a favorable carrier in lake waters. The strong correlation of iron and ^{10}Be in lake sediments, is shown in *Fig. 1* highlighting the need for a separation as to limit influences from the lakes redox cycle (Mann et al. 2012).

In the sediment core from Tristan da Cunha (Ljung et al. 2007) ^{10}Be is found attached to both organic and inorganic particles. Berggren et al. (2010) also recognize organic particles as efficient scavengers whereas Kaste & Baskaran (2012) argue that, even though ^{10}Be can form complexes with organic particles, there is a significantly higher adsorption to inorganic particles. It is reasonable to assume that different processes within the lake may govern ^{10}Be transport and deposition at different sites depending on the properties of the lake studied.

4.2 Case study: comparison of ^{10}Be lake records for the last 100 years

Sediment cores from both Lake Lehmilampi (Berggren et al. 2010) and from the Swiss lakes, Baldegg and Zurich (Mann et al. 2012) overlap during the period 1901-2006. With respect to solar variation and the dynamics of ^{10}Be transport in sediments they are therefore a good base for a comparison. Further, the impact of the catchment and surface area of the lakes can be studied and compared since they vary significantly in size. It is acknowledged for the comparison that, the Lake Lehmilampi paper (Berggren et al. 2010) predates that of the Swiss Lakes, Mann et al. (2012). Mann et al. (2012) also refers to the Lake Lehmilampi data which has a fundamental discussion with regards to the dynamics of ^{10}Be when it comes to local weather and solar activity. The Lake Lehmilampi data discussed by Berggren et al. (2010) is also included in an extended data set published by Berggren et al. (2012).

In order to compare and contrast the ^{10}Be concentrations from Lake Lehmilampi with ^{10}Be concentrations from the two Swiss Lakes, both figures and methods to improve the identification of solar activity are studied. Comparison will also be made with the 11 - year solar cycle in order to discuss the usefulness of the records for identification of such short-term signals. Also, findings from previously reviewed papers are considered when comparing these records covering the last 100 years.

As *Fig. 3* illustrates the raw data presented in the two articles do not show a clear anti-correlation with the 11-year cycle illustrated by the sunspot numbers data. It is clear that variations such as those described affecting the ^{10}Be deposition, impact on the data and lower the signal to noise ratio (SNR). The signal is harder to isolate during a short time-span, and the noise will potentially mask the ^{10}Be signal completely. When studying the two different data sets for Lake Baldegg (*Fig. 3*, upper graph), Ba09-03 with Ba10-01 it is clear that there are some differences between the data, possibly due to environmental influences at the different core sites.

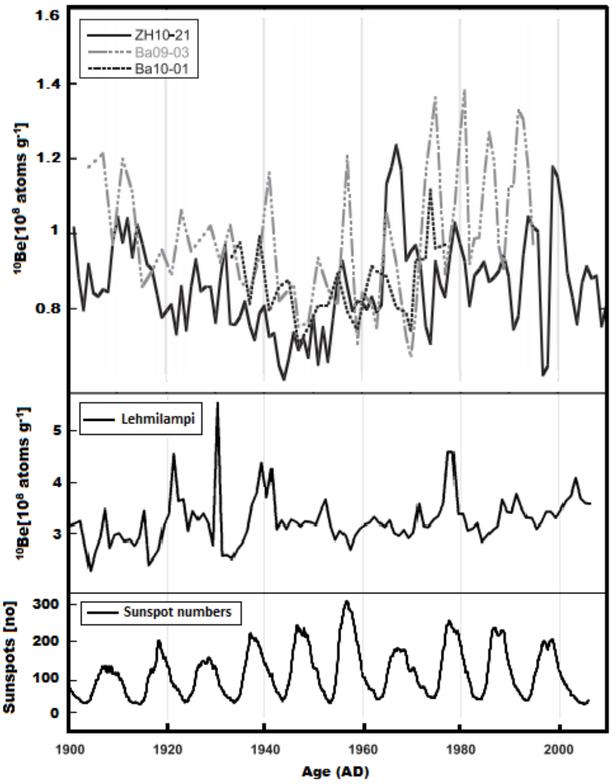

Fig. 3. Figure comparing ^{10}Be concentrations for the Swiss lakes, Zurich (ZH10-21) and Baldegg (Ba09-03), (Ba10-01) (Mann et al. 2012) with Lake Lehmilampi (Berggren et al. 2010). Number of sunspots is also included (Clette et al. 2015) for visual comparison with the 11-year cycle.

