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Luminescence dating approaches to reconstruct the formation of plaggic anthrosols

Jungyu Choi[1,2], Roy van Beek[1,3], Elizabeth Chamberlain[1,2], Tony Reimann[4], Harm Smeenge[5], Annika van Oorschot[1], Jakob Wallinga[1,2]

[1] Soil Geography and Landscape Group, Environmental Sciences Group, Wageningen University, Wageningen, 6700AA, the Netherlands
[2] Netherlands Centre for Luminescence Dating, Wageningen University, Wageningen, 6700AA, the Netherlands
[3] Cultural Geography Group, Environmental Sciences Group, Wageningen University, Wageningen, 6700AA, the Netherlands
[4] Institutes of Geography, University of Cologne, Cologne, 50674, Germany
[5] Bosgroepen, Ede, 6717LL, the Netherlands

Correspondence to: Jungyu Choi (jungyu.choi@wur.nl)

Abstract. Plaggic anthrosols are one of the major features that contributed to the formation of the present-day landscape of northern part of Europe since the Middle Ages, but their formation history is rather poorly understood. The formation of plaggic anthrosols had an impact beyond the arable fields, impacting the entire landscape surrounding the arable fields, mainly through plaggen management activities. Therefore, plaggic anthrosols are a valuable archive for studying the interactions between human, soil, and landscape. Recently, luminescence dating methods have recently emerged as a tool for tracing the past movement of grains, including within the soil column. This study combines two primary luminescence methods -- single-grain feldspar infrared (IRSL) and post-infrared infrared (pIRIR) measurements, and small-aliquot quartz optically stimulated luminescence (OSL) -- to reconstruct the formation of a plaggic anthrosol at Braakmankamp (eastern Netherlands). We test: 1) how to identify well-bleached grains for single-grain feldspar pIRIR dating; 2) whether the single-grain feldspar pIRIR and the small-aliquot quartz OSL ages are consistent; 3) what additional information on the formation of plaggic anthrosols is provided by examining both single-grain feldspar pIRIR and small-aliquot quartz OSL equivalent-dose distributions. Toward this aim, we present a new method to identify well-bleached single grains of feldspar using the ratio of the grains' IRSL and pIRIR signals. Feldspar pIRIR ages obtained from bootstrapped Minimum Age Model (BsMAM) analyses of grains identified as well-bleached were in agreement with the BsMAM ages of small-aliquot quartz OSL for samples from the plaggen layer. In contrast, ages obtained from the two methods do not agree for samples where grains of different burial age are mixed through natural bioturbation. Our results demonstrate that single-grain feldspar pIRIR measurements provide a useful tool to identify the past light exposure and soil-mixing of sand grains in sediments of different depositional and burial histories. Augmenting this information with conventional quartz OSL dating allow us to reconstruct the timing and processes of plaggic anthrosol formation in Braakmankamp. According to luminescence dating results, land clearance around 900–1000 CE and accumulation of plaggen material began around 1200–1300 CE with the average accumulation rate of ~ 1.14 mm/yr.

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1 Introduction

Humans are considered the most, influential species in the terrestrial biosphere, since the emergence of the modern *Homo sapiens* (Ellis, 2011; Ellis, 2015; Lewis and Maslin, 2015; Vernadsky, 1998). The persistent interaction between humans and the landscape have created 'domesticated' (Terrell et al., 2003) or the 'anthropogenic' (Ellis, 2011) Holocene landscapes. While numerous cultural elements have impacted the landscape (Terrell et al., 2003), several researchers highlight agricultural practices as a primary factor in human landscape alteration (Briggs et al., 2006; Delcourt et al., 2004; Denevan, 1992), which was also the major driving factor of the creation of anthrosols (IUSS Working Group WURB 2022). The European landscape is one of the landscapes that went through a substantial transformation since the settling of the first farmers, which took place during the mid-Holocene (Kaplan et al., 2009). Here we focus on the Dutch landscape which has experienced significant transformation caused by agricultural activities with evidence dating up to 4300 BCE (Huisman and Raemaekers, 2014). Early agricultural practices can still be observed through the remains of prehistoric field systems (previously often described as Celtic fields, see Arnoldussen, 2018) and (early) historical open fields. The latter are characterized by plaggic anthrosols.

Plaggic anthrosols (Dutch: plaggendekken) are anthropogenic soils that have resulted from fertilizing nutrient-poor sandy soils. They develop through the artificial raising of the fields by the continuous input of sods (Dutch: *plaggen*), often mixed with manure. The sods came from various sources, which include heathlands and valleys (Groenman-van Waateringe, 1992; Pape, 1970). Plaggic anthrosols are commonly found in the sandy areas of North-West Europe, including the Netherlands, Belgium, northern Germany, and Denmark (Blume and Leinweber, 2004; Giani et al., 2014; Pape, 1970; Spek, 2004). In the Netherlands, the most typical type of plaggic anthrosols overlies a layer of xeropodzol soils, or hydromorphic sandy soils (Pape, 1970), but this may differ according to spatiotemporal circumstances.

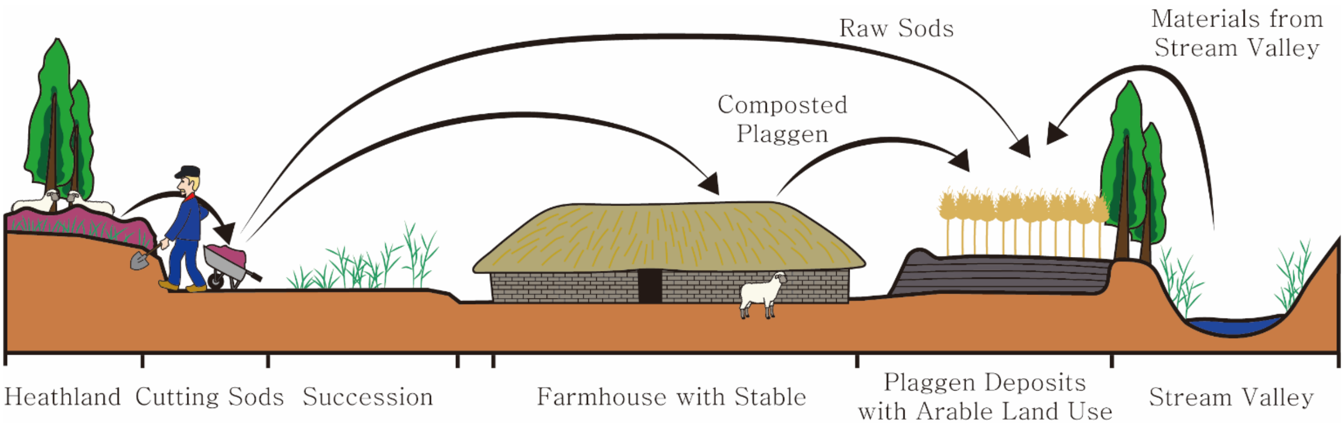

Figure 1: Schematic overview of the method of plaggen agriculture. Modified after the picture by Klaus Thierer presented in Giani et al. (2014) using observations from our study site, Braakmankamp. Typical plaggen agriculture involves the mixing of the sods with animal manure, but there are cases where raw sods are applied to the arable fields as well (Smeenge, 2020). The sods are typically collected from heathlands, but materials from the adjacent stream valley were also used in Braakmankamp (Smeenge, 2020).

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Plaggic anthrosols significantly contributed to the formation of the present-day sandy landscape of the northern part of Europe through alteration of glacial-to-early Holocene-aged coversand and mid-to-late Holocene-aged driftsand deposits. The formation of plaggic anthrosols had an impact beyond the arable fields, since the plaggen management activities involved areas surrounding the villages and arable fields, such as heathlands and valleys. In such areas, the difference in elevation, vegetation, and groundwater level was significantly altered by activities related to plaggen agriculture (Blume and Leinweber, 2004). Despite the significant influence of plaggen agriculture on the formation of the Dutch coversand landscape, the formation history of plaggic anthrosols is poorly understood, mainly due to the inconsistency between different sources of dating, such as historical data, archaeological records, radiocarbon dates, pollen analyses and luminescence dating (Bokhorst et al., 2005; Giani et al., 2014; van Mourik et al., 2012; van Mourik et al., 2011). When exactly the fields started to become raised and the depositional rate of the plaggen material remain topics that require further investigation.

In this research, we explore the utility of single-grain feldspar luminescence methods to plaggic anthrosols to: 1) establish the timing of the initial stages of plaggen agriculture, and 2) identify changes in soil-mixing intensity during the evolution of the plaggic anthrosols. Single-grain feldspar dating combined with post-infrared infrared stimulated luminescence (pIRIR) methods has the potential to investigate the pedogenic and geomorphic process over time (e.g. Wallinga et al., 2019). In this context, the advantages of feldspar compared to conventional quartz optically stimulated luminescence (OSL) dating are: 1) most sand-sized grains provide a usable luminescence signal, thus allowing single-grain analysis in regions where quartz OSL single-grain analysis is not practical; 2) feldspar can provide multiple signals with different bleachability from the same grain (Li et al., 2014; Thomsen et al., 2008). To examine whether single-grain feldspar methods can contribute in investigating the timing and process of the formation of plaggic anthrosols we address three research questions: 1) How can well-bleached grains be identified for feldspar single-grain pIRIR dating?; 2) Do results from feldspar single-grain pIRIR dating agree with more conventional small-aliquot quartz optically stimulated luminescence (OSL) dating?; 3) What new information on the evolution of plaggic anthrosols is gained from combining quartz OSL and feldspar single-grain pIRIR analyses?. To answer these questions, we focus on a high-resolution record of a single site with a plaggic anthrosol. The methods developed and results obtained have broad application potential for dating and reconstructing soil formation processes in human-influenced landscapes of the world.

2 Dating plaggic anthrosols

It is generally accepted that during the Middle Ages open-field agriculture was adopted throughout the northern half of the European landscape (Taylor, 1981; Renes, 2010). Since the sandy soils in coversand landscapes were poor in nutrients, agricultural activities were mostly limited to areas with specific geomorphological and hydrological characteristics. These tended to be relatively high and large coversand ridges, often bordered by valleys (Deeben et al., 2007; Renes, 2018; Spek, 2004). In the Dutch landscape, the open-field system was adopted in the form of so-called *essen* (singular: *es*). *Essen* are large and open arable fields, which are often (partially) communally used. They are generally parceled, based on the property rights of different parts of the arable field (Deeben et al., 2007).

