Optically Stimulated Luminescence Dating and Last Glacial Climate Reconstruction from the Lingtai Loess Section, Chinese Loess Plateau

Optisk stimulerad luminescence datering och klimatrekonstruktion av den senaste istiden från Lingtai loessektion, Kinesiska loessplatån

Emma Lagerbäck Adolphi
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Abstract

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High resolution dating of loess on the Chinese Loess Plateau (CLP) using Optically Stimulated Luminescence (OSL) has increased the understanding of past monsoon climate but also raised questions regarding dust mass accumulation rate (MAR), the presence of disturbances or gaps in the sediment record, a possible teleconnection between North Atlantic and East Asian monsoon climate, and whether these events are due to climate variability, local settings, or age model uncertainties. This study undertakes a detailed (<20cm sampling resolution) OSL investigation of the Lingtai section to create an independent age model using linear regression, to reconstruct monsoon climate changes using magnetic susceptibility (MS) and grain size (GS) proxies, as well as to calculate MAR for the site. The data shows that between 44-15 ka climate changes from a period of strong summer monsoon to a strong winter monsoon. GS data show variable trends attributed to changes in dust storm activity and local environmental conditions. MAR data does not correlate with grain size and is different from other loess records on the CLP. Such differences are either due to local variations or age model uncertainties. No clear correlation with Heinrich events or teleconnection with North Atlantic climate is visible in the records over the Last Glacial period, and hiatuses or gaps are not obviously present at this site. It is suggested that using linear regression for continuous age model construction from the luminescence ages comes with uncertainties due to subjective bias when fitting the lines and determining shifts in the data, especially during MAR calculations. Further studies are needed to ascertain optimal methods for creating age models, and to constrain the reasons behind the variability between different sites and loess records on the CLP.

Keywords: Last Glacial, optical stimulated luminescence dating, Chinese loess plateau, Lingtai, magnetic susceptibility, mass accumulation rate, climate reconstruction

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Optisk stimulerad luminescence datering och klimatrekonstruktion av den senaste istiden från Lingtai loessektion, Kinesiska loessplatån
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Högupplöst OSL-datering av loessjordar från CLP har ökat förståelsen av dåtida monsunklimat, men har även lyft frågan gällande MAR, närvaron av avbrott eller småskaliga event i jordsektionerna, möjligheten av en relation mellan de Nordatlantiska och Ostasiatiska monsunklimatamen, och om dessa förändringar sker till följd av faktisk klimatvariation, lokala förutsättningar, eller osäkerheter i åldersmodellen. Studien genomförde en detaljerad (<20cm) OSL-undersökning av Lingtai-sektionen för att skapa en oberoende åldersmodell, återge monsunklimatförändringarna genom tillämpning av MS och GS proxies, samt beräkna MAR från platsen. Resultaten påvisar att mellan 44-15 ka förändrades klimatet från en period av stark sommar- till en stark vinter-monsun. Kornstorleksresultaten påvisar stora variationer vilka kan kopplas till en förändring i sandstormsaktivitet samt de lokala förutsättningarna för deposition av sediment. MAR-resultaten överensstämmer inte med kornstorleksdatan och skiljer sig från den övriga empirin, detta kan bero på lokala variationer i regionen eller osäkerheter i åldersmodellen. Det finns ingen klar korrelation mellan "Heinrich events" eller en "teleconnection" i sektionen, och avbrott samt störningar i sektionen är inte förekommande. Avsaknaden av korrelation antyder att användningen av regressionslinjer för att skapa kontinuerliga åldersmodeller kommer innebära fortsatta osäkerheter i empirin, speciellt gällande beräkning av MAR. Ytterligare studier krävs för att bestämma optimala metoder för att framställa åldersmodeller, samt att utröna orsaken till skillnaden mellan resultat från olika platser på platån.

Nyckelord: Senaste istiden, Kinesiska loess-platån, Lingtai, magnetisk suszeptibilitet, massackumuleringshastighet, klimatrekonstruktion.

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List of Acronyms

CLP – Chinese Loess Plateau
De – Equivalent dose
DR – Dose Rate
GS – Grain size
IRSL – Infrared stimulated luminescence
LGM – Last Glacial Maximum
MAR – Mass accumulation rate
MS – Magnetic susceptibility
OSL – Optically stimulated luminescence
Pfg – Polymineral fine grains
SAR – Single aliquot regeneration
SR – Sedimentation rate
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1. Introduction

The East Asian monsoon is a major global climate driver that contributes to redistribute heat around the globe (Licht et al, 2014) and sustains current populations living in the region and is partly responsible for the agricultural and economic situations in the nearby countries (Clift et al, 2008). As the East Asian monsoon is essential as a water source and influence the lives of many the knowledge about the evolution and past changes in this climate system is of importance to be able to understand its future behavior. The monsoon system is driven by heat and pressure differences between the continent and the Western Pacific Ocean, and the seasonal change in this pattern creates the summer and winter monsoons. The summer monsoon brings in warm and humid winds from the Western Pacific Ocean to the mainland and thus the continent experience increased precipitation, whereas the winter monsoon brings cold and dry winds from the Siberian High, creating stronger winds over the area (Sun et al, 2009). It is the winter monsoon that is responsible for creating the Chinese Loess Plateau (CLP) in northern China.

Loess is defined as deposits of aeolian dominantly silt sized (mineral dust) sediment and is considered to be one of the most complete terrestrial climate records available for study. Loess sequences are comprised of alternating paleosol and loess units, formed during warmer and more humid climates and colder and drier conditions respectively. Generally, higher rates of dust deposition are associated with loess units, and occurred during glacial times, while interglacial climates drove lower deposition rates and weathering of the accumulated loess profiles into paleosols. In East Asia these stratigraphic alternations correlate well with shifts in monsoon pattern and strength over the CLP (Fig 1) (Sun et al, 2009), where the alternation between loess and paleosol units show oscillations between winter and summer monsoon dominance respectively. These changes in depositional environment and weathering are recorded in the loess sequences and can be studied in more depth by using proxies such as magnetic susceptibility (MS) and grain size (GS). Through analysis of dust mass accumulation rate (MAR) and weathering conditions of the loess it is possible to investigate a multitude of past climate events and environments such as atmospheric wind and dust patterns, dust source areas, precipitation and monsoon intensity.
The CLP contains some of the oldest and most extensive loess records, covering multiple glacial and interglacial cycles and potentially stretching back ~30 million years (Kohfeld & Harrison, 2003; Sun et al, 2009; Licht et al, 2014). Much focus of the loess studies on the CLP have been directed to reconstructing changes in the monsoon and MAR.

As mentioned, different loess climate proxies are used to reconstruct Asian monsoon strength as well as to determine the rate of dust accumulation, providing insights into past atmospheric dust activity, a major but poorly known climate driver (Albani et al., 2015). However, without detailed and accurate age models, climate proxy records are meaningless in terms of reconstructing the dynamics of climate change in the past. It is essential to produce reliable and accurate chronologies of past environmental and climate changes to increase our understanding of present day geomorphological and climatic processes. For that purpose independent and precise age models are necessary to calculate accurate MAR and correct use of proxy data. There have already been many studies that have provided age models of the Last Glacial period from different sections on the CLP, using a variety of both independent and non-independent dating methods (Kohfeld & Harrison, 2003). Non-independent models, such as correlation based models and those based on orbital tuning methods, do not directly date a loess sequence but rely on matching patterns (oscillations) in proxy data to those in other sequences that have already been dated or orbitally tuned. These methods are based on many assumptions: that there is synchronicity between the sequences, that sedimentation rate is broadly constant between known age points, that known age tie points are correct, and that there are no breaks in the record. It has been shown that such assumptions cannot be made as the resulting age models yield large offsets compared to independent ages on millennial timescales (Fig 2) (Stevens et al, 2007; 2008). It could be argued that it is difficult for such methods to attain detailed models since their temporal resolution is low and may be inaccurate over millennial timescales, and thus they do not
capture small scale events essential for understanding climate dynamics during the Last Glacial. This shows how important it is for further studies to apply independent radiometric methods and age models, which provides both accurate, absolute ages, but also provides more detailed age models. During recent years the number of independently dated loess sections has increased (Stevens et al, 2008, 2013, 2016; Buylaert et al, 2015) but these studies only cover a few sections. To get a complete picture of the CLP, further investigation is needed to understand variability between sections. Furthermore, many climate reconstructions from loess are based on the assumption that the record is intact and that the climatic signal stored in the sediment has not been altered after deposition. Such breaks or alterations may be visible only through detailed independent dating; thus, an accurate and detailed age model is required in order to determine the rate of dust accumulation recorded in loess profiles. Dust MAR records that can be calculated from independently dated loess also provide insight into past atmospheric dust activity, a major driver of global climate change but poorly constrained in the past (Kang et al, 2015).

Figure 2. The lower curve show MS (X_d) data plotted with age data constructed by correlation to marine oxygen isotope boundaries (marker horizons) (Martinson et al, 1987), while the upper curve is based on OSL. As seen there are large offsets between the independently and non-independently dated records. Picture modified from Stevens et al, 2008, used with permission.

MAR was generally high during glacial times when strong winds deposited large amounts of sediment; loess, marine and ice core records show increases in dust activity during these times. More recent studies have shown that there is some time offset between marine and terrestrial records of dust MAR (Kohfeld & Harrison, 2003; Kang et al, 2015). Few studies have calculated mass accumulation rates from loess and they have generally based these calculations on non-independently dated age models (Kohfeld & Harrison, 2003), which could explain this offset. If these discrepancies are due to inaccuracies in the age models due to the use of non-independent age models, or if they are real
differences caused by environmental or climatic reasons can be debated. Kohfeld and Harrison (2003) argue that comparison of loess records to marine or ice core ones are bound to give an erroneous interpretation of past dust activity due to the scale difference and differences in local geomorphic and geographic settings. A few key sites of loess sequences cannot be compared to an averaged signal over a much larger area, such in the case of marine records, without errors; the difference in settings will influence deposition and preservation of sediment. They also state that site specific MAR values from loess records should not be used to presume regional changes in dust accumulation over time, but that assessments of regional MAR must be produced from multiple sites and studies (Kohfeld & Harrison, 2003).

Furthermore, Stevens et al, (2006, 2008) suggested that the CLP contains hiatuses and disturbances in the record which could falsify many assumptions regarding the age of the loess sections and therefore the MAR values calculated using non-independent age models, and the question arises as to whether these factors are present at the same intervals all over the CLP. Additionally, without high sampling-resolution dating, i.e. applying a narrow sampling interval to get detailed temporal data, it is impossible to accurately discover rapid small scale events (such as Heinrich-, Bond-, Dansgaard-Oeschger events) in the records.

It has been suggested that such small scale climatic events should be visible in the loess records, and that there is a teleconnection between North Atlantic climate and the East Asian monsoon (Porter & An, 1995). However, whether this is true is still under debate (Sun et al, 2012; Stevens et al, 2008). Heinrich events are extreme climate occurrences driven by iceberg discharge events in the North Atlantic that occur every few thousands of years during glacial times. In the ice core records Heinrich events are visible as atypical climate fluctuations, and in the sedimentary records they are shown as periods of increased ice rafted debris (Hemming, 2004). It is proposed that Heinrich events are accompanied by stronger winds and a stronger winter monsoon in China (Porter & An, 1995), and thus should be visible in the CLP loess records if the resolution is high enough. However, as these events occur only over a few thousand years, the accuracy of the age models used in loess records is critical to determine whether Heinrich events are recorded in loess sediments. Inaccuracies in age models caused by non-independent dating methods may lead to erroneous conclusions regarding the links between North Atlantic climate and the monsoon. Consequently, due to the lack of independent age models, records of climate change from the CLP may contain significant errors (Stevens et al., 2008).

In recent years luminescence dating has been used to create detailed independent age models of loess records. High resolution luminescence dating is time consuming due to the sheer volume of laboratory work needed to cover a large period at fine sampling intervals, and is thus not usually performed. The use of broader sample intervals is more commonly used to allow covering larger time intervals, although without high temporal resolution. Optically stimulated luminescence (OSL) dating has become an increasingly popular dating method to use, especially on aeolian sediment, due to its high practical age range (~100 to 300,000 ka) as well as its accuracy in aeolian sediment that has been
well exposed to light (Duller, 2008). With such detailed studies new questions regarding previously unobservable events have arisen on regard, for example, the presence of hiatuses in the records (Stevens et al., 2007, 2008, 2016), if teleconnection between North Atlantic climate events are visible in the loess record (Porter & An, 1995; Sun et al., 2012; Stevens et al., 2008), the need for loess MAR data and how these data compare to marine records (Kohfeld & Harrison, 2003), and how age models are constructed and what error they have (Stevens et al., 2016).

This study will address a few of these questions by combining high resolution OSL dating and using the data to derive independent age models of MS and GS climate proxies from a site on the Chinese Loess Plateau. From these records it should be possible to discern rapid changes in monsoon and wind strength during the Last Glacial and also discover hiatuses or disturbances in the loess record. Using a fine sampling interval may enable a correlation in the proxy records to contemporary global events from other records, and also the effect on the global dust cycle which is largely unstudied (Stevens et al., 2013). The age models also permit detailed, independent MAR calculations that will give a site specific estimation of dust accumulation during the Last Glacial period.