One should observe that sunspot number and solar variation potential is usually presented inversely, so that a peak in these values corresponds to a peak in ^{10}Be concentration for the sediment. *Fig. 3* (sunspot numbers) is however not presented with the data inversed with the result that a peak in sunspot numbers corresponds to a minimum in 10Be concentration for the lake sediments.

Both Mann et al. (2012) and Berggren et al. (2010) similarly aim to investigate the ^{10}Be signal in lake sediments. They both collect the ^{10}Be concentrations from the lake sediment, however they process the data slightly differently. Berggren et al. (2010) calculate the ^{10}Be accumulation rate (by multiplying the ^{10}Be concentration with SAR, sediment accumulation rate) in order to link measured ^{10}Be to the production

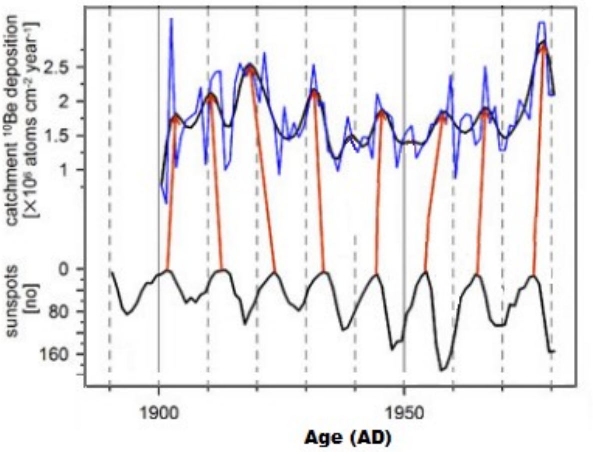

Fig. 4. ^{10}Be data from Lake Lehmilampi compared with the number of sunspots. Red lines show leads and lags between 11 -year cycle events, illustrated with sunspot numbers (black). the ^{10}Be data has been processed with a low pass filter (1/6a^{-1}). Figure from Berggren et al. (2010).

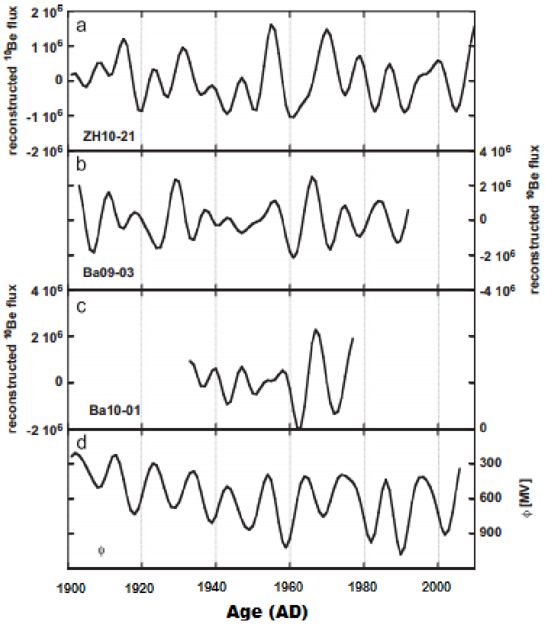

Fig. 5. ^{10}Be concentrations modeled with a low pass filter (1/6a^{-1})from the two swiss lakes, compared to the solar modulation potential (ϕ). Data collected and processed from Mann et al. (2012).

and deposition rate. The ^{10}Be accumulation rate was then reduced by 20% in order to remove hypothetical dry deposition producing catchment ^{10}Be deposition. Mann et al. (2012) also reworks the concentration data, producing a "depositional flux" similar to the accumulation rate calculated by Berggren et al. (2010). Efforts are also made to remove the long term modulation related to the redox-driven iron cycle, as a strong coupling between ^{10}Be and the iron signal was found. The method used to separate the lakes redox cycle from the ^{10}Be signal to avoid the masking of the solar influence, was singular spectrum analysis (SSA). SSA is a popular way to study a time series using a mathematical approach trough linear algebra. The disadvantage mentioned by Mann et al. (2012) with the SSA approach is that, when removing the modeled data related to the redox-cycle, long term trends are lost. While the short term variations (such as the 11-year cycle) appear to agree better, the method does not allow the study of variations across longer periods of time from this record.

