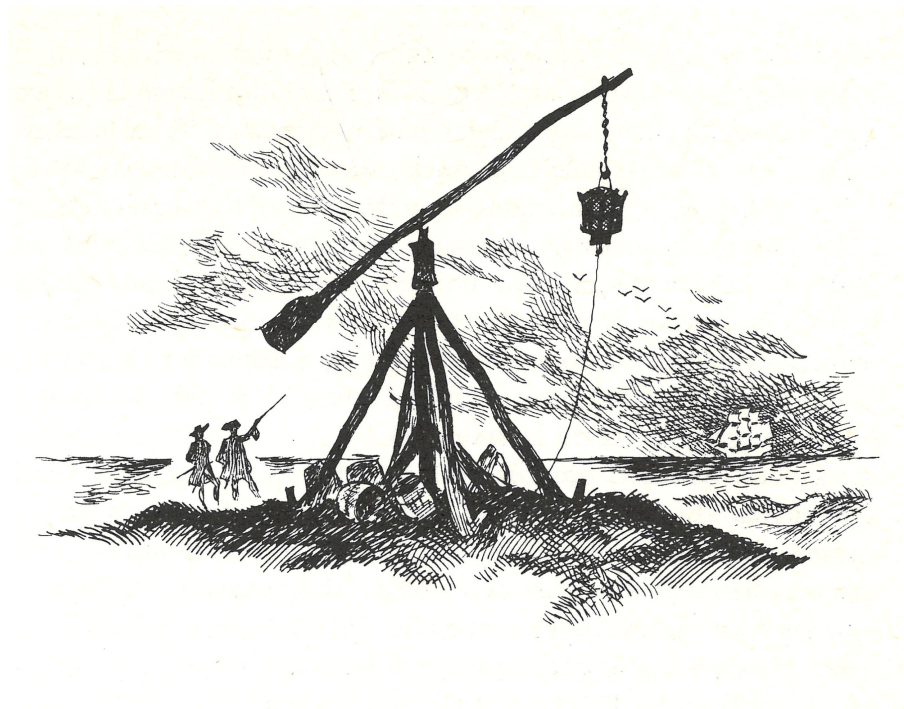


Establishment, history and internal architecture of Kolabacken, the former beacon at Falsterbo, southern Sweden

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Dissertations in Geology at Lund University,
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Department of Earth and Environmental Science
Lund University
2026

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Cover Picture: Artistic illustration by Gunnar Brusewitz of "Falsterbo lykta" as described by Carl Linnaeus in 1749 (von Sydow, 1977).

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SHENGLIANG DONG

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Abstract: Kolabacken is a small grass-covered mound near the southern tip of the Falsterbo Peninsula in southern Sweden. The site is known as the former beacon at Falsterbo, where a so-called tilting beacon helped ships navigate along the shallow and dangerous coast before the present lighthouse was built in 1795. Although Falsterbo's importance for maritime traffic and trade during Medieval times is well known, the internal structure and historical development of Kolabacken have not previously been studied in detail. The study is based on hand-auger sampling to depths of 1 – 6 m at twenty points along two crossing transects through Kolabacken. The sediments were described in the field and later analysed using grain-size analysis, microscopic analysis, portable OSL profiling, quartz OSL dating and radiocarbon dating. Historical maps and written sources were also used to compare the sediment record with the known history. The results show that Kolabacken is a complex structure situated on a former beach ridge close to the early Medieval coastline. The natural beach sand is overlain by a succession of mainly wind-deposited fine- to medium-grained sand, with varying amounts of residues from beacon operation and other human activities. Six sedimentary units were identified: from bottom to top, brown beach sand with gravel, grey sand with charred wood remains and brick fragments, black sand with incompletely burnt coal, yellowish-white aeolian sand, grey sand with coal slag, and greyish-white sand with coal residues and a soil horizon.

Four radiocarbon dates on charred wood from the lower unit with wood remains yielded ages in the range of 1025-1260 CE. Considering the inherent age of the trees used as fuel, these dates broadly confirm historical records stating that King Valdemar II allowed the construction of a beacon site at Falsterbo sometime during 1225-1241 CE. A peat fragment from the underlying beach sand was radiocarbon dated to 645-775 CE, showing that the shoreline was located close to the present site of Kolabacken several hundred years before the beacon site was established. The grey sand with charred wood remains represents Medieval beacon activity, when wood, probably from local woodlands, was used as fuel, while the brick fragments may derive from some form of foundation or building at the site. The overlying black sand represents a subsequent early phase of coal burning when large fragments of unburnt or partly burnt coal were left in the deposits. According to historical sources, coal burning probably began during the 1620s. Higher in the stratigraphic sequence, the grey sand with coal slag suggests a later phase of more complete burning, regular cleaning, maintenance, and more efficient beacon operation. Between these coal-rich units is a layer of aeolian sand from the late 1600s. It is unclear whether this layer resulted from a longer period of sand drift or a single storm event, but in combination with war-related interruptions in coal deliveries it probably affected beacon operation.