### 1.1 Purpose & questions

The objective of this study is to perform detailed (10 cm sampling resolution) independent OSL quartz dating on the CLP for parts of the Last Glacial period aiming to construct an age model, which combined with monsoon proxies would reveal gaps in the record and changes in MAR, and potential correlation with other records of climate and atmospheric dust change. The samples are from the Lingtai section (35° 04'N, 107° 39'E), situated in the SW-central part of the CLP on the Wuxin tableland at 1350m above sea level (Fig 1). This study is the first detailed dating of a western CLP section.

The data was used to construct an age model for climate proxy records and calculate mass accumulation rates. Different standard luminescence tests were performed to investigate the reliability of the data; rejection criteria for sample aliquots (subsamples) were analyzed together with the trustworthiness of the linear regression method for constructing age models. Magnetic susceptibility and grain size of the samples were used to infer monsoon climatic changes, such as precipitation intensity, wind pattern and speed. The data was used to test for the presence or lack of hiatuses and Heinrich events in the record. The results were related to other similar studies to ascertain regional trends in the findings.

The study tried to answer the following research questions:

- Are hiatuses or disturbances present in the Lingtai section and are mass accumulation rates spatially variable on the CLP?
- Are monsoon equivalent Heinrich events visible in climate records from this high resolution analysis? If yes, how do they compare to other loess and monsoon records?
- What are the uncertainties when creating age models and how can the errors be minimized?
These questions were addressed by using quartz blue light OSL and polymineral post IR blue light OSL dating of fine grain (4 to 11 μm) loess samples from the last glacial L1 unit of the western CLP, Lingtai section, and local MS and GS data.

2. Background

Loess climate records from the Last Glacial period on the CLP have been well studied using different approaches and proxies, where the most commonly used methods are MS, GS, and MAR. These proxies are especially useful for applications on the CLP since they capture changes in dust accumulation and monsoon intensity. Thermal seasonal differences between the Western Pacific Ocean and the Asian continent, plus the augmenting effect of the Tibetan plateau lead to a climate control on the CLP by the East Asian monsoon (Liu & Ding, 1998; An et al, 2015). In summer, the western Pacific subtropical high coupled with a deepening low pressure over continental Asia brings hot and humid winds forming the summer monsoon, resulting in heightened precipitation on the CLP, leading to weathering and soil forming processes. During winter, cold and dry winds from the Siberian high and the Aleutian/Equatorial low pressure systems increase dust deposition and dust storms in the region via winter monsoon circulation (An et al, 1991; Zhang et al, 2002). Over longer timescales of 10s to 1000s of years, during warmer climate periods, a stronger summer monsoon drives weathering of loess material and enhanced soil formation. In contrast, colder climate is often connected with weakening of the summer monsoon and strengthening of the winter monsoon, which drive enhanced loess deposition and reduces soil formation.

2.1 Proxies

Changes in pedogenesis can be observed through MS analysis of sediment samples and is widely argued to be a proxy for summer monsoon driven soil formation (Tang et al, 2003). During weathering of the loess, iron cations become oxidized. Increased precipitation and temperature during enhanced summer monsoon conditions lead to more reducing conditions that alternate with the oxidizing conditions. This alternation produces more reduced iron oxides such as magnetite, maghemite, and micromagnetite, which have a high magnetic susceptibility (Tang et al, 2003). This means that during phases of a strong summer monsoon a heightened MS signal should be seen in the corresponding loess sediments. Hence, MS is a proxy used to observe changes in the summer monsoon, which on the CLP is controlled dominantly by precipitation intensity (Balsam et al, 2011). However, it has been argued that other factors could affect the MS values, for example Han et al, (1996) comments on the importance the effect of local climate, vegetation, topography, and the parent material have on the weathering and oxidation of minerals.

Grain size by contrast is usually used as a proxy for changes in dust accumulation and the strength of the winter monsoon and the winds bringing dust to the CLP (Sun et al, 2006). When a strong winter
monsoon was present there was a colder and drier climate, and larger amounts of sediment was deposited on the CLP. Due to heightened wind speeds and strengths, but also the more frequent occurrence of dust storms, these periods are often characterized by an increase in GS (Újvári et al, 2016). Yet this is a simplistic view that does not account for all aspects of wind transport. Sediment can be transported through various means (dust storms, high or low atmospheric transportation, etc.) depending on the size of the particles and the efficiency of the wind. Present day loess accumulation on the CLP is mainly driven by gradually deposited fine grain material (clay and silt) and larger grains transported by dust and sand storms (Stevens & Lu, 2009). Drier conditions with higher wind speeds during periods of strong winter monsoon could potentially favor dust storm activity and thereby lead to accumulation of larger grain size material; but, modern observations show that dust storms are still present during interglacials (Derbyshire et al, 1998). Even though it is still thought that dust storm activity is more prevalent during cold and dry conditions (Újvári et al, 2016; Stevens & Lu, 2009) and that low level atmospheric winds are the main transport mean of dust during interglacials (Zhang et al, 2002), the notion that large particles could accumulate during periods of strong summer monsoon and bring in mixture of grain sizes complicates GS interpretation. The source material and the distance from origin also affect the grain size, as do local variations in weathering such as precipitation, temperature, and altitude (Stevens & Lu, 2009). Thus, using GS as a proxy comes with uncertainties that are not always easy to account for, i.e. what is caused by a change in wind speed versus a change in source region (for example expansion or restriction of deserts). Stevens and Lu, (2009) demonstrate that sedimentation rates are highly variable over millennial timescales and that this disparity is not clearly replicated by changes in grain size, besides, sedimentation rate is very affected by local settings such as wind conditions and distance from source to sink (Stevens & Lu, 2009). All this would lead to uncertainties when interpreting sedimentation rates and possibly grain size, as it would undermine calculations of MAR that are sometimes based on a presumed linear relationship between sedimentation rate and grain size (Nutgeren & Vandenberghe, 2004).

To attempt to account for different modes of transport, various types of grain size measurements are used. Volumetric mean or median GS is often used as an indicator of general average wind strength. Though, it has been argued that the mean GS could be used to investigate past aridity and dust storm prevalence in the region, and that median GS would rather reflect expansion and retraction of desert regions and thereby distance to dust source (Újvári et al, 2016). Újvári et al (2016) states that mean GS is firstly a proxy for wind intensity and secondly an indicator for aridity and source distance. Different fractions of loess grain size have also been used as indicators for specific parts of atmospheric circulation. A high volume percentage of fine grained (<5.5 μm ) material is an indication of prevalent high level ‘background’ atmospheric transport of finer grains influenced by changes in the high altitude westerly jet stream (Xiong, 2002; Sun, 2004), while the fraction of larger grains (>63 μm) has been used to infer the abundance of dust storms and lower atmospheric wind regimes and to observe changes in dust source distance (Újvári et al, 2016) and low level winter monsoon winds (Xiong,
The U-ratio is the ratio between the coarse silt fraction and the medium-fine silt portion (16–44 μm/5.5–16 μm), removing the clay and sand fractions (Újvári et al, 2016). A high U-ratio indicates a cold climate and strong winds, and a low ratio the opposite. An advantage of this proxy is that the clay sized particles are excluded, which prevents the need to account for secondary formed pedogenic clay minerals which are not relevant when looking at actual deposition (Újvári et al, 2016).

### 2.2 Independent dating and MAR

Few studies have attempted to calculate sedimentation rates on the CLP, and the majority that have done it have used correlation based models or loess stratigraphy linked to marine isotope data (Kohfeld and Harrison, 2003). These models are based on several assumptions, such as a constant relationship between GS and sedimentation rate, which causes inaccuracies in the interpretation of the records. These assumptions are necessary when applying correlation based methods as they try to match oscillations in the loess record with those recorded in other dated sequences. Such assumptions cannot be easily made thus more recent studies have often used independent age models calculating sedimentation rates directly and then deriving MAR through mathematical methods based on bulk density. While sedimentation rate gives information of the rate of deposition on a surface (2D) the MAR is a measure of the deposition rate of a volume of sediment calculated from the sedimentation rate and bulk density to give the mass (3D) accumulated over given time. As the MAR gives an estimate of deposited sediment over specific time intervals it can be used to understand past wind regime and how the atmospheric dust loading has changed. Variation in MAR is often attributed to changes in aridity of the source region and dust loading in the atmosphere (Ding et al, 2001) forced by changes in ice volume (Ding, 1995; Xiao 1995, Stevens & Lu, 2009). High accumulation rate events were largely present during glacial times on the CLP when conditions were drier and the dust cycle more active, while a wetter environment during the interglacials were more conductive lower rates. Even though deposition was most efficient during colder periods in history, high deposition events could also take place in a warmer climate in case of regional dust storms (Derbyshire et al, 1998), which makes it difficult to ascertain the cause of high deposition events. To get accurate and detailed MAR over the CLP, independent age models are needed: MAR is derived from sedimentation rate, which is calculated based on the slope of the age model with depth. Yet few studies have attempted to calculated MAR, often because bulk density measurements are lacking, and the studies have used a variety of dating methods at varying resolutions to derive age models (Kohfeld & Harrison, 2003).

The Last Glacial period in loess sequences has been dated before using both non-radiometric (correlation to Milankovitch cycles, pollen, paleomagnetism, speleothems) and radiometric methods (radiocarbon, luminescence dating) (Sun et al, 2000; Kohfeld & Harrison, 2003). In more recent years the focus has been on radiometric methods, which give independently derived absolute ages, and luminescence dating has been one of the most applied of them. Kohfeld and Harrison (2003)
summarizes a variety of loess studies attempting to calculate MAR on the CLP based on different methods, such as; pedostratigraphy, \(^{14}\)C, fossil records, micromorphology, thermoluminescence, pollen, MS, GS, magnetic polarity, and various chemical and isotopic parameters. Many of these records have applied age models that presume that a direct, synchronous relationship exists between MS, soil formation, and changes in overall ice volume. Kohfeld and Harrison (2003) state that such assumptions should be made with caution due to apparent poor correlation between MS records from the CLP and marine isotope data, and that the use and trust in correlation based methods (matching climate proxy oscillations between records) are problematic.

2.3 Key debates

There has been an increase in the application of luminescence dating methods for developing age models for the CLP during the last years (Buylaert et al, 2008, 2015; Sun et al, 2012; Kang et al, 2013, 2015; Stevens et al, 2006, 2008, 2016) which has given more insight into past climate and loess deposition on the CLP. While these luminescence studies have overcome many of the limitations of non-independent age models, they have also generated considerable debate about key aspects of loess deposition and age model generation.

The key debates are:

1) Gaps (hiatuses) in the record; many loess sequences exhibit incongruous ages at the base of soils, which is argued to be due to disturbances caused by anthropogenic activities or soil forming processes (Stevens et al, 2008, 2016). Large centennial to millennial age gaps in the loess record have been reported by Stevens et al, (2006), Lu et al, (2006) and Buylaert et al, (2008) at different sites, while studies by Lai et al, (2010) and Buylaert et al, (2015) showed no gaps in the record which seems to point to that this is a site specific occurrence. A further complicating factor is that currently many researchers presume that CLP loess records are continuous since this have long been the consensus (Liu & Ding, 1998), and some of the widely accepted climate reconstructions are based on that assumption. Some authors argue that erosive events combined with episodic deposition may have left hiatuses and disturbances in the records (Lu et al, 2004; Stevens et al, 2006), and based on luminescence data Stevens et al, 2007 and Buylaert et al, (2015) state that loess records should not be assumed to be continuous, especially at marginal sites where depositional conditions are very dynamic. Such disconformities could invalidate previous climate curves based on the postulation that the loess record is complete and parallels the marine isotope record. Singhvi et al, (2001) offers support for the idea that the loess record is disrupted due to episodic deposition as they found depositional hiatuses. In their study Stevens et al, (2006) also discovered a depositional hiatus in the Beiguoyuan site in the 15 to 10 ka interval using OSL and in 2007 they studied multiple sites in the central CLP and performed high resolution OSL dating of loess and came to the conclusion that episodic sedimentation and erosive events are present in the record (Stevens et al, 2007). Using magnetostratigraphic methods, Zhu et al, (2007) states that the deposition on the CLP may only have
been discontinuous at finer time scales, which to some extent supports Singhvi et al., (2001) and Stevens et al., (2006) but suggests the hiatuses may be of shorter duration. The potential presence of hiatuses calls for more detailed dating of the CLP to investigate if these episodic events only are local features or visible over the whole area.

2) Accumulation rate changes; related to the first debate (1) is whether MAR shows the same patterns over the late Quaternary across the CLP or if there is site to site variability in the trends. Stevens and Lu, (2009) argue that dust accumulation varies over the CLP depending on site, while Kang et al., (2015) made a compilation of MAR on the CLP and, based on that, argue that there are trends in MAR during the last glacial period that are consistent between sites across the CLP and that peak sedimentation at the Last Glacial Maximum may be offset in loess compared to marine and ice core records (Kang et al., 2015) Though some studies suggest that the rate of sedimentation itself appears to vary between sites and through time (Stevens & Lu, 2009), a recent analysis of luminescence dated records questions if this may be due to differences in dating methods and age model construction, or caused by actual climate change (Stevens et al., 2016).