Fig. 4 and *Fig. 5* illustrate the necessity of working with the data to remove noise and other masking factors which allow the identification of trends. Low-pass filtering is another practical method used by both studies to remove short-term noise from variable weather. Here, it should also be observed that the sunspot numbers and the solar modulation potential has been presented inversely for both figures, with the intention of aiding visual perception.

Another difference between the two studies is the fact that Berggren et al. (2010) chooses to compare the data from Lake Lehmilampi with sunspot numbers data, while Mann et al. (2012) considers the solar modulation potential to be more closely related to ^{10}Be production as it reflects the intensity of galactic cosmic rays at Earth. However, number of sunspots and the solar modulation potential differ only slightly, both showing the 11-year cycle and are expected to have a lead time of roughly 1.5 years prior to ^{10}Be deposition. Results from the two studies show leads and lags of 2 years (Berggren et al. 2010) and 0-3 years (Mann et al. 2012) with regards to the 11-year cycle, highlighting the chronological uncertainties present in the data.

Further the impact of the catchment area, while considered an important source of disturbance for the ^{10}Be signal, does not impact the data from the Swiss lakes in a way that makes the signal unidentifiable. This revelation contradicts the statement that a smaller catchment would significantly improve chances of obtaining a reliable solar signal, as argued by Ljung et al. (2007). This could potentially mean that locations previously considered inappropriate could give interesting findings, if caution is taken when considering correlations with scavengers and other natural processes.

4.3 Comparison to other natural archives

4.3.1 ^{10}Be in Ice cores

In polar regions such as Greenland or Antarctica it is possible to obtain ice cores, which are considered one of the best sources for climatic reconstruction. ^{10}Be has successfully been used as a solar proxy in Greenland ice cores (Berggren et al. 2009). Many other proxies are also found and stored in the ice due to the yearly accumulation of precipitation in the form of snow. Together with radionuclides such as ^{10}Be solar signals can be identified.

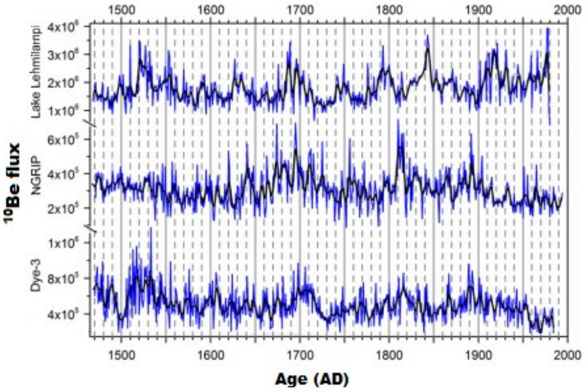

Fig. 6. ^{10}Be deposition from the sediment data (Berggren et al. 2013) compared to Greenland ice cores, Dye-3 and NGRIP with units for ^{10}Be flux in atoms cm^{-2} year^{-1}. The data has been smoothed using an 8 year low-pass (Butterworth) filter. Figure from Berggren et al. (2013).

The 11-year solar cycle has been identified in the Dye-3 and NGRIP ice cores (Greenland), where the high snow accumulation rate allows for annually resolved ^{10}Be measurements (Berggren et al. 2013) The cycle has also been identified in some Antarctic cores, however the lower accumulation rate means that identification in most cases is more difficult (Baroni et al. 2011).

Surface melting is another factor affecting the development of well layered ice cores, something which has limited the extraction locations to Greenland and Antarctica (Berggren et al. 2013). Further, air mass circulation and deposition pathways are factors which will give short term variations of ^{10}Be in glacial deposition just as it does for lake sediments (Martin-Puertas et al. 2012). Even though the amount of snowfall and its redistribution due to wind, will affect the ^{10}Be deposition these are factors which likely have a lower impact compared to the complexities of transport in lake sediments.