In arable areas like *essen* and other types of open fields, the fertility of the soils was maintained or improved by the application of plaggen agriculture (Edelman, 1950; Pape, 1970; Renes, 2018; Spek, 2004). The exact timing of the emergence of plaggic anthrosols is still under debate, due to a scarcity of information and general incompatibility of different types of data (Dyer et al., 2018; Renes, 2010; Taylor, 1981). A number of studies place the substantial spread of plaggen agriculture in northwestern Europe in the beginning of the High Middle Ages, around 1000 CE (Blume and Leinweber, 2004; Giani et al., 2014), based on various methods. The applied methods range from the '1 mm per year theory', in which the thickness of the plaggen is divided by an assumed accumulation rate of 1 mm per year, to isotopic dating methods (Spek, 2004). Early radiocarbon dating attempts in the 1960s produced dates as early as 600 to 800 CE (Giani et al., 2014). In one case, a Dutch plaggic anthrosol was dated between 500 BCE to 100 CE based on pollen analysis (Blume and Leinweber, 2004; Giani et al., 2004). The oldest plaggic anthrosols that have been reported is located on the German north coast islands of Sylt and Föhr, which are assumed to be more than 3000 years old (Blume and Leinweber, 2004). Given the widespread occurrence of plaggic anthrosols in the norther part of Europe, plaggen agriculture may have been practiced in different regions at different times. Improving dating methods for plaggic anthrosols would be an important contribution to the understanding of the temporal position of open-field systems.

A number of more recent publications dated the soils using the Optically Stimulated Luminescence (OSL) dating method (Bokhorst et al., 2005; van Mourik et al., 2011; van Mourik et al., 2012). Luminescence dating is advantageous for sedimentary landscapes because the obtained ages reflect the moment of the depositional event, provided that the material is exposed to light prior to deposition and shielded from light since that time and that a suitable protocol is used. Comparison of OSL ages to radiocarbon dates of plaggic anthrosols yielded a discrepancy (van Mourik et al., 2011; van Mourik et al., 2012), with the former providing much younger ages than the latter. They conclude that the luminescence ages reflect the deposition of plaggic horizons while the radiocarbon dates are indicative of the organic material related to the beginning of agricultural land use and are largely affected by mixing of organic matters of different ages (van Mourik et al. 2011; Wallinga et al., 2019).

Although OSL dating of plaggic anthrosols yield consistent and seemingly reliable results for the accumulation phase, which generally begins around 1600 CE in the Netherlands (van Mourik et al., 2011; van Mourik et al., 2012), several challenges remain. Firstly, robust dating of the initial stages of the development of plaggic anthrosols has proven to be problematic as only part of the grains in the lowest parts of plaggic deposits are exposed to light. Secondly, standard methods provide little information on the intensity of mixing as a function of time. These challenges are related to within-aliquot averaging effects for small-aliquot quartz OSL dating (Cunningham et al., 2011; Wallinga, 2002).

The averaging effect of the multi-grain luminescence dating can be overcome by performing equivalent dose (D_e) measurements at a single-grain level. The ideal situation would be to perform a measurement on single-grain quartz since the fast-component OSL signal of quartz bleaches faster than feldspar infrared stimulated luminescence (IRSL) or pIRIR signals (Kars et al., 2014b; Murray et al., 2012). However, in sediments from the North European Plain and many cases elsewhere,

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the luminescence sensitivity of quartz is low, with typically less than 3–5 % of the grains providing sufficient OSL signal to determine D_e values (Cunningham et al., 2015; Duller, 2008). Therefore, single-grain quartz OSL dating is not practical in most settings.

As an alternative to quartz OSL, feldspar grains can be useful for single-grain IRSL or pIRIR dating, since they are more sensitive, with approximately 50 % of the grains providing sufficiently bright signals to produce a D_e (Reimann et al., 2012). However, feldspar has its own deficiencies, which hindered it from being commonly used as a natural dosimeter. The first problem is anomalous fading: a-thermal loss of the luminescence signal with time (Spooner, 1994; Wintle, 1973), causing luminescence ages to underestimate the actual burial age. To largely avoid the problem of fading, the use of pIRIR signals, measured at elevated temperature(s) following the evacuation of the lower temperature IRSL signal, was suggested by Thomsen et al. (2008). The pIRIR signals are increasingly stable (i.e., less affected by anomalous fading) at higher stimulation temperatures (Buylaert et al., 2012; Cheng et al., 2022; Kars et al., 2014b; Reimann and Tsukamoto, 2012). However, the pIRIR signals reset much more slowly upon exposure to light than feldspar IRSL or quartz OSL signals (Kars et al., 2014b; Thomsen et al. 2008). As a consequence, pIRIR signals of fewer grains will be completely reset compared to other luminescence signals and pIRIR-derived ages are more likely to overestimate the burial age. pIRIR signals are increasingly hard to bleach at higher stimulation temperatures (e.g. Kars et al., 2014b).

Therefore, in this research, we investigate appropriate measurement parameters for single-grain feldspar luminescence dating of the plaggen and underlying deposits, seeking an optimal compromise between bleachability and stability. In addition, we develop a new approach to identify those grains for which the pIRIR signal is well bleached.

3 Materials and Methods

3.1 Site information and samples

3.1.1 Site information

The sampling took place in the a site named Braakmankamp, where ~ 1 m thick plaggic anthrosol development is present. Braakmankamp is located in the eastern Netherlands, south of Denekamp, Overijssel (Fig. 1, inset). This region is a part of the 'European Sand Belt', which extends from Northwestern Europe to Poland, and the Baltic region. The majority of the landscape is veneered by aeolian coversand deposits of the last glacial (Weichselian, OIS 4-2). In the Netherlands, these aeolian sands are characterized by a fairly uniform grain size, which ranges from 105 to 420 µm, and form hummocky landscapes with sand dunes varying in height and slope values (Koster, 2009). During the Holocene, and especially after 1,000 BCE, coversands were locally reactivated under the influence of increased human pressure resulting in drift sand often deposited in dunes (Pierik et al., 2018). The Braakmankamp site is located in a coversand landscape dissected by the river Dinkel and its tributaries forming 'sand islands' of different sizes. Braakmankamp positions itself on one of the sand islands on the east of the Dinkel (see Fig. 1). It may have been one of the first reclaimed sites in this region because of its proximity to the Dinkel, and its

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relatively large extent, which qualifies as a favorable settlement area (Groenewoudt and Lubberink, 2007). The site has been used as an agricultural field, but has not been deep-ploughed in the past 50 years, and therefore, was selected as a suitable research site.

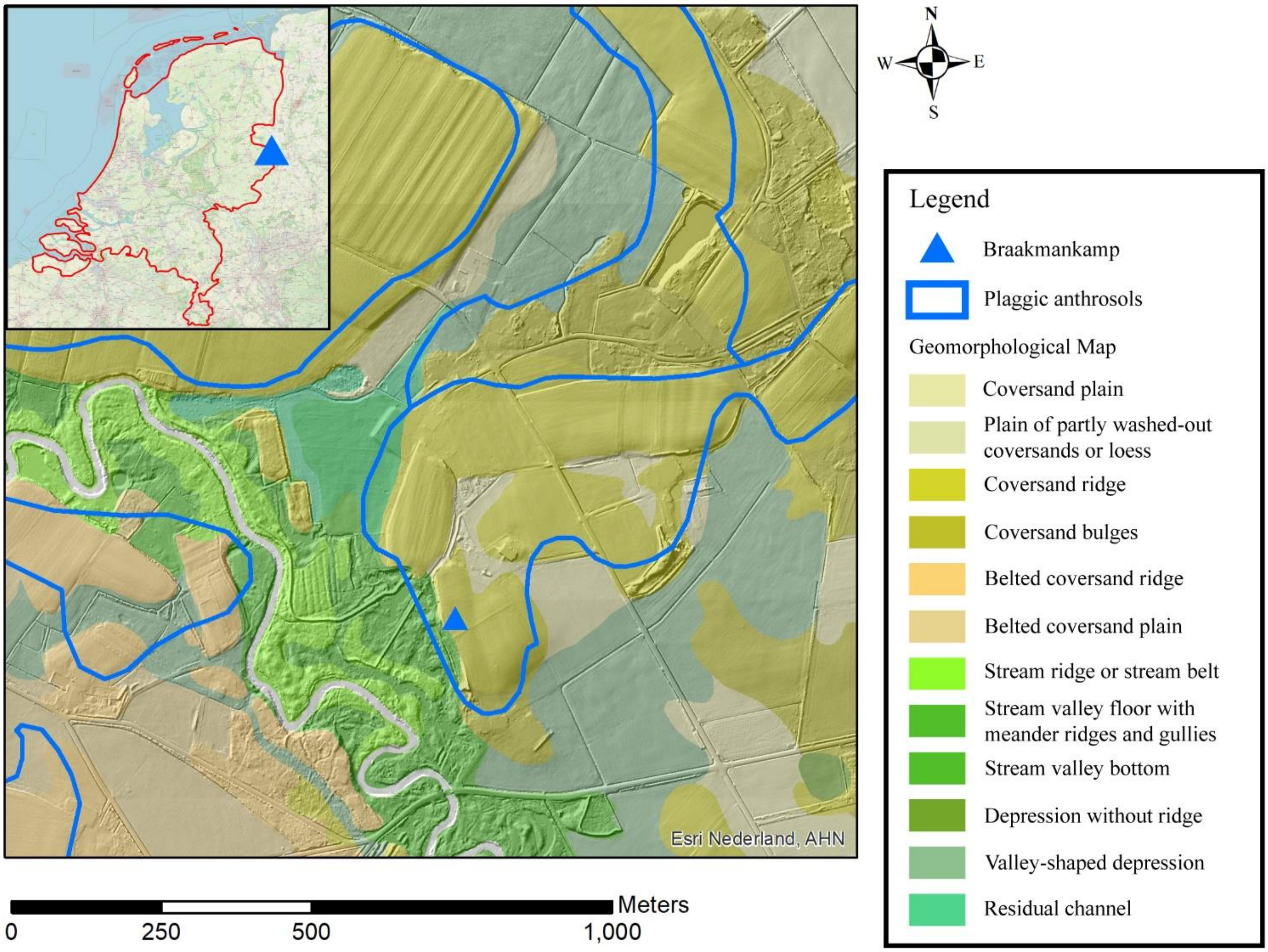

Figure 2: The location of the Braakmankamp site on the geomorphological map of the Netherlands (BRO, 2023). Plaggic anthrosols occur mostly on areas with coversand deposition.