3) Age model construction and luminescence tests; OSL-dating of loess has been a widely used method during recent years and improvements in the method are ongoing. The most used protocol, when applying OSL-dating, is the SAR protocol by Murray and Wintle (2000, 2003). The protocol is often accompanied by multiple tests to remove erroneous data and choose optimal settings for the protocol (read more about this in chapter 3); however, not all studies have applied the same protocols or tests. Furthermore, many of the luminescence studies that have driven these debates have either used a coarse sampling resolution or have focused on a shorter time scale but with higher sampling resolution (Stevens et al., 2006, 2007; Buylaert et al., 2015) due to resource limitations. These studies have also focused on the last glacial-interglacial cycle and few have directly quantified loess dust MAR. This may account for some of the differences in the interpretation of data from luminescence studies on the CLP. Kohfeld and Harrison, (2003) constructed various MAR records from published data on the CLP and concluded that non independent age models resulted in inaccurate MAR records. They noted that MAR values had large inconsistencies between proxy based and absolute dated age models, which they attributed to inaccuracies in the former (Kohfeld & Harrison, 2003). This demonstrates the need for more radiometric age model based MAR reconstructions which take into account possible hiatuses and abrupt changes in accumulation rate. Furthermore, it has been suggested that high resolution vertical sampling (10-20 cm) for OSL dating should be able to catch short time period changes in sedimentation rate (Stevens et al., 2007, 2016), which would make this method very useful when determining MAR, but that lower sampling resolution analysis may not show fine scale events. Thus, there is a pressing need for both high resolution and high temporal scale radiometric data in this region to broaden both our understanding of dust accumulation. Furthermore, various methods have been applied to turn discrete luminescence dates into a continuous age model for the sequence and the accuracy of some of these methods is unclear. Recent studies have used regression lines where
specific accumulation phases are identified visually from age depth trends in OSL ages, and then used the regression equation to calculate the age model and MAR values (Stevens et al., 2016). However, a key question is how reliable it is to assign trend lines based on only visual interpretation.

4) The timing of loess proxy changes in relation to Heinrich events; based on the apparent relationship between loess grain size and sediment records in the North Atlantic, some studies propose a teleconnection between the North Atlantic Oscillation and the East Asian Monsoon (Porter & An, 1995), especially with respect to Heinrich events (Stevens et al., 2013). These iceberg rafting events are associated with rapid cooling and are very pronounced in the North Atlantic region. The regional extent is uncertain and any associated changes in atmospheric dust are unclear. Studies have also suggested that oscillations in the loess records could be linked to events in the North Atlantic such as Heinrich events and Dansgaard–Oeschger (D-O) cycles (Porter & An, 1995; Yu et al., 2006). Sun et al., (2012) found a possible link between the North Atlantic record and their OSL dated sequence on the CLP. Stevens et al., (2016) suggested that some evidence existed for Heinrich event concurrent events on the CLP, while Stevens et al., (2007, 2008) states that there are no clear connection between Heinrich events and the East Asian monsoon and argue that previous studies proposing such link may not be accurate as they are based on non-independent age models. The inconsistencies could be due to local variations of the sampling sites and deposition settings, or as Stevens et al., (2016) suggest, sampling interval and resolution of the studies. Hemming, (2004) also states that care should be given to the actual influence of specific proxies in certain settings; “…it is possible that the records in which only Heinrich events are seen would show the other millennial scale events with different proxies. Additionally, it is possible that records where Heinrich events are not seen as clear extremes could contain proxies that do emphasize these events over the others”. Given that Heinrich events are the most prominent rapid climate events during the Last Glacial period, concurrent changes in monsoon circulation and dust deposition might also be expected, as suggested by Porter and An, (1995), yet the mechanisms and relations are apparently unclear and no consensus has been reached, which calls for further studies.

In summary, many new studies have focused on high resolution luminescence dating, which has significantly increased the understanding of climate records and MAR on the CLP, but there are still limitations. More specifically, there is disagreement between studies and the lack of detailed dated sections from multiple sites on the CLP. Filling this research gap with detailed luminescence dating and analysis of a key section in a poorly studied location on the CLP could make it possible to address many of the problems above.
3. Theory and practice of OSL dating

Luminescence dating was developed in the 1960s, and optically stimulated luminescence (OSL) dating was first attempted 1985, with further advancements by Aitken and others (1998). OSL dating is generally used to date the last exposure of sediments to sunlight, providing absolute depositional ages. Luminescence dating involves direct measurements of the actual sediment sample, where the luminescence signal is proportional to the radiation dose received since the last time of exposure, which is a function of age (Aitken, 1998). An advantage over many other techniques such as radiocarbon dating is the large age range that luminescence dating can cover, with general age limits which lies between 0.1 to 1000 x 10^3 years (Wintle, 2008).

Ionizing radiation from the decay of radioactive isotopes in surrounding sediments affects mineral grains by ‘exciting’ electrons and trapping them in impurities in the crystal structure (Aitken, 1998). These traps fill up over time during long-term radiation exposure, but can also be emptied by exposure to sunlight or heating: a process called bleaching. The stored energy is then partially released as light, which can be measured and is proportional to both the received dose and the age (Duller, 2008).

During exposure of sunlight, or in the case of a laboratory setting (LEDs or lasers), the electrons in the traps are released and reach recombination centers where some emit light that is measured by the laboratory Risø TL/OSL readers. When all electrons in the traps are emptied due to long enough exposure to light, the sample is bleached and no longer contains a signal. If buried anew the sample will build up its signal again through exposure to ionizing radiation. This is the reason the luminescence method date the last exposure to sunlight. In a laboratory setting, the photons released from the recombination centers are counted when exposing the sample to stimulation. The measured luminescence is the natural signal, and by comparing this natural signal to known laboratory radiation doses, an estimate of the total dose the sample has received since burial is obtained, termed the equivalent dose (De) (Duller, 2008).

The laboratory doses comprise a range of values that help define how luminescence intensity in the sample changes with increased dose. By plotting these measurements a dose response curve can be created and, by comparison with the natural signal, a De value can be calculated (Fig 3-4). When obtaining the De only electrons from the deeper traps are needed since shallow traps usually are thermally unstable (Aitken, 1998). The shallow traps are emptied by preheating the sample before making the OSL measurements. The optimal temperature for the preheating varies depending on the sample (section 4.2 will expand on this).
Figure 3. Example growth curve of sample 11 gives a natural dose of 86 Gy for the natural Lx/Tx.

Figure 4. Example growth curve of sample 38 gives a natural dose of 165 Gy for the natural Lx/tx. The last regeneration point in the curve approaches saturation.

To ascertain the age of the sample not only the De is needed but also the surrounding environmental dose that the grains have been exposed to over time. This measurement is called the dose rate (Gy/ka), and represents the amount of radiation the sample has been exposed to through α, β, particles and γ rays from the surrounding sediment, but also from cosmic rays (Prescott & Hutton, 1994). The radiation usually originates from uranium, thorium, and potassium isotopes, and their daughter
isotopes. A higher environmental dose leads to more electrons getting trapped over a given time interval. It is important to account for the past and current water content of the sample when calculating the dose rate, since water absorbs radiation, otherwise underestimation of the age can occur (increased water content leads to increased estimated age) (Aitken, 1998; Duller, 2008). Cosmic ray and internal dose (from decay of K in feldspars and U in quartz) should be accounted for; although the contribution of this radiation is usually very small and doesn’t give a significant change in the estimate.

The age calculation can therefore be written as:

\[
Age \ (years) = \frac{\text{equivalent dose (Gy)}}{\text{dose rate (Gy/year)}}
\]

### 3.1 Limitations of OSL-dating

Luminescence dating is based on the assumption that the sample used is well bleached by sunlight. However, partial bleaching does occur and results from inadequate exposure of sunlight before burial of the sediment (Madsen & Murray, 2009). This can lead to overestimation of the age (Wallinga, 2002; Fan et al, 2013; Duller, 2008). Mixing of the samples through bioturbation or other natural causes may also lead to uncertainties during age calculations as disruption in the sediment leads to age inversions and scattering. In more modern loess anthropogenic disturbance of the sediments can occur (Kohfeld & Harrison, 2003; Stevens et al 2016). Another limitation with regards to modern loess and young sediment is low light levels. In young samples the luminescence signal is very small and the signal to noise ratio is low and results in high uncertainties when estimating age (Madsen & Murray, 2009). Thermal transfer of charge between traps can cause uncertainties in the age determination, but this is mainly a problem in younger samples where the natural signal is close to zero (the OSL signal is a large part of the natural signal) (Madsen & Murray, 2009).

Difficulties may also arise when determining the dose rate of the sediment. It is assumed that the dose rate is constant during the burial time and that the surrounding environment has not changed. It is however possible for both concentrations of radioactive isotopes and sedimentary setting to change over time (Madsen & Murray, 2009). There is still no precise way of determining an accurate value for the burial period of a sample, and this poses a limitation to the luminescence method. The dose rate calculation is also based on the assumption that daughter isotopes are in equilibrium with their respective parent isotopes throughout the U and Th decay series, which may not always be the case. It is also worthwhile to note that depending on sedimentation rate and amount, which can vary over time, the γ and cosmic rays contribution to dose rate will vary due to the attenuating effects of sediment (Madsen & Murray, 2009).
4. Methods

4.1 Sampling and preparation

Samples were obtained using stainless steel cylinders hammered into the cleaned loess profiles in 10 cm intervals across a total of 12 m. In total, 47 samples were dated using standard blue OSL, and 21 samples were dated using post IR blue OSL (Table 4). The inner material of the cylinders was used for OSL dating and the outer material for dose rate measurements. GS and MS data was provided by co-supervisor Buylaert, and was measured in 5 cm intervals over the whole section. The grain size data was measured by laser diffractometer and bulk densities were measured on sediment from the OSL sampling tubes after removing the outer material and correcting for moisture content. Low frequency MS data was measured using a Bartington MS2 meter on 10 g dried samples.

This study focused on fine grain (4 to 11µm) OSL-dating of quartz grains. During the preparation of the samples all carbonates were removed using HCl (10-30 %), clay coatings removed by sodium oxalate (C\textsubscript{2}Na\textsubscript{2}O\textsubscript{4}), and organic material removed by hydrogen peroxide (30 %). The samples were sieved and then the 4 to 11µm fractions were settled out and separated in water using Stokes settling techniques. The sample was separated into two parts, one that was retained and containing multiple minerals (termed polymineral) and one that was further processed for quartz. To attain only quartz grains, feldspars and other minerals were removed through etching in fluorosilic acid (H\textsubscript{2}SiF\textsubscript{6}) over 3 to 5 days. The remaining sample was washed with distilled water and dried. Fine grained discs were made by adding suspended sample in acetone on to discs (stainless steel cups 8 mm in diameter) using pipettes and letting them dry.

4.2 Applied OSL method

All the laboratory work and measurements were performed at Nordic Laboratory for Luminescence dating (NLL), Denmark, using Risø TL/OSL systems for OSL-dating and high resolution gamma spectrometry for dose rate. Protocols and analysis were done using the Risø software ‘Sequence Editor’ and ‘Analyst’ tools (Duller, 2015). Specific readers used were; Risø TL/OSL DA-12, Risø TL/OSL DA-20, and two readers of the DA-15 model. The readers have their own beta source and therefore the dose rate of the reader to the sample varies between them. Calibration to absolute Gy values is explained below. The reader has an OSL unit which excites the aliquots using a light source (blue LED’s 470 nm, 80 mW/cm\textsuperscript{2} and infrared diodes 875 nm, 135 mW/cm\textsuperscript{2}), and a heating element is used to pre-heat the aliquots. A filter is used to filter out non sample derived light, with photons passing through counted using a PMT (photomultiplier tube). For quartz dating an UV filter was used, while polymineral used a blue filter.
4.2.1 Calibration

To be able to make age calculations, the dose rate in Gy per s of exposure to the reader radiation source needed to be known for each reader. This was undertaken using fine grain calibration quartz dosed with a known dose of 4.81Gy. For future reference the readers of model used were, one TL/OSL DA-12 from now on referred to as reader D, one reader of model TL/OSL DA-20 as reader A, and two readers of the model TL/OSL DA-15 now referred to as reader X and J. Multiple calibration measurements for each reader gave average dose rate of 0.242 Gy/s for reader X, 0.121 Gy/s for reader D, 0.061 Gy/s for reader J, and 0.051 Gy/s for reader A.