Fig. 6 comparing the ^{10}Be deposition in Greenland ice cores to the Lake Lehmilampi ^{10}Be sediment concentration shows that there are similarities in the deposition trend as well as similarities in variable short-term noise. The data which covers a longer time frame compared to previously reviewed data sets covering the 20th century, shows some cyclic variation which is consistent with the 11-year cycle. However, considering the entire data set the 11-year cycle is not clearly identifiable. While the visibility of the 11-year cycle is debatable, it is clear that some long term variations can be identified with similar signals in the three different data sets. The Maunder grand solar minimum 1645-1715 is clearly visible in all tree data sets, as indicated by Berggren et al. (2013). On the other hand there is an increasing trend in ^{10}Be concentration for Lake Lehmilampi covering the last 100 years, while a decrease can be observed for the ice cores.

The fluctuations in the Lake Lehmilampi data does not seem to be more erratic compared to the two ice cores, even though there are instances where the lake data does not correspond to solar activity, such as the peak 1840-1850. This possibly indicates that sediment transport is a lower source of disturbance than previously expected.

4.3.2 ^{14}C in tree rings

Carbon-14 (^{14}C) is present in trace amounts in organic matter, allowing tree rings to be studied as another natural archive for solar activity (Kovaltsov et al. 2012). The concentrations of the radionuclide ^{14}C does, similarly to ^{10}Be partly reflect the activity of the sun. Unlike ^{10}Be, ^{14}C is taken up by plants (recording atmospheric changes with a ^{14}C/^{12}C ratio) through photosynthesis. Because the atmospheric variation of ^{14}C changes over time, each tree ring represents the atmospheric concentration present the year it grew. Since ^{14}C and ^{10}Be are produced by similar processes accurate dating can be obtained when combining records from the two isotopes (Ljung et al. 2007) which allows comparison between different locations (Nilsson et al. 2011).

As shown in *Fig. 7* there is a correlation between the GRIP ice core (^{10}Be) and ^{14}C data. The ^{10}Be values measured from the sediment core at the Hillpiece bog on the island of Tristan da Cunha also agree with other data sets to some extent even though, the trend for the last 100 years is inconsistent.

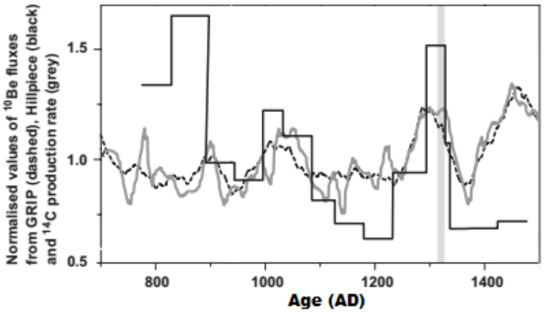

Fig. 7. Comparison of the ^{10}Be normalized values measured in the Hillpiece Bog on Tristan da Cunha, the Carbon- 14 production rate based on tree ring ^{14}C records and ^{10}Be data from the GRIP ice core (Greenland). The bold grey band indicates an ash layer. Figure from Ljung et al. (2006)

5 Conclusions

^{10}Be in lake sediments shows good potential for solar activity reconstruction, with all of the reviewed articles agreeing that solar signals such as the 11- year (Schwabe cycle) can be identified under the right conditions. As predicted it was found that an array of processes affects the transport and deposition within lake sediments. All of which lower the signal to noise ratio (SNR) so that the solar signal becomes difficult to identify on short (yearly to decadal) timescales. Environment and lake chemistry can also cause the ^{10}Be concentrations to vary, with trends that are not related to the solar signal. Such interference from the surrounding environment highlights the need to correct the data when e.g. a strong correlation is found to a trace element or e.g. when there is a lag in the expected ^{10}Be sediment concentration due to vegetation cover. Although these processes are problematic, dealt with efficiently, reviewed articles show that results can be relied upon to show solar activity variations. By comparing lake sediments to other archives used in the past for solar reconstruction it is clear that these too, do not come without some disturbance. Ice cores for example also have a low SNR due to factors affecting the snow in a similar manner in which they affect the lake sediments. It is clear that the ^{10}Be concentration in lake sediments is a useful proxy for studying solar variation, independently or in combination with other archives.

6 Acknowledgements

I would like to thank my supervisors at the Geology department, Markus Cyzmzek and Raimund Muscheler, for their time and valuable inputs. I would also like to thank family, friends and training partners who have encouraged other than academic pursuits for a nicely balanced lifestyle.