A pit was dug at the Braakmankamp site for the documentation of the soil layers (Smeenge, 2020; van Oorschot, 2018) (Table 1), and for the collection of samples for luminescence dating and pollen analysis. The soil was identified to be a plaggic anthrosol. In all depths, the texture of the soil is weakly loamy sand, with a median grain size of 210 µm. The plaggen layer is divided into 1Aap, and 2Aap, distinguished based on the colour which may reflect differences in the plaggen material used. It is probable that the brighter color of 1Aap originated from forest/heather plaggen, and the darker color of 2Aap is derived from plaggen containing more organic materials, which would likely have been collected from the adjacent Dinkel valley (Smeenge, 2020). Below the plaggen horizon is the non-plaggic 2Ap horizon. The 2Ap horizon has a lighter color than the overlying Aap

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horizons, which is due to the inclusion of grey-colored grains. The color of these greyish particles resembles the color of the eluviation horizon of podzols. Below the 2Ap horizon is the brown weathering horizon (2Bw). A coversand layer, which is the parent material, underlies the soil matrix, and gleiing phenomena are observed in this layer (Cg). Considering the presence of the Bw layer, the soil that formed prior to the practice of plaggen deposition is a brown forest soil.

Table 1: Description of soil horizons at the sampling location. The descriptions of the soil horizons are based on the Dutch soil classification system (de Bakker and Schelling, 1989).

Depth (cm)	Horizon	Color	Remarks	Samples
0 - 30	1Aap	10YR 2/2	Brick pieces present	NCL-1117134 (22 cm)
30 - 50	1Aap/2Aap	10YR 3/2	Brick pieces present	NCL-1117133 (31 cm) NCL-1117132 (41 cm)
50 - 105	2Aap	10YR 3/3		NCL-1117131 (50 cm) NCL-1117130 (60 cm) NCL-1117129 (70 cm) NCL-1117128 (81 cm) NCL-1117127 (96 cm) NCL-1117126 (101 cm)
105 - 120	2Ap	10YR 4/2	Grey colored stains from podzol	NCL-1117125 (112 cm)
120 - 130	Bw	10YR 4/3.5		NCL-1117124 (123 cm)
130 - 170	Cg	2.5Y 5/4	Fossil gley mottles of cm-scale	NCL-1117123 (142 cm) NCL-1117122 (165 cm)

Archaeological data demonstrates that the Twente region has been occupied by humans since the Late Paleolithic age (van Beek et al., 2015). Large coversand ridges along the Dinkel valley were favourable habitation sites since late prehistoric times. One of the earliest pieces of evidence of human occupation in the vicinity of the study area is found in Mekkelhorst, adjacent to Braakmankamp. In Mekkelhorst an Iron Age settlement has been identified. Since the Middle Ages, farmers formed essen on the sandy ridges east of the Dinkel (Smeenge, 2020). The Braakmankamp site is located on a part of such an essen complex. The suffix ‘kamp’, common in the eastern Netherlands, refers to a (generally fairly small) arable field, whereas ‘Braakman’ probably is an old family name.

3.1.2 Sampling

Thirteen luminescence dating samples were collected in a vertical sequence at the Braakmankamp site, with at least one sample from each of the identified soil horizons (Table 1). Each sample was collected by horizontally hammering in a sampling tube with a length of 20 cm and a diameter of 4.5 cm into the excavated and cleaned soil profile. After removing the sampling tubes

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from the soil profile, both ends of the tubes were sealed with lids and tape to prevent exposure to sunlight. For dose rate measurements, additional soil material was collected from the same depth as the sampling tubes and placed into a plastic bag.

3.2 Sample preparation

All sample preparations and measurements were performed under safelight conditions at the laboratory of the Netherlands Centre for Luminescence dating, at Wageningen University and Research. Materials from the outer 3 cm of the sampling tubes, which may have been exposed to light during sampling, were used for dose rate measurements. Of the remaining material, 100 g was wet-sieved to obtain 212–250 µm sand grains. These were cleansed through magnetic separation, removing magnetic particles. After magnetic separation, the samples were treated with 10 % HCl for 1 hour to remove carbonates and 10 % H2O2 for more than 15 hours to remove organic materials. Subsequently, the samples went through a density separation process using LST heavy liquid of 2.58 g/cm^3, separating K-feldspars (2.57 g/cm^3), and quartz (2.64 g/cm^3) grains. The heavy fraction (2.58 g/cm^3) was etched with HF for 40 minutes to obtain a purified quartz extract and to remove the outer layer exposed to alpha irradiation. After HF treatment, the quartz grains were cleansed in HCl for 1.5 hours and rinsed and then sieved over a 180 µm sieve to remove grains that were severely affected by the HF treatment.

For the measurement of dose rate, the material removed from the outer 3 cm of the sampling tubes was combined with sample-adjacent material collected in plastic bags. The materials were dried at 105 °C for more than 12 hours to determine gravimetric moisture content. The organic matter content was measured by calculating the loss on ignition at 500 °C. The remaining materials were ground using a ball mill to a particle size smaller than 300 µm. The ground material was mixed with wax in a 70 : 30 sediment : wax ratio and was molded into 2 cm thick pucks. The puck was analyzed by the gamma spectrometer to measure the activity of ^{40}K and several isotopes in the ^{238}U and ^{232}Th decay chains. Dose rate was calculated from the radionuclide concentrations following Guérin et al. (2011). We assumed an internal K-content of 10 ± 2 % for the K-feldspar grains to calculate the internal dose rate (Smedley et al., 2012). The cosmic radiation contribution to the dose rate was determined following Prescott and Hutton (1994), assuming gradual burial of the samples between deposition and present. Beta dose attenuation correction for the used grain size was performed according to Mejdahl (1979). Dose rate attenuation due to water and organic contents were taken into account following Aitken (1998).

3.3 Luminescence measurements

Automated luminescence readers (Risø TL/OSL DA-15) equipped with ^{90}Sr/^{90}Y beta source, Blue-LED diodes, and IR-laser (Bøtter-Jensen et al., 2000; Bøtter-Jensen et al., 2003) were used for all measurements.

3.3.1 Quartz OSL

The quartz was positioned on stainless steel discs, placed within a circle with a 2 mm diameter (~ 50 grains / disc) on the center of the discs using silicone oil ("Silkospray"). The measurement was conducted by applying the standard SAR protocol (Murray and Wintle, 2003) (see Supplementary Material A) with a preheat temperature of 200 °C, and the stimulation temperature was

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125 °C. The OSL signal was measured for 20 seconds, the first 0–0.5 s interval was used for analysis, and the subsequent interval of 0.5–1.76 s was used for early background subtraction (Cunningham and Wallinga, 2010). To determine the temperatures to be used for preheat and post-measurement bleaching, a thermal transfer (TT) test was performed (Truelsen and Wallinga, 2003). In the TT test, we first removed the luminescence by bleaching with the blue LED stimulation for 600 s in total. Subsequently, we gave the preheat for 10 s from 160 °C to 300 °C in 20 °C intervals. After each preheat, OSL signals were measured. We summed up the luminescence signals from each measurement to obtain a cumulative dose transferred from the preheat.

At the end of each SAR cycle, aliquots were bleached with Blue-LED for 40 seconds at an elevated temperature of 210 °C to completely reset the OSL signals. The acceptance of the results was based on the following criteria: 1) the recycling ratio should be smaller than 10 % of the unity; 2) the recuperation value smaller than 10 % of the largest regenerated signal; 3) the test dose error should be smaller than 10 %; 4) the IR signal should be less than 20 % of the total OSL signal, or the decrease of OSL signal after the exposure to IR should be less than 10 %. Errors were incorporated into the acceptance criteria.

A dose recovery test was performed to examine whether the samples could reproduce a given dose through the SAR procedure. For the dose recovery test, we first removed the luminescence with exposure to blue LED lights for 600 s in total and then gave each aliquot a dose of approximately 3.5 Gy.

3.3.1 Feldspar pIRIR

The prepared feldspar grains were placed on aluminum single-grain discs with 300 µm diameter holes arrayed in a 10 × 10 grid, each holding up to 100 grains. The grains were stimulated for 2 seconds with a 150 mW 830 nm IR laser. To select the emissions from K-rich feldspars around 410 nm, a LOT/Oriel D410/30 interference filter was utilized. A SAR measurement protocol was adopted for De estimation, largely based on the pIRIR protocol proposed by Thomsen et al. (2008), which has been modified for single-grain measurements, in accordance with the observations made by Reimann et al. (2012) and Brill et al. (2018).

Prior to the measurement of the De, tests on remnant doses, dose recovery ratios, and fading rates were performed on feldspar grains that were bleached in a Hönle SOL2 solar simulator for 48 hours. Two samples were selected for the tests, one from the Cg horizon (NCL-1117023), and one from the 2Aap horizon (NCL-1117029). The tests incorporated three different pIRIR stimulation temperatures (150 °C, 175 °C, 225 °C), to inform an appropriate stimulation temperature for this work. The tests on remnant doses and dose recovery ratios were performed on a single-grain level, and the fading rates were measured based on multi-grain aliquots (Auclair et al., 2003). Ultimately a preheat of 200 °C for 120 s and a pIRIR stimulation temperature of 175 °C were selected (see Results, section 4.2.).