4.2.2 The SAR protocol

The single aliquot regenerative dose (SAR) protocol was created and improved by Murray and Wintle, (2000, 2003, 2006) and is currently the most widely used method for De estimation. To get an accurate value of the equivalent dose and account for variation in radiation dose between aliquots, the luminescence signal had to be calibrated (Duller, 2008). This was done via the application of multiple, different known doses to the same aliquot that the natural signal was measured on. The aim is to find the laboratory dose that corresponds to the natural luminescence signal (Duller 2008) and generate a dose response curve (Fig 3-4). However, as the luminescence behavior of an aliquot changes with heating and optical stimulation, simply measuring natural and ‘regeneration doses’ would lead to inaccurate results. The SAR protocol uniquely overcomes this through the application of a constant test dose to standardize the signal for each aliquot and the account for sensitivity changes (Murray & Wintle, 2000, 2003, 2006). The test dose was the same for every dose applied at every natural and laboratory dose. Since each aliquot had different sensitivity due to intrinsic properties, the test dose made it possible to standardize this difference and obtain accurate De estimations. The resultant dose response curve couldn’t be used to read off the equivalent laboratory dose for the natural ‘Lx/Tx’ value (Lx being the natural or laboratory generated luminescence from the varying regeneration dose, and Tx being the luminescence of the test dose) (Fig 3-4).

The SAR protocol (Table 1) measured the natural dose, that is the original luminescence signal accumulated after burial, as well as regeneration points measured from known doses after the sample has been reset. The regenerated points created a dose response curve of how the signal changes with different dosing (Fig 3-4). The aim of the regeneration points is to build a set of points that can be used to obtain a dose and luminescence response relationship that corresponds to the natural luminescence signal. The protocol included repeating cycles (the setup shown in Table 1 is repeated multiple times, changing the dosing of the aliquot) of laboratory and natural dose measurements. The cycles are very similar and only the given doses (regeneration doses) change. As mentioned above a preheat step was necessary to remove unwanted signal. The minimum temperature for a preheat is 160°C to ensure that signal in the TL peak at 110°C is removed, as this is unstable over geologic time. At
very high temperatures thermal transfer (i.e. shifting of charge among traps due to heating) may occur, which needs to be avoided. Consequently, preheat plateau tests become important (further explained in the chapter 4.3).

**Table 1.** SAR protocol procedures and settings used for sample OSL measurements and De determination.

<table>
<thead>
<tr>
<th>Step</th>
<th>Procedure</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Natural or lab dose</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Preheat</td>
<td>260° C</td>
</tr>
<tr>
<td>3</td>
<td>IRSL</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>OSL (Ln or Lx)</td>
<td>125° C</td>
</tr>
<tr>
<td>5</td>
<td>Test dose</td>
<td>1/3 of natural dose</td>
</tr>
<tr>
<td>6</td>
<td>Preheat</td>
<td>220° C</td>
</tr>
<tr>
<td>7</td>
<td>OSL (Tn or Tx)</td>
<td>125° C</td>
</tr>
</tbody>
</table>

After an IRSL step to rule out feldspar contamination (if there is a high signal during IR stimulation feldspars is still present, read more below in the chapter 4.3.1), the first OSL measurement was taken and used for De estimation and referred to as Lx (or Ln when treating the natural dose). The remaining part of the cycle normalized the Lx measurement using the previously mentioned test dose. The test dose is usually 1/3 of the natural and remains the same for a sample during all the cycles of the protocol to account for intrinsic properties of the grains and for sensitivity changes due to dosing and heating during the runs. After the test dose, another preheat, at lower temperature than the first one (usually 40°C less), was performed to circumvent sensitivity changes. The second OSL step, called Tx (Tn for the natural dose), was used for the test dose correction (that is, the signal when having accounted for the test dose). By dividing the first OSL signal (Lx) with the second one (Tx) the signal was normalized and sensitivity change over the SAR protocol was accounted for. The Lx/Tx ratio of the natural signal is then used to obtain De through comparison with the growth curve obtained from plotting a trend line through the laboratory regenerated Lx/Tx values for the multiple regeneration doses. A final bleach (applying high temperature to clean out remaining signal in the sample leaving it empty for next dosing) at the end of each cycle to improve recuperation results was proposed by Murray and Wintle (2003) but the necessity of this bleach is debated. These cycles were repeated changing the given dose in each cycle. The protocol ends with a couple of cycles applied for testing the performance of the procedure for each aliquot, as well as the effectiveness and accuracy of the protocol, described in section 4.3.

**4.3 Quality checks**

A succession of quality checks was performed on the samples to determine the appropriate settings for the SAR protocol as well as check for feldspar contamination (which would cause inaccuracies in the quartz dating).
4.3.1 Purity check

The quartz subsamples were first tested for feldspar contamination with a purity check. The purity check is measured using a SAR-protocol. Two SAR cycles were measured, one without an IRSL step and one with (Table 2). The first cycle OSL Lx measurement included the signal from any potential feldspar in the sample and gave an Lx/Tx value based on that. The second measurement used IRSL, which removes the signal from the feldspar (since feldspars are bleached by infrared light) prior to the OSL Lx step and therefore gave a lower Lx/Tx value if there was feldspar present. If the difference of the two cycles was more than 10% (if the second cycle is >10% lower than cycle 1) the aliquot was rejected due to feldspar contamination. Only samples that passed the check with less than 10% deviation from unity in the Lx/Tx ratios were allowed further analysis. In the purity runs 3 aliquots of almost every sample was tested, with exception of a few samples in which the amount of sample was insufficient. However, since an IRSL step was added in the De runs, and all samples turned out to lie within limit, it should not affect the accuracy of the measurements.

Table 2. Table of cycles used in a purity check where the first cycle measures the signal without an IRSL step, and the second cycle with the step. The cycles are compared and if they are within 10% deviation from each other the sample is regarded as pure and can be used for De determination.

<table>
<thead>
<tr>
<th>Step</th>
<th>Cycle 1</th>
<th>Cycle 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Natural or lab dose</td>
<td>Natural or lab dose</td>
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<tr>
<td>2</td>
<td>Preheat</td>
<td>Preheat</td>
</tr>
<tr>
<td>3</td>
<td>IRSL</td>
<td>IRSL</td>
</tr>
<tr>
<td>4</td>
<td>OSL (Ln or Lx)</td>
<td>OSL (Ln or Lx)</td>
</tr>
<tr>
<td>5</td>
<td>Test dose</td>
<td>Test dose</td>
</tr>
<tr>
<td>6</td>
<td>Preheat</td>
<td>Preheat</td>
</tr>
<tr>
<td>7</td>
<td>OSL (Tn or Tx)</td>
<td>OSL (Tn or Tx)</td>
</tr>
</tbody>
</table>

4.3.2 Dose recovery test

The dose recovery test was done to determine if the protocol was able to accurately recover a known laboratory administered (given) dose (Wintle & Murray, 2006). The given dose was assumed to be unknown when the protocol was run, and if the protocol was working then it considered able to recover the dose correctly. For the dose recovery test to be passed the ratio of the measured to the given dose was expected to be close to 1 (Wintle & Murray, 2006). The protocol was assumed to be working if the ratio was within 10% of 1. If this was not the case then the parameters of the protocol needed to be altered (Wintle & Murray (2006).

Dose recovery sequences contained four regeneration doses, a zero dose, a recycling point, and an IRSL step. Two initial bleaches were performed with a pause of 10 000 seconds between them to remove the natural signal from aliquots prior to laboratory dosing. The size of laboratory administered initial dose was chosen based on being as close as possible to the estimated natural dose. The test dose
was set to one third of the estimated natural dose. Dose recovery was performed on 3-4 aliquots from every other sample.

4.3.3 Preheat plateau test

The test applied varied first preheat temperatures over an interval of 180°C to 300°C (second preheat tracking by 40°C lower) to see how preheat temperature in the SAR protocol affected the De. The optimal temperatures for the protocol should lie where the De values formed a plateau of constant values (hence the name of the test) and one of these temperatures was used for the first preheat in the cycle, and a temperature 40°C lower than this was used for the second preheat (cutheat) in the cycle (Duller, 2008).

Preheat temperatures of 260°C (first preheat – step 2 Table 1) and 220°C (second preheat – step 6 Table 1) were decided upon based on the test results (Fig 7-8, and Appendix Fig 1-4). Test runs were done with and without a final high temperature bleach, and the results showed that the final bleach could be disregarded. Following measurements were done without a final clean out. A spread of samples was used for this test to see if optimal temperatures varied with age. The samples used were the fine grained quartz sample 16 and 40 and the polymineral fine grain samples 1, 16, 40, and 60, using 24 aliquots of each sample.

4.4 Equivalent dose

The equivalent dose was obtained using similar protocol as the dose recovery but, instead of prior bleaching and laboratory dosing, the natural signal was first measured to calculate De on 6 aliquots or more for every sample. No final bleach was used in the protocol since empirical tests (multiple measurements both with and without final bleach) showed that there was no difference in the dose recovery results when excluding the final bleach. Aliquots were divided between machines and a weighted average calculated from the results. The specific settings in the SAR protocol used can be seen in Table 1.

De values were obtained from luminescence signals using integration limits of signal 1-3 and minus a background of 4-10. The signal represents intervals over which the luminescence signal (counts) decay over time. The initial ‘fast component’ signal of the luminescence decay was used to determine the De, in this case the interval 1-3 s (as seen in Fig 5-6), and the background signal was removed. An exponential plus linear growth curve line was fitted through the regeneration dose values and errors on the resultant De values were obtained from Monte Carlo simulation of 1000 repeats.
The post IR blue method was also applied to polymineral samples to check if exposure to IRSL was enough to remove the signal from the feldspar and obtain the quartz signal, and thus compare the reliability of this method to OSL dating of etched quartz. Post IR blue is an alternative method where instead of removing feldspar and other unwanted minerals by etching the sample, an IRSL step is added into the SAR sequence before the OSL step, to remove the signal generated from the feldspars. In the laboratory setting polymineral aliquots are exposed to an IRSL step before measuring the luminescence signal (OSL step), otherwise it follows the same SAR-protocol as the pure quartz aliquots. The use of post IR blue has been debated, and most often etching to remove feldspars is preferred, but depending on the sample it can be possible to get accurate data even with the post IR blue method. However the accuracy of this method is varied depending on sample type and site. If similar De values are obtained using post IR blue dating of polymineral samples as using blue OSL dating on quartz samples it means that post IR blue is a valid method for De determination and offers a time efficient way to date samples.
4.4.1 Rejection criteria

The recycling test repeated the signal measurements after the dose response curve was created; the goal was that the SAR protocol replicated the result from previous measurement. The aliquot passes and the SAR protocol was deemed working if the ratio between the two Lx/Tx values was within a 10% limit from unity. Recuperation, or the zero-dose, test if there is a residual signal when giving the aliquots a dose of 0 Gy, optimally the resulting Lx/Tx should give no signal and we should get a natural De of 0 Gy, but due to thermal transfer and residual charge this may not be the case. In practice an additional cycle is added in the SAR protocol dosing the aliquot with 0 Gy. Aliquots were rejected if the resulting value is 5 to 10% from 0. Aliquots were originally accepted if their recycling was between 0.9 and 1.9, and if the recuperation was within a 10% deviation. However, the data from the rejected aliquots was saved to determine how well the rejection criteria apply and if it necessary to keep such strict criteria on the cost of usable data because it is arguable that aliquots outside the boundary could still be used and the criteria could be too strict. This study addressed this issue, and showed De and age calculations based on both the original criteria together with aliquots that did not pass the standards. The recuperation criteria are set as 5% left over signal from the zero doses.

4.5 Dose rate

The annual dose rate was measured through high-resolution gamma spectrometry on an untreated sample. The concentrations of radioactive elements (U, Th, K, Ra) were calculated from the γ-activity. The dose rate was calculated from these concentrations using conversion factors from Adamiec & Aitken (1998), and cosmic radiation contribution was calculated based on altitude, depth and geographic location, as outlined in Prescott & Hutton (1994). Most samples were measured directly for dose rate but for those samples for which dose rate measurements were missing an average of all other samples’ dose rate values were used. The water content was estimated to be 20% since this is a site typical value because the southern part of the CLP has a wetter climate; however, it is difficult to recreate past water content and there has been discussion regarding the amount impact the water content has on age determination (Stevens et al, 2013). Using too high water content may lead to overestimation of ages as the dose rate decreases with an increase in water content, furthermore no consensus has been reached regarding water content values on the CLP (values ranging from 1-25%) (Stevens et al, 2013) and Duller (2008) states that the influence of water on dose rate varies from sample to sample but it is believed that a 1% water increase leads to a 1% increase in age.