7 References

Baroni, M., Bard, E., Petit, J.-R., Magand, O. & Bourles, D., 2011: Volcanic and solar activity, and atmospheric circulation influences on cosmogenic 10Be fallout at Vostok and Concordia (Antarctica) over the last 60years. *Geochimica et Cosmochimica Acta 75*, 7132-7145. doi: 10.1016/j.gca.2011.09.002

Berggren, A.-M., Aldahan, A., Possnert, G., Haltia-Hovi, E. & Saarinen, T., 2013: Linking ice sheet and lake sediment archives of 10 Be, 1468–1980 CE. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 294*, 524-529.

Berggren, A. M., Aldahan, A., Possnert, G., Haltia-Hovi, E. & Saarinen, T., 2010: 10Be and solar activity cycles in varved lake sediments, AD 1900-2006. *Journal of Paleolimnology 44*, 559-569. doi: 10.1007/s10933-010-9437-1

Berggren, A. M., Beer, J., Possnert, G., Aldahan, A., Kubik, P., Christl, M., Johnsen, S. J., Abreu, J. & Vinther, B., 2009: A 600□year annual 10Be record from the NGRIP ice core, Greenland. *Geophysical Research Letters 36*.

Clette, F., Svalgaard, L., Vaquero, J. M. & Cliver, E. W. 2015: Revisiting the sunspot number. *In The Solar Activity Cycle*, 35-103. Springer,

Czymzik, M., Muscheler, R., Brauer, A., Adolphi, F., Ott, F., Kienel, U., Draeger, N., Slowinski, M., Aldahan, A. & Possnert, G., 2015: Solar cycles and depositional processes in annual (super 10) Be from two varved lake sediment records. *Earth and Planetary Science Letters 428*, 44-51. doi: 10.1016/j.epsl.2015.07.037

Fink, D. & Smith, A., 2007: An inter-comparison of 10 Be and 26 Al AMS reference standards and the 10 Be half-life. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 259*, 600-609.

Heikkilä, U., Beer, J., Abreu, J. & Steinhilber, F., 2013: On the atmospheric transport and deposition of the cosmogenic radionuclides (10Be): a review. *Space Science Reviews 176*, 321-332.

Kaste, J. M. & Baskaran, M. 2012: Meteoric 7Be and 10Be as process tracers in the environment. *In Handbook of environmental isotope geochemistry*, 61-85. Springer,

Korschinek, G., Bergmaier, A., Faestermann, T., Gerstmann, U.C., Knie, K., Rugel, G., Wallner, A., Dillmann, I., Dollinger, G., Von Gostomski, C.L. & Kossert, K., 2010. A new value for the half-life of 10 Be by heavy-ion elastic recoil detection and liquid scintillation counting. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, *268*(2), 187-191.

Kovaltsov, G. A., Mishev, A. & Usoskin, I. G., 2012: A new model of cosmogenic production of radiocarbon 14 C in the atmosphere. *Earth and Planetary Science Letters 337*, 114-120.

Ljung, K., Bjorck, S., Muscheler, R., Beer, J. & Kubik, P. W., 2007: Variable 10Be fluxes in lacustrine sediments from Tristan da Cunha, South Atlantic: a solar record? *Quaternary Science Reviews 26*, 829-835. doi: 10.1016/j.quascirev.2006.12.016

Mann, M., Beer, J., Steinhilber, F. & Christl, M., 2012: 10 Be in lacustrine sediments—A record of solar activity? *Journal of Atmospheric and Solar-Terrestrial Physics 80*, 92-99.

Martin-Puertas, C., Matthes, K., Brauer, A., Muscheler, R., Hansen, F., Petrick, C., Aldahan, A., Possnert, G. & Van Geel, B., 2012: Regional atmospheric circulation shifts induced by a grand solar minimum. *Nature Geoscience 5*, 397-401. doi: 10.1038/ngeo1460

Masarik, J., & J. Beer (1999), Simulation of particle fluxes and cosmogenic nuclide production in the Earth's atmosphere. *Journal of Geophysical Research: Atmospheres 104*, 12099–12111, doi:10.1029/1998JD200091.

Nilsson, A., Muscheler, R., Snowball, I., Aldahan, A., Possnert, G., Augustinus, P., Atkin, D. & Stephens, T., 2011: Multi-proxy identification of the

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