Before the actual measurements, we expected two types of scenarios for soil mixing. First, the slow and less intense mixing dominated by natural bioturbation, and second, the rapid and intense mixing mainly caused by agricultural activities. This contrasting effects of different dynamics are also demonstrated in the results of von Suchodletz et al. (2023). However, since the plaggic anthrosols also incorporate a rapid deposition rate of materials, the samples collected from the plaggen layers were

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expected to contain a significant amount of poorly bleached grains due to slow bleaching of pIRIR signals and potentially short light exposure during soil mixing processes. Therefore, a method was devised to identify well-bleached grains. The adopted approach utilizes the different bleaching rates between the IRSL and pIRIR signals. It has been reported in previous studies that IRSL signals bleach much faster than pIRIR signals (Buylaert et al., 2012; Kars et al., 2014b; Poolton et al., 2002). Therefore, if a grain is sufficiently light-exposed to fully reset the pIRIR signals, the IRSL signals will also be fully reset. This implies that well-bleached grains should provide matching D_e values for the pIRIR and IRSL signals. In contrast, if a grain is only briefly exposed to light, we expect the IRSL signal to be better bleached than the pIRIR signal. This would result in a greater pIRIR De value compared to that of IRSL. Comparison of feldspar D_e values at different temperatures has previously been proposed as a sediment tracer (e.g., Reimann et al., 2015; Chamberlain et al., 2017) and for identifying well-bleached samples with single-aliquot approaches (Buylaert et al., 2013) but it has not yet been used to identify well-bleached grains on a single-grain level for dating purposes.

Based on the above, a robust comparison between the D_e values of IRSL signals, and the D_e of pIRIR signals was made by the ratio of the two ($D_{e\ IRSL}$ / $D_{e\ pIRIR}$). Considering that IRSL signals are more prone to fading, we used a ratio of 0.9 as the threshold rather than unity. If the ratio is greater than 0.9 within a 2-σ error, we accepted the grain to be well-bleached. If it is smaller than 0.9 within the 2-σ error, the grain was classified as poorly bleached, and therefore rejected from age modeling of the feldspar single-grain datasets. While we acknowledge that the value of 0.9 is arbitrary, it was also adopted by Buylaert et al. (2013) for comparison of IRSL and $pIRIR_{290}$ signals. In this study, we use the term "filtering" to refer to the differentiation of well- versus poorly bleached grains using the $D_{e\ IRSL}$ / $D_{e\ pIRIR}$ ratio described above.

3.4 Age models

To determine the age of the samples, this research applied the bootstrapped minimum age model (BsMAM) suggested by Cunningham and Wallinga (2012), to both quartz and feldspar D_e datasets. For single-grain feldspar samples, to extract the grains with depositional information from the soil samples, we used the maximum age model (MaxAM) suggested by Olley et al. (2006). Comparing the ages obtained by the BsMAM and MaxAM can provide a narrative on the formation history of the soils. Evaluating between the quartz and feldspar datasets was done by comparing ages, which was achieved by dividing the individual D_e of each aliquot / grain by the sample-average mineral-specific dose rate.

The chosen overdispersion input, or σb value, can have a significant effect on the outcome of the BsMAM (Chamberlain et al., 2018; Cunningham and Wallinga, 2012). The σ_b value indicates the characteristic overdispersion within a D_e dataset for well-bleached sediments within a certain environment and for a given number of grains per disk (Cunningham and Wallinga, 2012). To determine the value of σ_b to be applied for the BsMAM, this research adopted the method proposed by Chamberlain et al. (2018). This method obtains the characteristic overdispersion of well-bleached and un-mixed samples within the dataset by applying the BsMAM with σ_b = [0 0] to the relative overdispersion values obtained for the samples using the central age model (CAM) (Galbraith et al., 1999), and assumes that at least some samples within the dataset are well bleached. We determined the value by rounding the outcome of BsMAM applied to the relative overdispersion to the second decimal place.

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4 Results

4.1 Quartz OSL tests

The average result of the thermal transfer test on the quartz samples demonstrates that there is little thermal transfer up to 300 °C of preheat temperature, with the average value agreeing with 0 Gy within 1-σ standard error (Fig. 3.a.). However, the individual aliquots demonstrate that the majority of the aliquots are affected by thermally transferred doses after the preheat of 240 °C. Therefore, we adapted the preheat temperature of 200 °C, and the temperature of 210 °C for the bleaching at the end of SAR sequence.

The dose recovery test of the SAR sequence for quartz demonstrated that the quartz aliquots were able to recover D_e close to the given dose (CAM dose recovery ratio: 0.98 ± 0.01; given dose 3.56 Gy). The σ_b input for quartz multigrain aliquots was determined to be 0.15 ± 0.04.

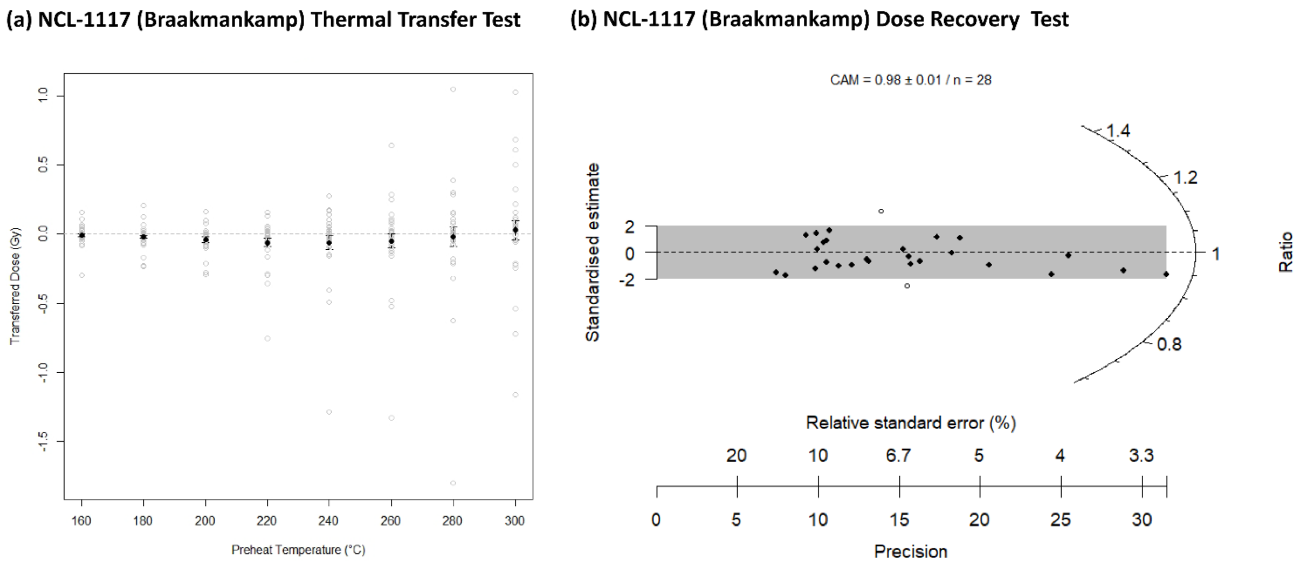

Figure 3: The results of (a) thermal transfer test; (b) dose recovery test on quartz samples from the Braakmankamp site.

4.2 Feldspar pIRIR tests

We found that remnant doses after 48 h SOL2 bleaching increased with preheat temperature and temperature for pIRIR stimulation (Fig. 4.a). As the $IRSL_{50}$ remnant doses increase as well, but less than those obtained through pIRIR, we attribute the increase to a combination of thermal transfer (caused by preheating) and lower bleachability of high-temperature pIRIR signals (Kars et al., 2014b; Reimann et al., 2012).

The dose recovery tests on the pIRIR signals yielded ratios within 5 % from unity for all tested pIRIR temperatures (Fig. 4.b). In contrast, the dose recovery ratio of the $IRSL_{50}$ signals showed satisfactory results for $pIRIR_{150}$ and $pIRIR_{175}$ sequences but

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underestimated severely for pIRIR$_{225}$ sequence (Fig. 3.b). This result corroborates the finding by Kars et al. (2014a) and is possibly attributed to trapping sensitivity changes occurring at high-temperature preheat (Wallinga et al., 2000).

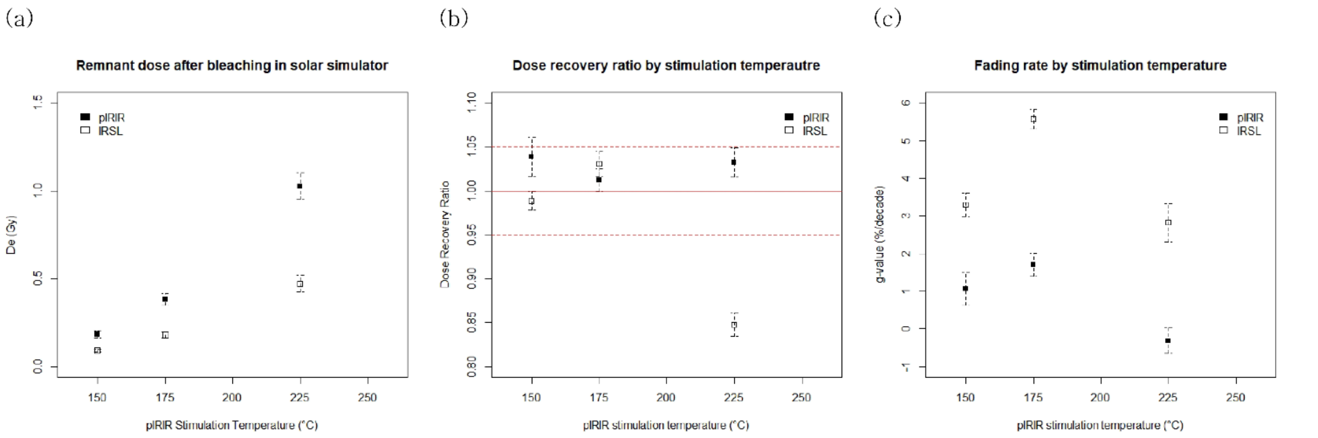

Figure 4 The results of (a) remnant dose after bleaching in a solar simulator; (b) dose recovery test; (c) fading rate with different preheat / stimulation temperatures. The tests were performed on samples NCL-1117023 and NCL-1117029 after bleaching in the SOL2 solar simulator for 48 hours.