4.6 Age model

An age model was created based on linear regression techniques. Since the data is composed of discrete points rather than a complete age series multiple regression (trend) lines were added to specific intervals of the data. These intervals were chosen based on visual inspection of the
luminescence ages with depth, to identify where changes in the age depth relationship occurred. A single regression line was fitted to data where the age depth relationship appeared constant, and a second one was fitted where this relationship changed in the profile. Based on observation of the data, 3 outliers (samples: 4, 33, 35) were removed, of which two were situated outside of error limits (Fig 18). Point 33 was within the limits but showed a large age inversion, inconsistent with all other data around it, hence it was assumed it was erroneous and removed. These outliers skewed the trend which was clear from all the other samples, and including them in the regression equations and age model construction would have led to regression lines which would be offset from the majority of the data, hence the removal was justified. It was assumed that saturation (when the traps in the quartz crystals are completely filled with electrons after long term dosing, and the signal cannot build up anymore) occurred below 460 cm therefore the age series stopped at that point. As the choice of where to fit regression lines is a subjective exercise, based on visual inspection of the changes of age with depth, and could be ambiguous, two different regression age models were made; age model 1 (Fig 19) with four trend lines, and age model 2 (Fig 20) with six trend lines. The trend lines were used to attempt ‘best fit’ of the lines with the data; however there are difficulties with applying regressions lines based on only visual means. This is the most common method applied in the literature even though there no consensus yet on how to obtain a continuous age depth model from luminescence dates. By comparing these two models and their differences in the proxy records it was possible to check how much uncertainty could be introduced by choice of age model. A big difference between the models would mean that the choice of regression lines in making age models leads to errors and uncertainty depending on how the researcher interprets the age data and choses the position of trend lines. The equations of the regression lines were used to calculate age for every 5 cm depth increase, which correspond to the depth intervals in the proxy data. These new age values provided a complete age model that was used to examine changes is the proxies; MS and mean GS, as well as to calculate MAR.

4.7 Proxies

Various grain size measurements were used; mean and median GS, GS fraction, and the U-ratio. However, mean GS was used as the primary proxy since it is a measure of the general average wind speed and arguably a general proxy for winter monsoon conditions. Both GS and MS were measured at 5 cm intervals, and then plotted against the two age models to study amount of offset depending on regression lines used. The different GS proxies were plotted against MAR (Fig 31).

4.8 Mass accumulation rate

The mass accumulation rate was calculated based on the formula by Kohfeld and Harrison (2003), \( MAR = SR \times f \times BD \), where \( SR \) is the sedimentation rate, \( f \) proportion of aeolian sediment (assumed
1), and $BD$ is the bulk density. The sedimentation rate was based on the slopes of the trend lines, while bulk density was based on direct measurements on samples. MAR was calculated over 10 cm depth intervals from 20 to 440 cm.

### 4.9 Heinrich events

The timing of Heinrich events is based on results from Hemming (2004) (Table 3). Heinrich events 1 and 2 have been dated by radiocarbon and is thus not directly comparable to OSL ages which gives calendrical ages and not BP dates, and while that age difference is small enough to be irrelevant over the studied time scaled, the duration of the Heinrich events are more problematic to determine due to the chaotic nature of the events themselves with high sediment flux increase (Hemming, 2004). Heinrich events 3, 4, 5, and 6 have been determined by correlation to Greenland ice core $\delta^{18}O$ data (Hemming, 2004), and should therefore as all correlation based method be treated with caution.

Table 3. Heinrich events and their corresponding age (cal. ka b.p.) based on radiocarbon and ice core $\delta^{18}O$ measurements from Hemming 2004.

<table>
<thead>
<tr>
<th>Heinrich Event</th>
<th>H0</th>
<th>H1</th>
<th>H2</th>
<th>H3</th>
<th>H4</th>
<th>H5</th>
<th>H6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (ka)</td>
<td>~12</td>
<td>16.8</td>
<td>24</td>
<td>~31</td>
<td>38</td>
<td>45</td>
<td>~60</td>
</tr>
</tbody>
</table>

### 5. Results

#### 5.1 Tests and luminescence characteristics

All etched fine grained quartz sample passed purity check to within 10% and could be used for OSL dating. All dose recovery tests were passed to within 10% of unity and hence it was concluded that the applied SAR protocol had the right settings for age determination (table 1).

Preheat plateau tests showed that the appropriate temperatures to use were a first preheat of 260°C and a second preheat of 220°C (Fig 7-8), since the first preheat temperature 260°C was in the middle on the plateaus for all samples. Hence, these temperatures were used throughout the study. This was also done for polymineral samples which gave the same optimal temperatures as the quartz samples (260 to 220°C). The polymineral preheat plateaus (Appendix Fig 1-4) also showed plateaus at the 260°C first preheat temperature, and on that base and the possibility of thermal transfer at higher temperatures the first preheat temperature was set at 260°C and the second preheat temperature at 220°C.
Figure 7. Preheat plateau for sample 16 pure quartz, showing that 260°C lies in the middle of the plateau of similar De values. The x-axis show the preheat temperatures for the first preheat in the SAR protocol, whereas the second preheat tracks this with temperatures 40°C lower than the first preheat.

Figure 8. Preheat plateau for sample 40 pure quartz, showing that 260°C lies in the middle of the plateau of similar De values. The x-axis show the preheat temperatures for the first preheat in the SAR protocol, whereas the second preheat tracks this with temperatures 40°C lower than the first preheat.

5.2 Equivalent dose

The De values increased with depth up until approximately 150 Gy where they flatten out. A minor decrease in De was seen in the lower samples from 380 cm and downward where more scattering occurs (Fig 9). Note that the error bars also increased in size in the lower samples.
Figure 9. De change with depth; showing an increase in De with depth with some scattering. Inversion of De values below ~440 cm.

5.2.1 Rejection criteria

All but a few aliquots passed standard rejection criteria. The recycling values outside the criteria ranged between 0.64 and 0.88. The comparison between De values of included and excluded data that failed the standard rejection criteria showed little difference (Fig 10). All but one sample fell on the line, indicating that the change in De between including and rejecting aliquots based on >10% deviation from unity on recycling ratios or large recuperation values was empirically unimportant. The only point (sample 18) deviating from the line contained high error in recuperation (70.37%). In Fig 11 the aliquot with the recuperation error was removed and as seen, the error bar crossed the line.
Figure 10. Comparison of De values when applying and not applying rejection criteria (recycling ratios within 10% of unity and recuperation <10%).

Figure 11. Comparison of De values when applying rejection criteria (recycling ratios within 10% and recuperation <10%) and when rejecting aliquots based only on recuperation criteria.

When compared the recycling ratios to the normalized De values for every aliquot, the data formed a cluster with no apparent trend (Fig 12). Representative graphs of recycling for each sample plotted against its normalized De values can be found in the appendix (Appendix Fig.5 to 8).
5.2.2 Post IR blue

The post IR blue results of the polymineral samples were compared to the quartz De values (Fig 13). The comparison showed that the polymineral De generally resulted in lower De values than the quartz samples, and therefore apparently underestimated the OSL signal. This was clearest over the 100 to 150 Gy interval where the polymineral samples generated very low De values compared to the pure quartz signal.

Figure 12. Recycling ratio of the aliquots plotted against their normalized De.

Figure 13. Comparison between blue OSL pure quartz and post IR blue polymineral De values from the same samples. A general underestimation of post IR blue polymineral De is seen in the data.
5.3 Dose rate

The activity of $^{40}$K, $^{232}$Th, and $^{226}$Ra were plotted by depth (Fig 14-16). Since $^{238}$U is poorly measured during laboratory gamma spectrometry, its daughter isotope $^{226}$Ra is used in order to calculate the $^{238}$U content. Activity is nearly constant over depth in similar patterns, with some minor variation over specific intervals.

Figure 14. Spread of radioactive element $^{40}$K (Bq kg$^{-1}$) for dose rate measurements by depth.

Figure 15. Spread of radioactive element $^{232}$Th (Bq kg$^{-1}$) for dose rate measurements by depth.
Figure 16. Spread of radioactive element $^{226}$Ra (Bq kg$^{-1}$) for dose rate measurements by depth.

The dose rate calculated from these elemental activities in the profile varies mainly between 3 to 4 Gy/ka (Fig 17). The dose rate is nearly constant over depth, but some scattering is visible below 400 cm. The first dose rate point has a larger error than the rest, potentially due to characteristics of the top soil such as mixing or bioturbation. It should be noted that the constant trend of the values below 300 cm is due to interpolation based on the section average because many measurements were missing from this interval, which could add some error in the age calculations.

Figure 17. Dose rate distribution by depth show dose rate values ranging between 3 to 4 Gy/ka. Interpolation of values from ~300 cm and down.
5.4 Ages, age model and proxies

The ages generally increase with depth even though there is some variability between samples (Table 4, Fig 18). For example, there is a large age gap of ca 14,000 year between sample 1 and 3 (over a 50 cm difference). Sample 4 has an anomalously high age (~22 ka) compared to succeeding samples, and sample 33 has a much lower age than what would be expected from the rest of the data. The maximum age was seen at sample 35 (~52 ka) that is whether an anomaly or quartz is saturated and underestimates ages after this point is uncertain; it was decided to treat sample 35 as another outlier. These three anomalous outliers (samples 4, 33, and 35) are therefore not included in the age model. The record continues to show consistent age increases with depth until sample 41 (460 cm depth). Following 460 cm the age no longer increase with depth which suggests that the ages are underestimated due to saturation of the quartz signal (Buylaert et al., 2007). Buylaert et al., (2007) suggested 150 Gy as an upper limit for quartz dating by and these samples approached such value. Hence, it may be best to treat these as minimum ages and exclude them from the age depth model.

Table 4. De values from blue OSL of quartz and post IR blue of polymineral samples. Dose rate and ages of blue OSL measurements of quartz. Blue OSL of quartz De was only measured up to sample 49 as saturation was expected to occur, while post IR blue of polymineral was tested up to sample 56.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth (cm)</th>
<th>De quartz (Gy)</th>
<th>De pfg (Gy)</th>
<th>Dose Rate (Gy/ka)</th>
<th>Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>20</td>
<td>6.06 ± 0.22</td>
<td>5.44 ± 0.48</td>
<td>3.58 ± 0.58</td>
<td>1.69 ± 0.28</td>
</tr>
<tr>
<td>03</td>
<td>70</td>
<td>55.68 ± 4.51</td>
<td>57.59 ± 2.77</td>
<td>3.49 ± 0.20</td>
<td>15.79 ± 1.60</td>
</tr>
<tr>
<td>04</td>
<td>80</td>
<td>77.30 ± 0.91</td>
<td>3.50 ± 0.20</td>
<td>22.08 ± 1.36</td>
<td></td>
</tr>
<tr>
<td>05</td>
<td>90</td>
<td>56.58 ± 1.04</td>
<td>3.62 ± 0.21</td>
<td>17.58 ± 1.21</td>
<td></td>
</tr>
<tr>
<td>06</td>
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<td>3.68 ± 0.21</td>
<td>13.78 ± 1.16</td>
<td></td>
</tr>
<tr>
<td>07</td>
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<td>50.72 ± 2.98</td>
<td>3.74 ± 0.22</td>
<td>15.77 ± 1.00</td>
<td></td>
</tr>
<tr>
<td>08</td>
<td>120</td>
<td>58.96 ± 0.49</td>
<td>69.84 ± 2.37</td>
<td>3.71 ± 0.22</td>
<td>18.32 ± 1.41</td>
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<tr>
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<td>69.91 ± 3.18</td>
<td>3.82 ± 0.23</td>
<td>16.72 ± 1.10</td>
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<tr>
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<td>3.97 ± 0.24</td>
<td>19.16 ± 1.34</td>
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<tr>
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<tr>
<td>Sample</td>
<td>Depth (cm)</td>
<td>De quartz (Gy)</td>
<td>De pfg (Gy)</td>
<td>Dose Rate (Gy/ka)</td>
<td>Age (ka)</td>
</tr>
<tr>
<td>--------</td>
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<td>----------------</td>
<td>-------------</td>
<td>-------------------</td>
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<td>37.99 ± 2.61</td>
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<td>160.78 ± 7.95</td>
<td>3.69 ± 0.23</td>
<td>36.98 ± 2.84</td>
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<td>510</td>
<td>139.79 ± 1.69</td>
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<td>3.69 ± 0.23</td>
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<td>47</td>
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<td>138.54 ± 6.12</td>
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<td>3.47 ± 0.20</td>
<td>39.88 ± 3.00</td>
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<tr>
<td>Sample</td>
<td>Depth (cm)</td>
<td>De quartz (Gy)</td>
<td>Dose Rate (Gy/ka)</td>
<td>Age (ka)</td>
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<td>48</td>
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<td>59</td>
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<td>273.67 ± 7.16</td>
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</table>

**Figure 18.** Age plotted over depth show an increase in age with depth and some scattering. Inversion of ages occur below ~440 cm.

The two regression-based age models (Fig 19-20) showed a difference between the age models, mainly in the middle part of the time series. The time series in the first model is represented by one
regression line, while in the second age model is divided into three sections with their own trend lines. Despite the change in construction, the age models showed similar equations and thus generated similar ages, likely because the data remain similar, although split. It should be noted that the lowermost regression line of the two models could have underestimated the age based on scattering and possible saturation of the De values at this point in time. It should also be pointed out that the line between 20 to 70 cm that constitutes the Holocene and back to 15 ka is only based on two points and therefore does not contain high detail from this period. Consequently, this time interval should be treated with caution.

**Figure 19.** Age model 1 based on 4 regression lines.

**Figure 20.** Age model 2 based on 6 regression lines.
To compare the influence of the choice and construction of the age models the proxy data were plotted with both age models. The difference between the trends and timing of MS variability between the two models is small (Fig 21). The largest differences occur around 16 to 15 ka, and at 31 ka; with a maximum difference between the models of 1000 years on a 45 ka timescale. The age errors on the luminescence dates are therefore bigger than the age differences between proxy data reconstructions; thus the differences between age model 1 and 2 is within the errors of the age model.

**Figure 21.** MS record plotted against age based on the two different age models.

The changes in mean GS occurred at similar ages in the two models (Fig 22), the largest differences occur at 18 to 15 ka and at 31 ka. However, the differences in timing are not large and it is a question of rate of the change rather than the amount. Age model 2 showed oscillations during the general drop in mean GS during 18 to 15 ka while age model 1 showed a rapid smooth change. However, the age data showed scattering during this time interval that makes the interpretation of the occurrences of these changes difficult.
Since the two age models showed very similar patterns in the proxy data, which only varied within the error of the individual luminescence dates, it should be safe to continue the study. Given the amount of age scattering (Fig 18) in the middle part, age model 1 was considered a safer choice. Multiple lines over the section where scattering occurred could lead to regression lines being based on false trend given by the scattering rather than a general trend in the data. Further calculations and graphs were based on age model 1.

One peculiarity is the pattern which showed an increase in mean GS, from 15-0 ka, consistent in all GS data (Fig 22, Appendix Fig 9-11). Because Holocene climate is generally warmer and wetter on the CLP, with lower winter monsoon activity, the opposite would be expected (Újvari et al, 2016). This could be due to an artificially young age for the uppermost part of the sample due to disturbance at the base of the Holocene soil, which has been observed at other sites as well (Stevens et al, 2007, 2008, 2016) and this will be further discussed in chapter 6.1.2. As a consequence it was decided to create a new age model (Age model 3) modified from age model 1 but starting from a depth of 70 cm (Fig 23) which onward will be used for proxy and climate interpretations.
5.4.1 Magnetic susceptibility

The MS over the depth 70 to 170 cm are relatively steady, while the record after 170 cm showed a drastic increase in MS with depth down to 220 cm (Fig 24A). Thereafter, the MS values oscillated steadily between 120 and 150 ($10^{-8}$ m$^3$kg$^{-1}$) until they dropped at a depth of 385 cm. In general, three periods were clearly observed the first one, presumably still ongoing, at depth 0-40 cm with high MS values, the second from 40 to 200 cm with low MS values, and the last one 200 to 420 cm with high MS values.

Similar to the MS over depth data, the MS over age (age model 3) showed an increase starting at 44 to 40 ka, and kept showing high values around 130 ($10^{-8}$ m$^3$kg$^{-1}$) until around 25 ka where MS drops and reaches MS values of ~80 ($10^{-8}$ m$^3$kg$^{-1}$) (Fig 24B). A period of low MS values was identified from 20 to 15 ka, but large oscillations could be seen around 16 ka.
A comparison between the depth graph and the one based on age (Fig 24A-B, Appendix Fig 12 for sample distribution) showed a general similar pattern although the graph based on the age model shows a much different record between 25 to 15 ka. A linear age relationship with depth, as in a non-independent age model, would have led to large offsets in the records due to variable accumulation rate over time. This demonstrates the need for independent dating methods.

5.4.2 Grain size

Mean and median GS plotted with depth showed large and rapid oscillations (Fig 25). The mean GS exhibited an overall decreasing trend from 70 to 390 cm, with high GS peaks at 270, 320, 370, and 440 cm. The median GS was in general lower (ranges between 11 to 17 µm) than the mean (ranges between 16 to 23 µm) and did not show any specific trends, but did however exhibit similar peaks at the same depth as the mean GS.

Figure 24. MS variation with depth and MS variation with age (age model 3).
The clay and silt fractions over depth showed no clear trends (Fig 26). Both clay and silt presented rapid oscillations, and their behavior mirrored each other. There was a slight increasing trend of the sand fraction between 70 and 220 cm.

Both median and mean GS plotted with age (age model 3) exhibited similar patterns, as expected (Fig 27, Appendix Fig 13 for sample distribution). The median yielded lower values ranging around 15 µm and showed more pronounced drops than the mean. The mean GS ranged around 20 µm and presented larger peaks where GS increases occurred. Both graphs showed a general steady pattern in GS varying between 23 and 18 µm in the mean GS record and 17 and 11 µm in the median GS record.

The GS record doesn’t show any consistent trends, but rapid and varied oscillations in GS. The mean, median GS, and U-ratio have similar patterns, but the magnitude of the oscillations differs and small lag occurs between the peaks. Some discrepancy between the records occur ~22 ka where the
mean GS differs a bit from the median GS and U-ratio. Periods of interest are high GS events occurring at: ~40, 36, 32, 21, and 16 ka, and low GS events happening at: ~41, 34, 29, and 23 ka. From 44 to ~40 ka there is a decrease in GS until the rapid but short period of increase at ~40 ka. After that the GS increases until around ~36 ka, followed by much more varied oscillations in GS which are difficult to interpret. What should be noted are the rapid oscillations in GS at ~16 ka.

Figure 27. Left: Volumetric median and mean (µm) plotted against age (ka). Right: U-ratio plotted against age (ka).

The silt and clay fractions mirrored each other with peaks in the silt record occurring with similar drops in the clay record (and vice versa) (Fig 28, appendix Fig 14 for sample distribution). The total volume was dominated by silt (~70%), then by clay (~25%), and lastly a small percentage of sand (<5%). From 44 to 25 ka the records oscillated more but the changes are minor. There was a general increase in sand content from 25 to 15 ka. Both the clay and silt fractions fluctuated quite rapidly, especially around 16 ka. Notable changes occurred at ca 39 ka with a drop in the clay fraction; similar events occurred at around 31 and 21 ka. Distinct decreases in the silt fraction accompanied by increases in clay fraction happened at ~41, 35, 25, and 19 ka. Note that the rapid oscillations at 16 ka were visible in all GS records.
The MS and GS data plotted together showed an anticorrelation in the oldest samples, from around 44 to 37 ka, with high MS values and low GS (Fig 29, Appendix Fig 15 for sample distribution). Some overlap between the records could also be seen at 16 to 15 ka with low MS and high mean GS. Except for these similarities, no clear relationship is seen between MS and mean GS. The mean GS exhibited more frequent and large oscillations while the MS record was more stable over a long period of time.

Figure 28. Oscillations with age in clay and sand fraction on the left axis, and silt fraction on the right axis.

Figure 29. Change in MS with age on the left axis and mean GS change on the right axis.
What is important to note is the difference between the MS and GS data plotted against depth as compared to age (Fig 24-26). The differences in the oscillations and general trends when plotted by age really emphasized that a simple proxy depth relationship was not reliable to use for correlation based age model derivation. Correlation methods are prone to error as they use marker horizons and merely try to match oscillations in the data to other dated sequences, and do not construct independent age models. For example attempting to match the MS by depth curve (Fig 24A) with another dated record would lead to large offsets compared to the actually dated curve (fig 24B), the same goes for GS plotted with depth (Fig 25-26) compared to GS over age (Fig 27 and 28). This is also noted in Fig 2, where Stevens et al. (2008) showed the difference between independent dated models compared with a correlation based one.

5.5 Mass accumulation rate

The MAR data showed two distinct periods of change in sedimentation rate (Fig 30, Appendix Fig 16 for sample distribution). The graph indicated a period of low accumulation between ~44 to 38 ka, with an even lower accumulation between ~37 to 19 ka with rates of ~15 $\text{g m}^{-2} \text{a}^{-1}$. A big jump to very high accumulation rates of ~88 $\text{g m}^{-2} \text{a}^{-1}$ from ca 18 to 15 ka was identified. There was no straightforward correlation between MAR and mean GS, excepting from 16 ka where both showed a similar behavior that, considering the age model error, could be only a coincidence.

![Figure 30](image)

Figure 30. MAR and mean GS plotted by age.

None of the GS proxies showed a correlation to MAR, except at ~16 ka were both GS and MAR show an increase.
For comparative purposes of age model and MAR construction, original age model 1 and 2 (Fig 19-20) were presented as comparable over the same interval, note however that the climatic interpretation was not based on these models as age model 3 (Fig 23) was and that they were used exclusively to analyze the influence of the method applied when creating the age models and MAR. Interesting to note are the differences in the MAR values in relation with the age model used (Fig 31-32, Appendix Fig 17-18 for sample distribution). The age differences did not vary significantly between models but the results were very diverse when the slope value for the accumulation rate calculations was applied. MAR is therefore highly sensitive to age model choice. MAR graphs for age model 1 and 2 showed much higher mass accumulation rates for the first peak (up to 87 g m\(^{-2}\) a\(^{-1}\)) resulting from model 1 while model 2 only reached a MAR of 27 g m\(^{-2}\) a\(^{-1}\). Model 2 also showed more detail, with a further drop in MAR at 25 ka that was not present in age model 1. The only difference in construction of the MAR between the graphs was the slopes used for calculating accumulation rate, which was obtained from the two different age models.

![MAR based on age model 1 and mean GS.](image)

**Figure 31.** MAR based on age model 1 and mean GS.
5.6 Heinrich events

The Heinrich events: H0, H5, and H6 are not included in this record since they occur outside the dated record in this study. H1 is assumed to occur at 16 ka that is close to a big increase in MAR and an oscillation in GS (Fig 33). Whether it corresponded to a peak or drop in GS is unclear as both are possible within the age model due to the inherent age uncertainty in the model. The event H2 occurred at 24 ka when there is a slight rise in mean GS, this change is however small, whereas H3 occurred at ~31 ka where the mean GS record showed a large increase, having a value of 22 $\mu$m. An increase in mean GS takes place at 38 ka when H4 is assumed to occur, and MAR slightly increases at that point (see Table 3 for specific event and corresponding age). These events could fall within a 1000-2000 year interval due to the error of the model. Thus, pinpointing such small scale events requires consideration of the age model uncertainties.
6. Discussion

6.1 Equivalent dose

The flattening out and underestimation of De over depth when passing 380 cm and the cluster of samples in the results could be due the approach of quartz saturation (Fig 9). It could be presumed that post IR IRSL measurements are needed to get accurate ages below ~400 cm.

The post IR blue De values are generally underestimated compared to the OSL dated pure quartz samples (Fig 13), which indicates that the IRSL step was insufficient in removing the signal from the feldspars. Therefore the method is rejected in this study and the resulting data from these runs were not included. The samples from this section seemed to need etching to remove feldspars, since even an IRSL step in the SAR protocol appeared to be unable to remove the feldspars signal totally. Compared IRSL and post IR blue dating and have shown that post IR blue yield more consistent results (Roberts and Wintle, 2001) that gives De values independent of preheat temperature (Roberts and Wintle, 2003). Banerjee et al, (2001) compared different post IR blue, IRSL, and blue OSL stimulations and concluded that post IR blue is reliable and provides more accurate De values than IRSL (Banerjee et al, 2001). This study disagree with the proposed accuracy of post IR blue as it shows that it underestimates De compared to etched quartz blue OSL where the feldspar has been removed. This disagreement has some implications; either this underestimation of De using post IR blue is just a site specific occurrence in the Lingtai section, or this is possibly a common occurrence over the CLP and thus studies using this method would include large errors in age estimations. It should be further
studied if the post IR blue method results deviate from OSL measurements on other sites on the CLP, and if a pattern (such as underestimation) can be discerned in more sites than just Lingtai.

There was no trend in the graphs showing recycling plotted against normalized De (Fig 12). A trend may have suggested that the recycling ratio value may be linked to De and therefore be a useful basis to reject data. However, the lack of trends combined with the analysis of De values for aliquots with and without application of the criteria indicates that, as suspected by some authors (e.g., Buylaert et al., 2015), these rejection criteria may be too strict and may lead to reduced resolution in data due to lower numbers of accepted measurements. Including higher numbers of aliquots for average De determination would result in a more statistically robust De. Standard practice is to reject aliquots outside the rejection limit, even if they show reasonable De values. This could result in a waste of aliquots and a decreased possibility of a robust average.

Based on the data, the recycling rejection criterion of 10% is too strict and limits the amount of useable data. Deviation from the recuperation criteria does seem to have a larger effect on the De compared to the recycling criteria. Sample 18 included one aliquot with a recycling error of 0.64, almost 40%, and this could be the reason for the point deviating from the line (Fig 10). Based on this study it would be recommended not to use too strict rejection criteria since this seems to limit the data amount in the studies with no clear empirical benefit in terms of age. It would be preferable to allow a broader criterion, at least with recycling. It should however be noted that this can vary between sections and sites, and the rejection criteria should be investigated in similar way in different studies to apply a reasonable limit. The recuperation criterion does seem to need more restriction since it shows deviation from the 1:1 line (which symbolizes unity between De with rejection criteria applied and De without rejection criteria) (Fig 10). In this study the recuperation error of an aliquot of sample 18 was very high and thus the aliquot became an outlier (Fig 10). These results motivated the utilization of aliquots outside the usual rejection limit if their error bars crossed the 1:1 line (Fig 11). The recuperation criterion was still applied though.