For fading rates, the results show a lower correlation with the temperature used for pIRIR stimulation. It was demonstrated that the lowest g-value was obtained when the highest temperature (225 °C) was applied (Fig. 4.c). The g-value of the IRSL$_{50}$ signals were all substantially higher than the pIRIR signals, as expected. The g-values for the pIRIR$_{150}$ and pIRIR$_{175}$ agreed within the 1-σ error range. Based on these results, we decided to apply the pIRIR$_{175}$ protocol for age estimation. The main reason was that the dose-recovery results were most stable in both IRSL$_{50}$ and pIRIR signals when the pIRIR$_{175}$ protocol was applied, and this is important since we are using IRSL$_{50}$ and pIRIR signals for comparison. The σ_b input for the single-grain feldspar pIRIR$_{175}$ was determined to be 0.35 ± 0.03 for the complete dataset and 0.20 ± 0.04 for the 'filtered' dataset.

4.3 D_e distributions

For all samples from A and B horizons feldspar pIRIR D_e distributions show greater overdispersion than their quartz counterparts. In contrast, both samples from the Cg horizon show similar overdispersion for both approaches.

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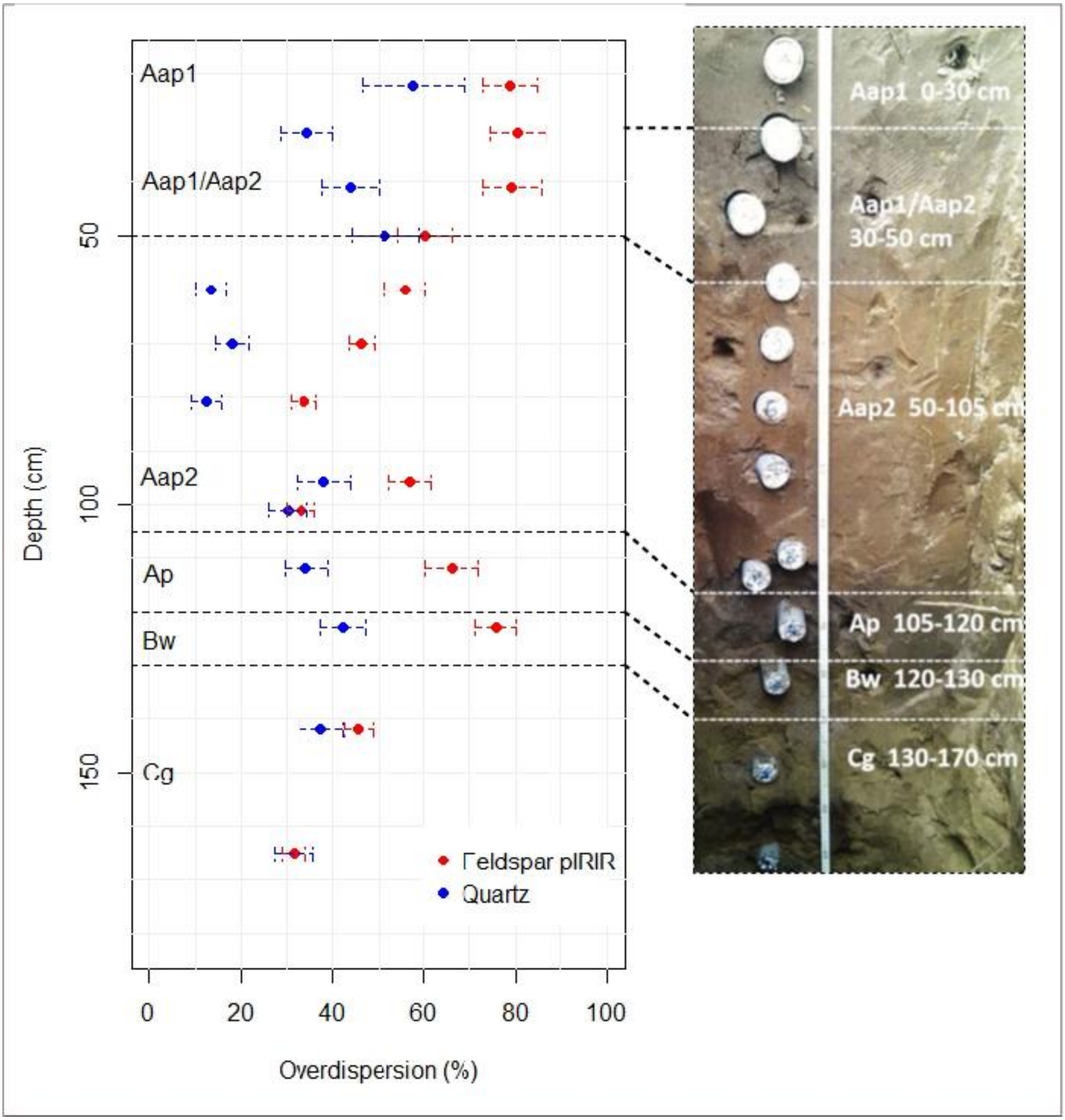

Figure 5: Comparison of the relative overdispersion of D_e values for each sample obtained with the CAM for quartz small-aliquot results and feldspar single-grain pIRIR results.

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4.4 Identifying well-bleached feldspar grains

When the comparison between $D_{e\ IRSL}$ and $D_{e\ pIRIR}$, or 'filtering', was performed, we observed that $D_{e\ pIRIR}$ values tend to be larger than $D_{e\ IRSL}$ values as expected (example provided in Fig. 6.a). There are a few grains that have larger $D_{e\ IRSL}$ values than $D_{e\ pIRIR}$ values, but for the majority of the $D_{e\ IRSL}$ / $D_{e\ pIRIR}$ ratio agrees with unity within a 2-σ error margin. Before examining the results of the comparison between $D_{e\ IRSL}$ and $D_{e\ pIRIR}$ values, we analyse the acceptance ratio as a function of depth (a proxy of age) to ensure that fading is not significantly affecting the results of the filtering. Since older samples are generally more affected by anomalous fading than younger ones, it is expected that fading would result in rejecting greater portions of grains for the deeper samples. However, the absence of a clear trend of acceptance from the Aap2 down to the Cg horizon with depth suggests that this is not the case (Fig. 6.b).

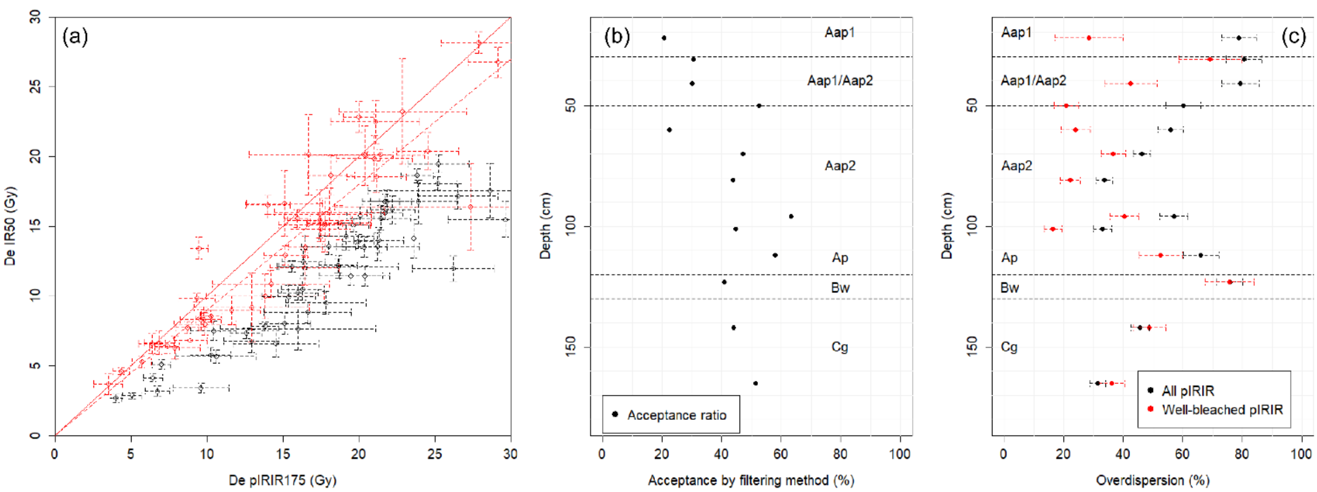

Figure 6: (a) Example of grains characterized as well-bleached (red) vs poorly bleached (black) through comparison between $D_{e\ IRSL}$ and $D_{e\ pIRIR}$ values for sample NCL-1117123. The solid diagonal line marks the 1:1 ratio between equivalent doses obtained from $IRSL_{50}$ and $pIRIR_{175}$ signals. The dashed diagonal line marks the 1:0.9 ratio adopted as threshold to identify well-bleached grains. (b) Acceptance ratio indicating the percentage of well-bleached grains with depth. (c) Relative overdispersion in the $pIRIR_{175}$ D_e distributions for well-bleached (red) and all (black) grains.

Filtering using the $D_{e\ IRSL}$ / $D_{e\ pIRIR}$ ratio threshold impacted the D_e distribution of most samples, with the strongest effect on the samples from the plaggen layer (Aap1, Aap1/Aap2, and Aap2 horizons). The overdispersion is reduced through the filtering approach for all samples from the Ap and Aap horizons, while negligible change is observed for samples from the Cg and Bw horizons (Fig. 6.c). A closer inspection of the D_e distribution shows that the reduced overdispersion for samples from the Ap and Aap horizons results from the preferential rejection of older grains. For the Bw and Cg horizon samples, rejected grains show no bias, which explains why the overdispersion remains unchanged (see Supplementary Material B for a full observation of the results).

When comparing the ages obtained from BsMAM before and after applying the filter, the effect of the filtering can be observed, with only 2 out of 13 samples showing agreeing ages with a 1-σ error range (Fig. 7.b.). While the agreement does not occur

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on the deeper samples collected below the Ap horizon (NCL-1117122 to NCL-1117124), the difference becomes more significant toward the present-day surface within the Aap1 and Aap2 horizons (that is, within the upper 1 m of the soil profile, Fig. 7.b.)..