6.2 Age models and proxies

The decision to remove the first part of the age model and start at depth 70 cm was made due to the inconsistencies in the GS proxy data in relation to the age. The large difference in age between sample 1 and 3 (Table 4) could either be due to that the sampling interval over this part is quite large, 50 cm, or that pedogenic and anthropogenic disturbances have altered and mixed the upper part of the section similar to the Xifeng section (Stevens et al, 2008, 2016). It could also be due to hiatuses but without sample 2 it is difficult to be certain. As Stevens et al, (2016) point out that sampling resolution of 10 cm intervals at minimum are needed to discover hiatuses; otherwise, such fine scale features and disturbances may be missed during interpretation. Sample 4 showed an unreasonable high age that could be due to mixing of the section or to errors during dating. The same can be said for sample 33, which shows a very low age compared to surrounding samples. It remains unclear what is the cause of
these outliers. It was decided to treat sample 35, as a deviating sample instead as the maximum age due to its diverging high age. At sample 40 the ages started to decrease with depth from ca 45 ka to ages around 37 ka; hence, an underestimation of ages is likely occurring presumably due to quartz saturation. Saturation of the OSL signal determines the upper age limit that can be dated using the method. Blue OSL quartz dating starts to become unreliable at around 50 ka (Lu et al, 2007; Lai, 2010), which is argued to be due to high dose rates of 3 to 4 Gy/s leading to saturation of the quartz luminescence signal (Buylaert et al, 2007, 2015). On regard to hiatuses, it has been reported that centennial to millennial-scale gaps occur at different sites on the CLP (Lu et al, 2006; Stevens et al, 2006; Buylaert, 2008). Neither in this study or some other studies the presence of hiatuses or gaps in the record have been found (Lai, 2010; Buylaert, 2015). This gives reasons to believe that such disturbances and gaps in the records are site specific and consequently due to local factors affecting the deposition and preservation of sediment. Stevens et al, (2008) reported scattering in late last glacial and Holocene ages, as well as large gaps over 10 cm intervals over late last glacial times, and Stevens et al, (2007) reported that many sites exhibit anomalously young ages in the Holocene soil. Stevens et al, (2016) reported a clear jump in ages in the 1m depth interval at the Xifeng section which they ascribe to human agricultural activity. Their record also showed a depositional hiatus between 22 and 10.5 ka at Beiguoyuan, which was not found at Lingtai. The first regression line only covered two points and therefore did not capture any detail over this time period. The first 70 cm of the record that covered 15 to 0 ka was removed from the study and the consequently the whole of Holocene is missing in this study. In order to understand if a disturbance occurred, a detailed OSL study of the 0 to 70 cm section, possibly at a 5cm interval, is recommended to get enough data to capture possible changes and events during the Holocene and to clarify if mixing or soil forming processes have altered the record during this period.

Large GS during the Last Glacial Maximum (LGM) around 23 ka were expected, which would then drop rapidly when entering the Holocene, this is not observed at Lingtai indicating that the record before 15 ka (70 cm) is erroneous. Kohfeld & Harrison (2003) found cultivated layers on the CLP, which made it impossible to interpret data from MIS (Marine Isotope Stage) 1. Anthropogenic effects such as cultivation, which began around 6000 years ago on the CLP, rework sediment and could cause mixing of layers (Kohfeld & Harrison, 2003). Stevens et al, (2008, 2013) also found scattering in Holocene data and late last glacial records as well as depositional hiatuses, which they attributed to anthropogenic effects and soil forming processes. They stated that Holocene and late last glacial records on the CLP may be disrupted and is thus untrustworthy (Stevens et al, 2007). This show that due to such disturbances and hiatuses the Holocene and late last glacial records from the S-W and central CLP may be unreliable, based on previous assumptions of continuity, and could thus alter the validity of the records.
6.2.1 Magnetic susceptibility

MS is generally considered to be dependent on in situ weathering of magnetic minerals, influenced by precipitation and temperature, and thus by extension the summer monsoon. In general, the MS values increase from the north to the south of the CLP due to the climatic variations in the region (Tang et al, 2003). Other factors beyond summer monsoon intensity could also affect the MS values. Since iron oxide formation are related to temperature and precipitation, topography ought to play a role in the process, as would the distance to a moisture source; for such reason Tang et al, (2003) reported higher MS values in the south CLP that experiences more precipitation. MAR could possibly also affect pedogenesis with thicker sections needing either more time to oxidize or more intense temperature and precipitation. These parameters would not only affect oxidation but also explain the differences in timing of MS events between different sections across the CLP; otherwise, the discrepancies could simply be due age model error or even a combination of both.

The MS record (Fig 24 B) showed an increase from 44 to 40 ka, going from a time of weak summer monsoon to a period of strong summer monsoon with high precipitation which is prevalent between 40 to 25 ka. After 25 ka the MS decreased, and a period of weak summer monsoon that lasts between 20 to 15 ka followed, with a short period of decreased precipitation at 15 ka. The Lingtai and Xifeng sections (Stevens et al, 2016) show dissimilar MS patterns. Lingtai exhibits higher MS values in general, around 135 (10^8 m^3 kg^-1) while Xifeng’s max value is ca 72 (10^8 m^3 kg^-1) (Fig 34). The magnitude of change in the MS data is much higher at Lingtai, between ~70 and 150 (10^8 m^3 kg^-1), whereas Xifeng varies between ~45 to 70 (10^8 m^3 kg^-1). The pattern is also different, where Lingtai experiences large shifts in MS, Xifeng (due to its scale) show less dramatic variations. At the period 44-40 ka where MS at Lingtai show a large increase, Xifeng has a very steady trend in the MS data and first shows an increase at ~36 ka. Similarly when Lingtai experience a large drop in MS at ~25 ka, Xifeng show a more steady long time drop in MS from ~32 ka and forward. This difference could be from local weathering effects due to regional environmental variations as Lingtai is south of Xifeng and thus closer to the ocean and a moisture source which could lead to increased weathering and consequently more dramatic shifts in the MS record. The MS record by Stevens et al, (2016) displays lesser short term variability than the GS data, which could indicate that the signal cannot capture sub-millennial events or that rainfall is not as variable as changes in dust deposition and wind speeds. Similarly to Beiguoyuan (Stevens et al, 2008), the MS record at Lingtai indicates slightly decreasing summer monsoon at 37 and 29 ka, even though the decrease is not as prominent as the one at 24 ka, where an onset of a strong winter monsoon can be seen. Lu et al, (2013) OSL-dating on three sites on the CLP (Luochuan, Yulin, and Xunyi) shows that the period between 21 to 8 ka had low MS, an increase in δ13C and TOC (total organic carbon) values (Fig 35) and is thus interpreted as a period of little precipitation. In this study however there is a drop in MS starting at 25 ka until 16 ka where rapid oscillations occur followed by an increase in MS. These discrepancies indicate that either the records
are offset or an age model error is present, as this study, Stevens et al, (2016), and Lu et al, (2013) use linear interpolation modelling. The possibility remains though that these discrepancies are related to geographic differences since none of the sections studied by Lu et al, (2013) was located in the S-W CLP where Lingtai is.

**Figure 34.** MS and mean GS from Lingtai compared to Xifeng show different trends in MS and GS compared to Lingtai (fig 24, 30), as described in the text. Data from Stevens et al, (2016), used with permission.

**Figure 35.** MS, TOC, and $\delta^{13}C$ from Lu et al. (2013) show low values while by contrast the MS from Lingtai show a drop in MS from 25-16 ka (fig 24, 30). Picture modified from Lu et al, 2013.
6.2.2 Grain Size

The mean and median GS is a measure of wind intensity, with higher GS indicating stronger winds (Újvári et al, 2016). Hence periods such as 40, 36, 32, 21, and 16 ka, with increases in mean and median GS should indicate an increase in wind intensity and thus a colder and drier climate where such wind patterns are favorable. The opposite could be said about time periods which show decrease in mean and median GS as at 41, 34, 29, and 23 ka. The U-ratio correlates relatively well with the mean and median GS record, it is safe to assume that both methods agree on wind intensity changes and climate fluctuations.

A high clay size fraction (<5.5 µm) is often interpreted to be related to high atmospheric winds which cannot entrain larger particles, while the >63 µm sand fraction is usually high when there is an increase in dust storm activity that has sufficient energy to transport grains of larger size (Újvári et al, 2016). Thus, the period of increase in sand fraction (25 to 15 ka) could be due to increase in dust storm activity. Since the sand fraction increases steadily after 25 ka to ca 15 ka, it is reasonable to assume that the frequency of dust storm that entered down to the western CLP increased. The fractions show no specific trend in the clay or silt data but variable oscillations over the whole record. Times of high clay content (at ~41, 35, 25, and 19 ka) accompanied with lower silt and sand content indicates periods of increased high atmosphere dust transport or weaker winds in general. High clay content could also be caused by weathering and formation of secondary clay mineral, but as the U-ratio decreases during these periods the clay is probably not caused by weathering. Periods of decrease in clay content co-occurs with increase in silt (at ~39, 31, and 21 ka), which indicates stronger winds during these times. With regards to the winter monsoon the GS record is difficult to interpret as it doesn’t show any clear trends, but from 44 to 40 ka there is a weakening of the winter monsoon, which after ~40 ka strengthens again. The increase in GS at ~16 ka accompanied with rapid oscillations caused by heightened accumulation point to a strengthening of the winter monsoon with stronger winds depositing more and larger sediment.

When comparing the GS record from Lingtai to Xifeng (fig 34) there are large differences. In general Xifeng exhibits larger GS than Lingtai, which could be due to its position further north, and thus closer to dust sources and closer to the incoming winds from the Siberian high. The GS record at Lingtai doesn’t show any clear trends, whereas Xifeng show an increase in GS from 34 ka indicating a strengthening in the winter monsoon not visible in at Lingtai. The discrepancies in the records could be due to the position of the sites, or local influences on deposition and preservation of sediment.

6.3 MAR

The MAR data based on the age model covering 44 to 15 ka (age model 3) showed three noticeable changes in accumulation rate; the first period started at 38 ka with slightly higher MAR, but a large drop in GS data was visible during this time, which is counterintuitive since weak winds causing the
decrease in grain size should not lead to high accumulation. Next, a time of lower accumulation from ~38 to 18 ka was identified, where the GS records do not correlate with the lowered MAR. This interval showed very variable GS values that did not seem to have any relationship with the accumulation rate. It would be expected to see heightened MAR at 36, 31, and 20 ka since these are periods with high mean GS, U-ratio, and sand and silt content. Furthermore, it would also be presupposed that an increase in MAR and grain size during the Last Glacial Maximum (LGM) ~23 to 19 ka (Hughes et al, 2013) would be seen as in other studies; for example Stevens et al, (2016) show MAR and mean GS increase from ~27 to 20 ka, and Kang et al, (2015) show increase in MAR at multiple sites around ~20 ka, whereas the maximum MAR and GS peak at the Lingtai section occurred at 16 ka. If this is due to a delay or lag in the system or age model error (ca 1000-2000 years) is uncertain. The third period ~19 to 15 ka showed high values concurrent with high mean GS and U-ratio. The question is why don’t the records exhibit any clear correlation between MAR and GS? MAR can be controlled by various different factors such as transport distance and mechanics, setting and distance from source region, and local environment (Stevens et al, 2016). Sediment may be trapped during transportation by topography, or preservation may be limited or interrupted, which could cause the calculations to show low MAR even if the other proxies showed a climate favorable for dust deposition. The lack of correlation may also be caused by uncertainties in the age model and MAR calculations. Stevens et al, (2008) report high accumulation rate at 21 to 19 ka, whereas Stevens et al, (2016) show high MAR at ~40 to 32 ka and 27 to 20 ka (Fig 36), which in this study showed low MAR (Fig 30). The magnitude of MAR is very different between the sites; Lingtai have maximum values close to 90 (g m⁻²a⁻¹), whereas Xifeng has a maximum value close to 270 (g m⁻²a⁻¹). This difference could be due to that Xifeng is further north and closer to both dust sources and incoming winds from the Siberian High. It is commonly presumed that accumulation rate and grain size changes occur at the same time in the records due to related forcing mechanisms, but this study and the study by Stevens et al, (2008) found no apparent relationship between grain size and sedimentation rate. This suggests that connection between GS and MAR may not be as intuitive as presumed and that comparison between MAR of different sample sites will be difficult due to inherent variation of site settings.
What is interesting to note is the big difference in MAR between age model 1 and 2, where the second model has overall much lower MAR values and more detail as it captures another accumulation phase at ~25 ka. This is due to the construction of the age model and the slope value used to calculate the accumulation rate used for MAR determination. It shows that even though construction of age models based on regression lines do not show large difference in age, the accumulation rate calculation based on the same regression lines are much more sensitive to changes. Visually there is not a big difference of the regression lines of model 1 and 2, yet the effect on accumulation rate can be significant enough to alter the MAR. This effect escalates when using the MAR calculation as seen in the graphs (Fig 31-32), in this case model 1 has 3 times as high values as model 2, likely due to that the accumulation rate for model 1 is 3 times higher than model 2. There are also changes in average bulk density based on the intervals of the regression lines but this do not seem to cause as large effect as the change in accumulation rate. This emphasizes the influence that the choice of regression lines can have on MAR calculations. Age models might be a useful method but their results on MAR calculation could be inaccurate depending on the choice of regression line, encompassing large uncertainties. MAR showed to be highly sensitive to minor changes in age model; MAR records should be consequently regarded as approximate estimates. This could also be the case for other studies using this method for calculating sedimentation rate or MAR (e.g Buylaert et al, 2015; Stevens, 2008; Stevens & Lu, 2009). Studies using linear regression for these calculations may include uncertainties that require careful considerations. This is an important point regarding how much confidence researchers should put in absolute values of MAR presented in the literature and an indication that studies using regression lines for age model construction and MAR calculation may contain uncertainties and further studies regarding optimal procedures and improvement of the method are recommended.
6.4 Monsoon reconstruction from the proxy records

Together the result highlights three periods of climate change (44 to 41, 40 to 26, and 25 to 15 ka). Based on the proxies, the climate at 44 ka was relatively cold with strong winds, and at 40 ka the MS increases and GS decreased indicating a warmer climate with increased weathering and consequently MS and clay content. This should have been a period of strong summer monsoon, increased precipitation, and low wind speeds.