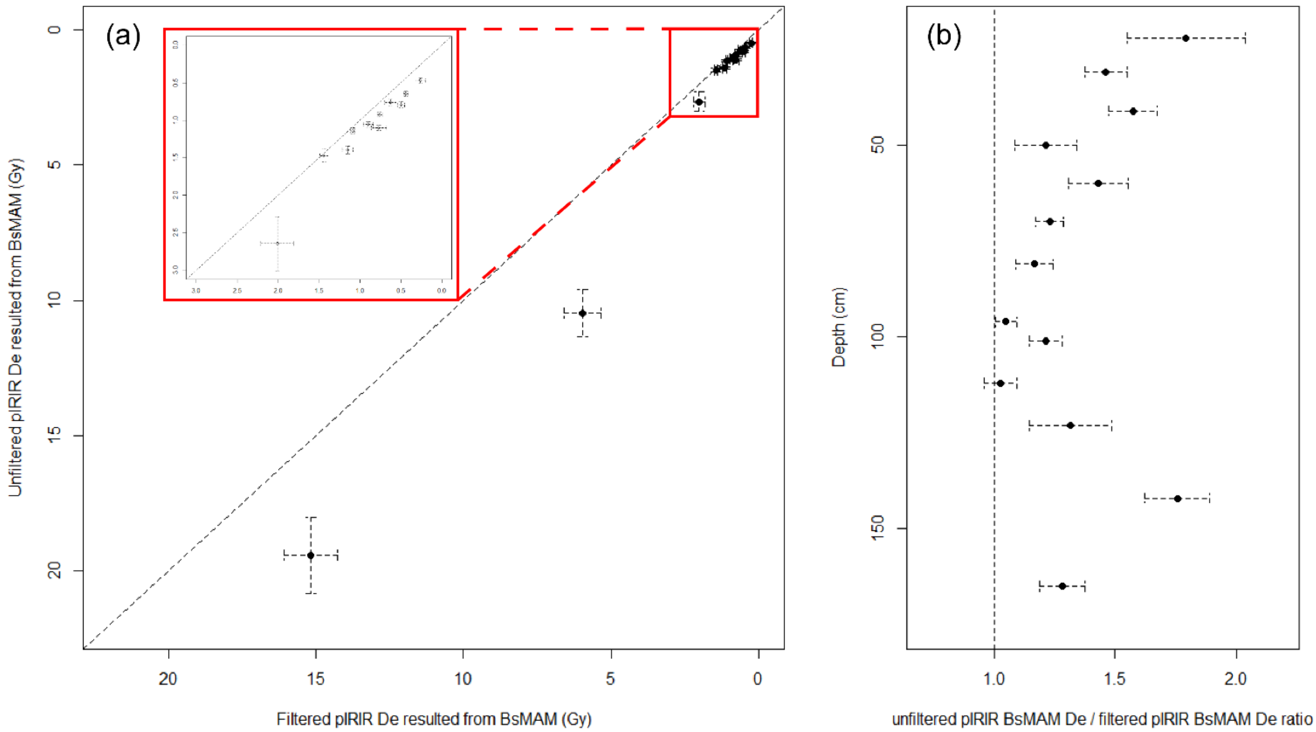

Figure 7: Comparison of age obtained by applying BsMAM to the filtered pIRIR dataset and the unfiltered pIRIR dataset.

4.5 Results of the age model

For age modelling, we applied the BsMAM to the small-aliquot quartz datasets with a σ_b input of 0.15 ± 0.04 and to the filtered single-grain feldspar pIRIR D_e datasets with a σ_b of 0.20 ± 0.04. Resulting paleodoses were divided by the mineral-specific dose rate for each sample to obtain age estimates. Ages are reported in years (a) relative to 2017 (Table 2). Both sets of ages are internally consistent showing older ages for deeper sediments, with the exception of the feldspar pIRIR result at 70 cm depth. Quartz and feldspar agree for nearly all samples from the Aap horizons. For the horizons below, age results for feldspar tend to be lower compared to those for quartz.

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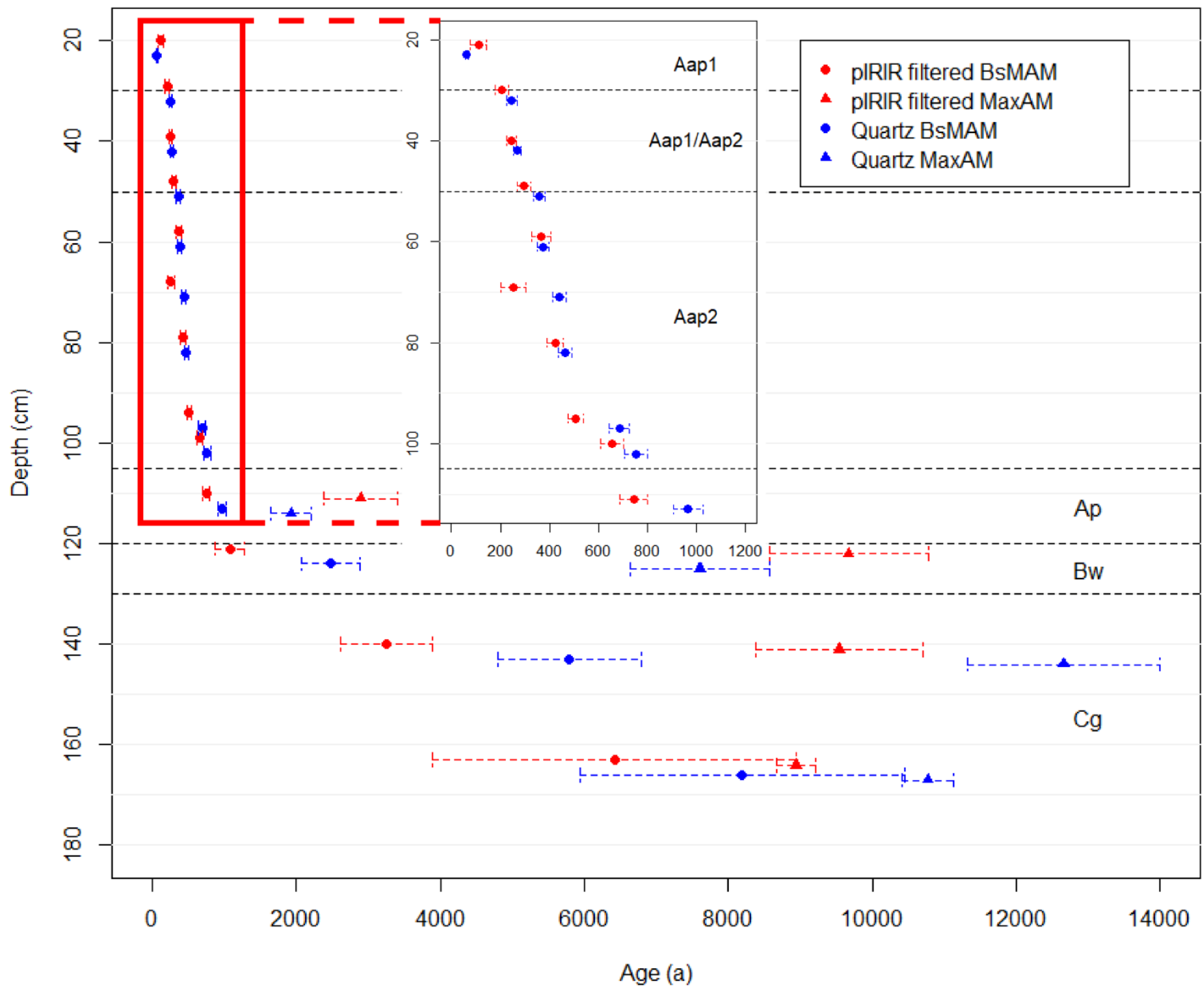

Figure 8: Comparison between ages obtained by applying BsMAM to multigrain quartz (blue) and filtered single-grain feldspar pIRIR$_{175}$ (red) D_e datasets. Note that the points are slightly displaced from their original position (quartz – bottom; feldspar – top) for the sake of visibility.

360 **Table 2: Results of applying BsMAM and MaxAM to ages obtained from quartz signals and filtered ages from feldspar pIRIR$_{175}$ signals. The reference year of the date is 2017, when sampling and preparation of samples were conducted. Note that the ages are rounded to decades.**

Sample	Depth (cm)	Quartz BsMAM (a)	Quartz MaxAM (a)	Feldspar (filtered) BsMAM (a)	Feldspar (filtered) MaxAM (a)
NCL-1117134	22	60±5	-	110±30	-
NCL-1117133	31	240±20	-	200±30	-

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NCL-1117132	41	260±20	-	240±20	-
NCL-1117131	50	350±30	-	290±30	-
NCL-1117130	60	370±20	-	360±40	-
NCL-1117129	70	440±30	-	250±50	-
NCL-1117128	81	460±30	-	420±30	-
NCL-1117127	96	680±40	-	500±30	-
NCL-1117126	101	750±50	-	650±50	-
NCL-1117125	112	960±60	1920±290	740±60	2890±520
NCL-1117124	123	2460±410	7600±970	1070±210	9660±1110
NCL-1117123	142	5790±1000	12650±1330	3240±640	9540±1160
NCL-1117122	165	8190±2260	10770±350	6410±2530	8940±270

5 Discussion

5.1 Identifying well-bleached grains for feldspar single-grain pIRIR dating

In this research, we used the ratio of $D_{e\ IRSL}$ and $D_{e\ pIRIR}$ values as a means to identify well-bleached grains within samples. From the results, we observed that there is a distinction between the population of grains that have been classified as well-bleached and poorly bleached. While the well-bleached grains are concentrated on the youngest population of the samples, the older grains consist of grains that have been classified to be poorly-bleached (NCL-1117126 to 134, see Supplementary Material B). The division of ages between the two classes of grains supports that the ratio of $D_{e\ IRSL}$ and $D_{e\ pIRIR}$ values does reflect the relative exposure time of grains to sunlight prior to being removed from exposure to sunlight.

The results demonstrate that identifying and selecting the well-bleached grains can have crucial effect on the output of age models. Comparing the ages obtained by BsMAM on both filtered / non-filtered datasets shows that the ages from the non-filtered dataset are overestimated up to 30 % on average compared with the filtered ages, which we take to be most representative (Fig. 7.b.). The main reason for the discrepancy in the ages is the difference in the selected σ_b values that were applied to the BsMAM. In this research, we applied the method suggested by Chamberlain et al. (2018) to assume that the lowest overdispersion of the dataset represents the overdispersion of a well-bleached sample. However, in our sample site, none of the samples are completely well-bleached. Rather all samples include at least some poorly bleached grains. This is also supported by the high proportion of poorly bleached grains within the samples collected from the plaggen layer, where some of them have less than a 30 % acceptance ratio when the threshold for the $D_{e\ IRSL}$ / $D_{e\ pIRIR}$ ratio is applied (Fig. 6.b.). The high percentage of poorly bleached grains yields high overdispersion values (Fig. 6.c.), and thereby overestimates the σ_b value that should be applied. When the σ_b value, is obtained from the filtered dataset of grains that have been classified as well-

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bleached grains, the outcome of the BsMAM of the OSL and pIRIR datasets is in better agreement (Table 3). This indicates that using the ratio of $D_{e\ IRSL}$ and $D_{e\ pIRIR}$ values can be a useful way to determine the σ_b value for feldspar samples.

385 **Table 3: Comparison of BsMAM results between the dataset of total grains using two different σ_b values and the dataset of grains classified to be well-bleached.**

Sample	BsMAM result (Gy) $pIRIR_{175}$ total dataset σ_b = 0.35 ± 0.03	BsMAM result (Gy) $pIRIR_{175}$ total dataset σ_b = 0.2 ± 0.04	BsMAM result (Gy) $pIRIR_{175}$ filtered dataset σ_b = 0.2 ± 0.04
NCL-1117134	0.28 ± 0.05	0.24 ± 0.04	0.23 ± 0.07
NCL-1117133	0.55 ± 0.09	0.36 ± 0.13	0.41 ± 0.05
NCL-1117132	0.70 ± 0.06	0.59 ± 0.08	0.50 ± 0.03
NCL-1117131	0.75 ± 0.03	0.71 ± 0.07	0.61 ± 0.05
NCL-1117130	1.09 ± 0.04	1.03 ± 0.08	0.77 ± 0.07
NCL-1117129	0.88 ± 0.10	0.65 ± 0.09	0.54 ± 0.10
NCL-1117128	1.09 ± 0.04	0.97 ± 0.08	0.89 ± 0.05
NCL-1117127	1.15 ± 0.04	1.09 ± 0.07	1.07 ± 0.04
NCL-1117126	1.51 ± 0.06	1.35 ± 0.09	1.31 ± 0.06
NCL-1117125	1.49 ± 0.13	1.30 ± 0.29	1.46 ± 0.08
NCL-1117124	3.38 ± 0.55	2.39 ± 0.32	2.16 ± 0.40
NCL-1117123	12.08 ± 1.73	8.01 ± 1.44	6.78 ± 1.30
NCL-1117122	19.40 ± 1.41	16.51 ± 3.37	13.82 ± 5.42

Notably, the overdispersion of 'well-bleached' feldspars is similar to that of quartz, resulting in similar σ_b values for both minerals (Fig. 5 and Fig. 6.c). Smedley et al. (2019) reported a constant offset of ~ 10 % between the overdispersion between single-grain quartz and single-grain feldspar. The difference is greater between the small-aliquot quartz OSL and the non-
390 filtered single-grain feldspar pIRIR dataset for the samples from Braakmankamp, which is ~ 20 %. Considering that aliquot-based measurements will have smaller overdispersion compared to single-grain measurements (Thomsen et al., 2012), this is within expectations. However, the overdispersion is significantly reduced by selecting well-bleached grains using the $D_{e\ IRSL}$ / $D_{e\ pIRIR}$ ratio. This indicates that feldspar single-grain measurements may have incorporated a significant amount of poorly bleached grains even for samples with well-bleached quartz OSL characteristics.

395 Another factor that should be considered with the overdispersions of OSL and pIRIR datasets is the influence of external microdosimetry. The dose recovery experiments conducted for both minerals, it has been observed that the overdispersion of small-aliquot quartz OSL is typically 5–10 % (e.g. Thomsen et al., 2005), and single-grain feldspar pIRIR is 15–20 % (e.g. Brill et al., 2018; Reimann et al., 2012). Based on the dose-recovery experiments, the difference of ~ 10 % overdispersion is caused by intrinsic characteristics of the minerals, and cannot be explained by the inclusion of poorly bleached grains.

However, the Braakmankamp samples with well-bleached quartz OSL characteristics do not demonstrate such a discrepancy. This may be an effect of external microdosimetry, while small-aliquot quartz is more influenced by external microdosimetrical variations than single-grain feldspar, which has significant influence by the internal K-content (Smedley et al., 2019). Thus, one possible scenario is that the external microdosimetry of the samples evens out the intrinsic ~ 10 % overdispersion difference by increasing the small-aliquot quartz OSL overdispersion to a more significant degree. However, the effects of external microdosimetry and internal K-content are not tested in our research and therefore are to be further researched.

5.2 Comparison of single-grain pIRIR and small-aliquot OSL ages

When comparing the ages obtained from the single-grain feldspar pIRIR dataset (selected grains using $D_{e\ IRSL}$ / $D_{e\ pIRIR}$ ratio filtering) with the quartz ages, we observe that five out of nine ages agree with each other within 1-σ error range. For two additional samples, the differences between ages are minor, that is, they agree within 2-σ. Most of the samples with agreeing ages are concentrated at the upper part of the plaggen layer, besides the top sample (NCL-1117134). From the samples from the lower part of the plaggen layer (NCL-1117126 & 127), the pIRIR signals produced younger ages than quartz OSL. This is also the case for the samples collected from the Bw and C horizons below the plaggen layer.

The disagreement in ages in the samples collected from the deeper layers beneath the plaggen layer may be largely due to the averaging of multiple quartz grains within aliquots. When we examine the outcome of the BsMAM and the MaxAM of the samples NCL-1117124 and NCL-1117125, it is observed that the age range obtained from BsMAM and MaxAM being applied to quartz OSL is within the age range derived by applying BsMAM and MaxAM to pIRIR signals (Table 2, Fig. 8). These samples seem to have heterogeneous age distribution, in which the youngest grains may be detected by single-grain dating methods, but not by dating methods based on aliquots.

The result of the youngest sample (NCL-1117134) demonstrates a different pattern. Unlike the other results, in which the ages obtained by BsMAM applied to pIRIR signals are younger than the ages from quartz signals, the age from pIRIR signals is older than that from quartz signals. This might have been caused by the presence of grains with hard-to-bleach yet relatively minor remnant doses with pIRIR signals (Kars et al., 2014b), which can also be observed by the test performed on grains bleached in the solar simulator (Fig. 4.b). However, it is difficult to conclude that this is the principal reason for the difference in NCL-1117134 since each individual grain can behave differently, which can also be seen in the NCL-1117134 sample itself, where grains that are bleached to near-zero dose are also present (Supplementary Material B). Near-zero dose bleached grains are also of low precision, meaning they have only a minor influence to the BsMAM.

Based on our results, multi-grain quartz OSL performed on small-diameter aliquots that provide a sufficient proxy for genuine single-grain quartz OSL measurements is a suitable approach for dating the plaggen layer because it appears to provide ages that are stratigraphically consistent and reflects the formation history of this anthropic layer. The ages obtained from pIRIR signals align with the quartz to a large extent, showing the possibility that single-grain feldspar pIRIR dating can be useful for obtaining reliable ages and may be an important tool for dating anthropogenic soils in settings where quartz does not possess suitable characteristics for OSL dating.

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5.3 Luminescence informed soil formation history

Beyond ages, luminescence dating can provide information on the formation history of soils (e.g. Wallinga et al., 2019). Especially the single-grain feldspar pIRIR signals can provide additional information on the formation process (e.g. Gray et al., 2020; Reimann et al., 2017; von Suchodoletz et al., 2023). The different age distribution patterns between the samples from plaggic anthrosols and natural layers demonstrate the effects of bioturbation and human activities on age distributions. Samples from the plaggen layers demonstrate a relatively larger proportion of poorly bleached grains, and a relatively small dispersion of age after being processed by the filtering method (Fig. 4.c). In contrast, few grains are identified as poorly bleached for the natural layers even though the age distributions are overdispersed. We propose that this contrast can be explained by the difference between the effects of natural bioturbation and anthroturbation.

The difference in the overdispersion between the samples collected from plaggen layers and the samples collected from the underlying deposits can be explained by the change in the pedoturbation caused by the change in land use. The overdispersion of single-grain pIRIR D_es within the natural layers can be explained by the effects of natural bioturbation driven by a deeper soil food web, involving deep-rooted trees and increased number of soil fauna that utilizes deep plant roots (Maeght et al., 2013) (Fig. 9.b). Such natural bioturbation is a constant but slow process, where grains that are brought to the surface will stay there for sufficient time to totally bleach luminescence signals (Bateman et al., 2007; Kristensen et al., 2015; Reimann et al., 2017; von Suchodletz et al., 2023). As a result, the material within this mixing zone will contain well-bleached grains of different luminescence age. The age range will be wide due to the long period between deposition (oldest grains, late Glacial) and end of bioturbation (youngest grains, plaggen agriculture introduction). In our data, the influence of bioturbation is visible within NCL-1117123 and not within NCL-1117122. This suggests that pre-agricultural bioturbation at Braakmankamp likely caused soil reworking to a depth of 30–50 cm below the pre-plaggen palaeosurface. Prior human land-use activities on this site (e.g. land clearance) before the start of agricultural activities are not evident in the luminescence dating results.