The period between 40 to 26 ka is difficult to interpret due to the variable GS record and there are many uncertainties with using it as a proxy. The MS increased from 44 ka and had high values until a drop around 28 ka. The MS and GS data show no general correlation over this time interval, except for a peak in MS at 40 ka concurrent with low mean GS and U-ratio, as well as a large increase in clay content and drop in silt and sand fraction. At 31 ka there was large drop in clay fraction and increase in mean GS and silt content, which would indicate stronger winds, possibly more frequent dust storms, and lowered weathering. Nevertheless, the MS record remained high and unchanged during this period. Thereafter follows a period of more variable GS values; however, the MAR kept a steady low value from ~38 to 18 ka.

The MS values indicated a colder and drier climate from 25 to 15 ka, concurrent with the MAR that showed high accumulation during this period. The GS data is not in agreement, since there was low mean GS during this time (Fig 29), which would indicate weaker winds that are more prevalent in warmer climates, except at 20 ka where MS drops and mean GS increased, as did the clay fraction while silt content increased, indicating very little weathering and stronger winds. The grain size data did, however, indicate dissimilar climate variations than the MS record for the rest of the low MS periods as it exhibits large variations in mean GS both before and after ~25 ka. It should be noted that the proxies recorded different climate parameters and did not have to follow the same trends, but it would not be expected such high peaks in GS (39, 36, 31 ka (Fig 29)) during a, according to the MS, warm climate. As there was a small increase in sand during these mean GS peaks, the heightened grain size could be partly due to an increase in dust storms. Based on the proxies, the most recent period 19 to 15 ka is interpreted to have a strong winter monsoon (as the record shows high MAR, high mean GS and U-ratio, as well as heightened fraction of sand and silt while clay is decreasing). The rapid oscillations in the GS records and in the MS records at ca 16 ka (a period of high MAR) could be due to that the reconstruction of the proxy records contracts parts of the data where accumulation rates are high, while periods of low accumulation rates appear stretched in the record.

Based on the different results between proxies (where GS, MS, and MAR sometimes contradicts each other) at the Lingtai section consistent climate changes are difficult to capture, and the lack of relationship could be explained by local settings or factors that affect deposition or preservation of
sediment. The real question is the reason for such a big site to site variability between the same proxies. This study also points out apparent uncertainties regarding age model construction and specifically MAR calculations using regression lines. Discrepancies between records over the CLP could be due to error between age models or OSL ages. It is important to note that many studies use different resolution and sampling interval when applying independent dating of loess which could induce uncertainties when comparing records which makes monsoon reconstruction variable on the CLP.

6.5 Heinrich events

Larger than average grain sizes on the CLP are said to be an indicator of concurrent Heinrich events (Porter & An, 1995), however the mean GS record from the Lingtai section did not show such correlation. Accounting for error on both age model and timing of Heinrich events by Hemming, (2004), it is possible that the large increase in mean GS at 16 ka could coincide with H1 at 16.8 ka, and that the large increase in mean GS at H3 ~31 ka could indicate a relationship between the Heinrich events in the North Atlantic. However, since there is no evidence of visible Heinrich events in the rest of the record the correlation during these times could just be a coincidence. The record is therefore inconsistent and to draw any conclusions about a teleconnection between the North Atlantic Oscillation and the East Asian monsoon based on this record would be unadvised especially since the error on the age model is quite large (1000-2000 years) compared to the timescale over which Heinrich events occur. Consequently, it would be difficult to match shifts in the age model with such small times events. Sun et al, (2012) and Stevens et al, (2016) found evidence of joint forcing of the North Atlantic and East Asian monsoon climate, while Stevens et al, (2008) found no clear correlation. Stevens et al, (2016) states that the relationship is not clear but that the apparent timing of GS increase with Heinrich events (H2-H6) provides support to the idea of a teleconnection at the Xifeng section. The Lingtai section did not show evidence for a connection however, it is worth mentioning that large increase in mean GS concurrent with H3 in the Lingtai section is not supported at Xifeng where MAR values during this time is low and peaks in GS data diffuse (Stevens et al, 2016). Both this study and Stevens et al, (2016) indicate that uncertainty of timing and duration of MAR and proxy events may lead to misinterpretations of the records. Thus the question whether a teleconnection actually exists remains unanswered.

Due to uncertainties in the model and error on ages and MAR intervals, it is possible that shorter events as Heinrich events may be overlooked in the records or dated during slightly different times. It is difficult to pinpoint specific short time occurrences in the models due to uncertainty and error limits of the record. How to address this problem is unclear and even more detailed high resolution data, however useful, may not be able to ascertain the presence or lack of a teleconnection.
6.6 Evaluation of performance of the method

Based on results from the tests the De values should be accurate and investigation of rejection criteria showed that it is possible to include data within a broader limit. Age model construction based on a well applied method showed many uncertainties and is questioned. The choice of limiting the age model between depths of 70 to 440 cm should limit the errors and give more accurate data. Uncertainties of the study and suggestions of improvements are suggested below.

6.6.1 Uncertainties

Since the dose rate was not measured for every sample, an average was used. This could lead to error in estimation of age, especially in older samples which more frequently lacked dose rate measurements. Still, the first part of the dose rate sequence, which had consistent measurements, showed similar rates. This pattern could be assumed to be more or less unvarying further down the sequence.

No new limit for the rejection criteria could be suggested from this study. It would be important for future studies and similar OSL research to examine the significance and limits of the rejection criteria and if its application depends on the specific site characteristics or if a new broader criteria may replace the old one.

Utilizing age models and regression lines for continuous age estimation, it is a subjective approach and further research is needed to create a standardized way for how to apply age models and criteria, e.g. to determine how to address scattering and age inversion in the data and where to connect regression lines. This study showed that the choice of age model can have a large effect on MAR (Fig 31 and 32), which could have implications for other studies (e.g. Buylaert, 2008, 2015; Lu et al, 2013; Stevens et al, 2008, 2009, 2016) where similar techniques have been used, and implies that more work needs to be done on quantifying these potential uncertainties.

6.7 Suggestion of future work

This study has contributed to add more data to an increasingly growing field of research and is a start to answering the questions raised by previous high resolution independent age model studies of the CLP. To be able to make generalized assumptions about the past climate on the CLP, detailed studies are needed on multiple sites to understand local changes and their attributions to the general picture. This study has also provided further evidence for the lack of disruptions and hiatuses in the loess record. The results highlight the importance of the method used, both for testing and rejecting aliquots, but also when creating age models and MAR and the uncertainties present. With regards to MAR and Heinrich events many uncertainties exist and further studies are needed to create a detailed image of the CLP.
It would be recommended to apply post IR-IRSL to continue the time series in which quartz saturation is assumed to occur to lengthen the dated record even further back in time to observe if hiatuses or disruptions are present during the last interglacial. It has been shown that the post IR blue method underestimates values and should therefore be used with caution, and it is preferable to etch samples and use OSL instead. The rejection criteria for recycling are too strict and only limit the amount of usable data. It is recommended for future studies to examine rejection criteria based on specific sequences to get full use of the data. It would be also needed to accurately determine the influence of the recuperation rejection criteria since it seems to be more sensitive than the recycling one. In other words, the standard OSL aliquot rejection limits needs to be updated.

In general, climate studies of the CLP are in need of improved methods for age model creation to be able to capture small scale events. Independent high resolution OSL dating provides accurate ages, but there are still difficulties regarding making continuous age models based on point data. Selecting age model and regression line method, the visual based determination of patterns in the age data introduces subjectivity in the method; however, the comparison of the two age models showed little change in the actual age, while only the level of detail changes. For future purposes, the choice of age model method needs to be evaluated, and for similar studies the uncertainty of the regression line method should be investigated.

To be able to give sufficient answers regarding hiatuses and the presence of Heinrich events, further high resolution dating and independent age model of the CLP is needed to discern if these are site specific occurrences are related to actual climate changes or due to the variability between methods and age model construction used in the studies. Several studies point towards site specific events, with some sites reportedly having hiatuses and correlation to Heinrich events (Porter & An, 1995; Sun et al, 2012) and others don’t (Stevens et al, 2008). Due to the short time intervals of Heinrich events, models have difficulties pinpointing these events due to the age model errors, especially in the MAR data, which is usually presented over larger time spans. It is recommended that in future studies the possibility of disturbances in the records and how that will affect the age model is considered, especially during the Holocene.

7. Conclusion

High resolution OSL-dating and independent age model construction of the Lingtai section gives a detailed view of monsoon climate change on the CLP and the influence of age model construction method on MAR calculations.

Regarding climate change over the period 44 to 15 ka, the MS proxy data shows a strong summer monsoon between 41 to 25 ka, followed by a decrease in MS and the onset of a weaker summer monsoon from 25 to 15 ka. The GS record is only anticorrelated with the MS record over certain intervals but mainly shows large variation in mean GS and fractions over the investigated period. The
lack of a continuous clear anticorrelation between GS and MAR as well as GS and MS could indicate that local settings may have influenced the transport, or it could simply be due to the nature of the techniques and that they record different climatic parameters that show different frequency variability. The high variability in GS and fractions are argued to be due to impacts from source distance changes, frequency of dust storms, and changes in local setting. The lack of correlation between MAR and GS indicates that the relationship is more complicated than previously thought, although potential bias in the age model construction could lead to uncertainties in the MAR. Changes in both proxies and MAR during the LGM would be expected, however increase in GS and MAR are delayed either due to actual lag or uncertainties in the model.

The record shows no apparent concurrence of increased GS and MAR during Heinrich events, except at H1 and H3. This could be due to the resolution and uncertainty in the model.

There are no hiatuses or erosional gaps present in the Lingtai section, but age inversion and scattering occur. This highlights the importance for high detail studies of Holocene and late last glacial loess, since previous records may contain uncertainties during this age interval.

In comparison to other studies in this region the proxies and MAR varies between loess sites. It is likely that changes in local settings may influence the records, but also the influence of the age model construction.

The accuracy when dating samples can increase with multiple tests, and site specific investigation of aliquot rejection criteria give a broader span of data for age determination.

Creating age models based on regression lines does not give a large difference in resulting ages, but the effect the regression lines when calculating sedimentation rate and thus MAR is of high importance.

In summary, differences in proxies, MAR, and thus monsoon reconstruction between sites on the CLP may be due to the lack of understanding of transport mechanisms, depositional processes, and preservation of sediment on the loess plateau. Combined with possible inaccuracy and imprecisions in the age model construction and MAR calculations, this may cause site specific variations visible in the records. Further studies are needed to provide more data but also increase the understanding of the processes occurring on the CLP to create more reliable monsoon reconstructions.
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9. References


Appendix

Figure A1. Preheat plateau sample 1 polymineral.

Figure A2. Preheat plateau sample 16 polymineral.

Figure A3. Preheat plateau sample 40 polymineral.
**Figure A4.** Preheat plateau sample 60 polymineral.

**Figure A5.** Sample 8 quartz recycling ratio plotted against normalized De for each aliquot.

**Figure A6.** Sample 16 quartz recycling ratio plotted against normalized De for each aliquot.
Figure A7. Sample 26 quartz recycling ratio plotted against normalized De for each aliquot.

Figure A8. Sample 39 quartz recycling ratio plotted against normalized De for each aliquot.

Figure A9. Median and mean GS data from age 0-44 ka (20-440 cm).
Figure A10. U-ratio from age 0-44 ka (20-440 cm).

Figure A11. GS fraction data from age 0-44 ka (20-440 cm).
Figure A12. MS sample distribution over depth.

Figure A13. Mean GS, median GS, and U-ratio sample distribution with age.
Figure A14. Clay, silt, sand fractions sample distribution with age.

Figure A15. MS and mean GS sample distribution with age.
Figure A16. MAR and mean GS sample distribution with age.

Figure A17. MAR based on age model 1 and mean GS sample distribution with age.
Figure A18. MAR based on age model 2 and mean GS sample distribution with age.