For the plaggic layer, natural bioturbation is replaced by intense anthroturbation through ploughing. This would likely cause the soil food web to be shallower with the reduction of specific subterranean fauna due to the removal of deep roots (Maeght et al., 2013). A much greater part of the grain is now (repeatedly) brought to the surface, but light exposure duration is expected to be much shorter (Poręba et al., 2013; van der Meij et al., 2019; von Suchodletz et al., 2023). Although plaggic material may contain Pleistocene-aged material when first applied, light exposure of the vast majority of grains will result in bleaching of luminescence signals. Subsequent shallow reworking will mix grains that yield similar (young) luminescence ages in smaller age dispersion (Fig. 4.c). This shift toward different ecological (forest vs grassland) and land use (natural vs agricultural) regimes and thereby different soil mixing processes that we interpret in the pIRIR D_e distributions and bleaching results is supported by the pollen analysis of the samples taken from the same site (Fig. 9.a). The pollen analysis demonstrates a significant decrease of pollen of trees and an increase of pollens of herbs and cereals, around 900 a (Fig. 9.a) (Smeenge, 2020).

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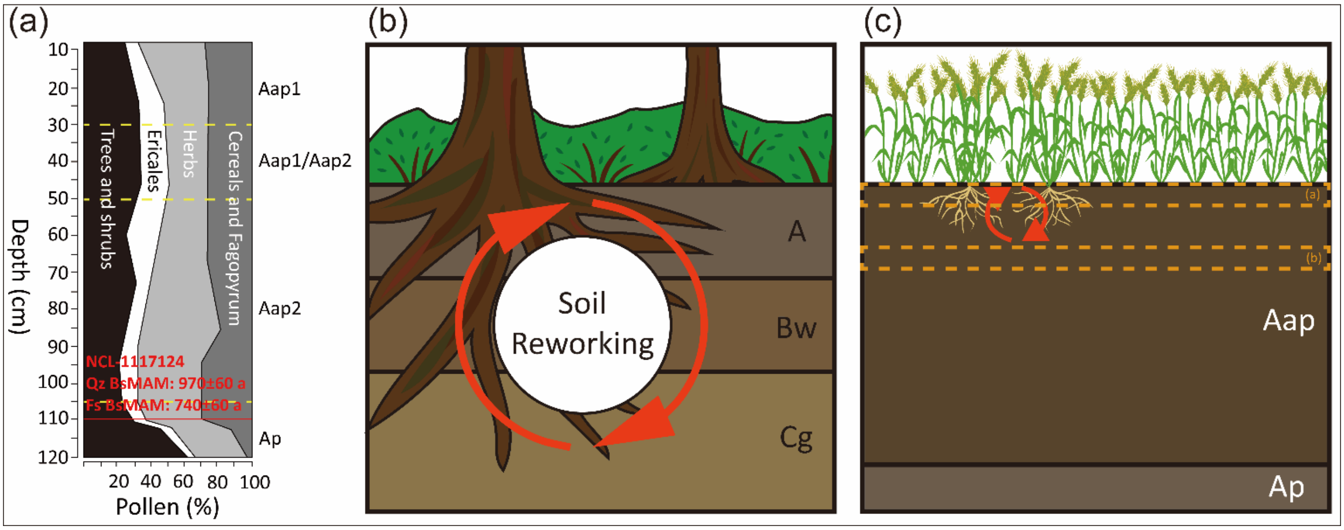

Figure 9: (a) Simplified pollen analysis result of Braakmankamp from Smeenge (2020). A sharp decrease in trees and shrubs coincides with the increase in herbs, cereals, and Fagopyrum. (b) Possible scenario of soil reworking before the introduction of plaggen agriculture at Braakmankamp. The deeper soil food chain, mainly deep-rooted trees, moves the grains from the surface to relatively deep layers. (c) Possible scenario of soil reworking after the introduction of plaggen agriculture at Braakmankamp. The decrease of the depth affected by the soil food chain, due to cereals and herbs with shallower roots and the decrease of soil fauna dependent on deep roots, cause decreased movement of grains. Also, the yearly addition of plaggen materials (indicated by the dashed box) results in previous deposits being excluded from the soil reworking process.

The high proportion of poorly bleached grains in the plaggen layer can be interpreted as an outcome of the combination of intensive ploughing activities and increased depositional rate of materials after the introduction of plaggen agriculture. This is evident in the depth-age plot (Fig. 8). The intensive ploughing caused more grains to be exposed to sunlight, which can be seen in the lower overdispersion within the D_e values of quartz signals (Fig. 5). However, the duration of the exposure for many of the grains would have been relatively short, compared to that before the introduction of plaggen agriculture, which resulted in a high proportion of feldspar grains with poorly bleached pIRIR signals. This result also align with the idea that the effects of agriculture is likely to superimpose the effects of natural bioturbation to soil reworking (von Suchodletz et al., 2023).

5.4 Implications for the timing and formation of plaggic anthrosol on the Braakmankamp site

Ideally, multiple dating methods are combined to obtain chronologies of landscape evolution, because this allows for cross-checking of assumptions and findings. Yet, the resulting datasets must be reconciled to obtain a single chronology for the site in question. Here, we use insights from both quartz and feldspar luminescence measurements, including dose distributions and comparisons of age datasets, to reconstruct the soil formation process at Braakmankamp. The comparison of multiple luminescence methods informs the selection of appropriate approaches for different deposit types and gives confidence in the assignment of time periods to the depositional events at Braakmankamp.

The first recorded event is the deposition of aeolian coversands, which occurred mainly around 9–10 ka ago according to the results of the MaxAM of feldspar (samples NCL-1117122 to 124). The aeolian sand functioned as the parent material for the brown forest soil that was formed on the site before the reclamation. We adopt the MaxAM to derive the depositional age to avoid underestimation of age due to bioturbation. For the same reason, we prefer the single-grain pIRIR ages over single-aliquot quartz OSL ages. The ages obtained from the MaxAM results on feldspar are more consistent with each other than those of quartz. However, the pIRIR age may have been affected by fading, and the actual age of the deposition of the aeolian coversand is likely to be around 12 ka, which is obtained from the quartz CAM of NCL-1117122. This corresponds with the ages of the Younger Coversand II in Lutterzand, Twente, which was dated between 13.6 ± 1.1 ka to 12.2 ± 0.9 ka (Vandenberghe et al. 2013). The degree to which fading affects the discrepancy between the single-grain feldspar BsMAM and the multi-grain quartz BsMAM should be further researched.

The reclamation of the Braakmankamp site seems to have occurred around 900–1000 a, which is around the 11th - 12th century CE. The quartz BsMAM result of the sample (NCL-1117125) from the Ap horizon is 970 ± 60 a. The feldspar BsMAM age for this sample is a bit younger, but the sample collected below the Ap horizon (NCL-1117124) gave the result of 1070 ± 210 a. Considering that the youngest population of the ages in this sample is likely to reflect the grains that have been reworked, the BsMAM result of the feldspar from the Bw horizon imposes that the soil reworking has affected the Bw horizon up to around 1000 a. The difference between the quartz and feldspar in these samples seems to have occurred by the difference between aliquot-based dating and single-grain-based dating.

The introduction of plaggen agriculture to the site seems to have occurred around 700–800 a (1220–1320 CE) based on the quartz BsMAM results of NCL-1117126 (Table 2). A nearly identical age is obtained from the feldspar BsMAM results of NCL-1117125 (Table 2). Based on the results, after the introduction of plaggen agriculture, the intensity of the mixing has increased, allowing more grains to reach the surface. However, the depth of the mixing has decreased during this period, due to human land-use practices. The main source of mixing would have been limited to ploughing, which would not have affected more than 20 cm of depth during the period (van der Meij et al. 2019). The rapid accumulation of plaggen materials would also preserve deeper layers from soil reworking. Based on the quartz BsMAM results, the accumulation rate is ~ 1.14 mm/yr, which is understood to be typical for the plaggic anthrosols in this area (Spek, 2004).

6 Conclusion

Establishing robust chronology and developing knowledge of the formation process of plaggic anthrosols are crucial to understanding the landscape evolution in western Europe and human-landscape dynamics. Our study approaches this through a combination of established and new luminescence methods for 13 luminescence samples collected from a plaggic anthrosol site in Braakmankamp, eastern Netherlands. This yields insights into both the formation history of an anthropogenic soil and luminescence approaches for quantifying soils formation. Our main observations are:

– The ratio of $D_{e\ IRSL}$ and $D_{e\ pIRIR}$ values is a new tool to largely exclude poorly bleached grains from luminescence age estimations and obtain robust overdispersion values for well-bleached grains, which are needed for minimum age modelling.

– Small aliquot quartz OSL is found to be viable for dating plaggen deposits. Single-grain feldspar pIRIR yields similar ages when filtered by $D_{e\ IRSL}$ / $D_{e\ pIRIR}$ ratio. For underlying natural layers that experienced significant bioturbation, single-grain feldspar pIRIR is judged to be capable of providing the ages related to the soil-reworking to the full extent.

– Single-grain feldspar pIRIR data reflect bioturbation history, making it possible to reconstruct the transition between forested and agricultural landscape regimes in the soil column.

– At Braakmankamp site reclamation involving land clearance occurred around the 11th to 12th century CE and plaggen agriculture began around the mid-13th century.

In summary, this research demonstrates that combining single-grain feldspar pIRIR and small-aliquot quartz OSL measurements can be a useful tool in dating and reconstructing soil formation processes. The application of single-grain feldspar pIRIR measurements has added value in understanding the dynamics of different sources of pedoturbation. Overall, this research provides a methodological approach to luminescence dating and an example of its application on anthrosols, which will be useful for the reconstruction of anthropogenic landscapes elsewhere.

Data availability

Data and metadata will be prepared for sharing in a public repository.

Author contributions

JC, RvB, EC, HS, and JW contributed to the conceptualization of the research. TR, HS, and AvO conducted the fieldwork and sampling. Funding acquisition was undertaken by JW and RvB. HS carried out the main investigation on the research site, including site selection, soil profile, and pollen analysis. JC, TR, and AvO carried out the main investigation on luminescence dating, including measurements and analyses of the data. JC prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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