Complementary luminescence dating results provide general chronological support, although dating of this type of mixed coastal and anthropogenic deposits is challenging. Cleaner units of aeolian sand give more reliable results, while the mixed lower units were affected by reworking, partial bleaching and later disturbance. Optimal chronological control is therefore obtained by combining the dating results with sedimentology, microscopic observations and historical records.

Potential future studies of the origin and history of Kolabacken could include wood-anatomical analysis of charred wood remains in order to clarify the age and origin of the fuel. Refined luminescence dating of selected sediment layers, combined with comparisons with similar studies from other parts of the Falsterbo Peninsula, could improve the chronology. In addition, possible remains of the tilting beacon and surrounding structures could be mapped using ground-penetrating radar.

Keywords: Falsterbo peninsula, beacon, geoarchaeology, OSL dating, radiocarbon dating

Supervisor(s): Dan Hammarlund, Helena Alexanderson, Mats Rundgren

Subject: Quaternary Geology

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Sammanfattning: Kolabacken är en liten gräsbevuxen kulle nära den södra spetsen av Falsterbohalvön i sydvästra Skåne. Platsen är känd som den tidigare fyrplatsen i Falsterbo där en s.k. vippfyr hjälpte fartyg att navigera längs den grunda och farliga kusten innan den nuvarande fyren byggdes år 1795. Trots Falsterbos betydelse för sjöfart och handel under medeltiden har Kolabackens uppkomst, inre uppbyggnad och historiska utveckling hittills inte studerats i detalj. Detta arbete syftar till att klarlägga bildningens historia och relationer till naturliga kustprocesser och mänsklig aktivitet genom att undersöka och åldersbestämma dess lagerföljd. Studien är baserad på spadborrnig till 1 – 6 m djup på 20 punkter längs två korsande linjer genom Kolabacken. Sedimenten beskrevs i fält och analyserades med hjälp av kornstorleksanalys, mikroskopisk analys, samt åldersbestämning genom C14-datering och olika typer av luminescensdatering. Historiska kartor och skriftliga källor användes som jämförelse för att klarlägga platsens historiska utveckling. Resultaten visar att Kolabacken är en komplex bildning belägen på en tidigare strandvall nära den tidigmedeltida kustlinjen. Den naturliga strandsanden är överlagrad av en succession av huvudsakligen vindavsatt fin- till mellansand med varierande inslag av restprodukter från fyrverksamheten och andra mänskliga aktiviteter. Sex sedimentära enheter identifierades: underst brun strandsand med inslag av grus, därefter grå sand med förkolnade vedrester och tegelfragment, svart sand med ofullständigt förbränd stenkol, gulvit flygsand, grå sand med kolslagg, och överst gråvit sand med kolrester och jordmån.

Fyra C14-dateringar av träkol från den undre enheten med vedrester gav åldrar i intervallet 1025–1260 e.Kr., vilket med beaktande av egenåldern hos de träd som användes som bränsle i huvudsak bekräftar historiska uppgifter om att Kung Valdemar II tillät uppförandet av en fyrplats i Falsterbo någon gång under perioden 1225–1241 e.Kr. Ett torvfragment från den underliggande strandsanden C14-daterades till 645–775 e.Kr., vilket visar att strandlinjen var belägen nära den plats där Kolabacken nu ligger flera hundra år innan fyrplatsen anlades. Den grå sanden med förkolnade vedrester representerar den medeltida fyrverksamheten då ved, troligtvis från lokala skogsbestånd, användes som bränsle, medan tegelfragmenten kan komma från någon typ av grundläggning eller byggnad på platsen. Den överliggande svarta sanden representerar en efterföljande tidig fas av eldning med stenkol då stora fragment av obränt eller bara delvis förbränt kol lämnades kvar i avlagringarna. Enligt historiska källor inleddes stenkolseldningen sannolikt under 1620-talet. Högre upp i lagerföljden avspeglar den grå sanden med kolslagg en senare fas av mer fullständig förbränning och effektivare fyrdrift. Mellan dessa kolrika enheter finns ett lager med flygsand från slutet av 1600-talet. Det är oklart om det härrör från en längre period av sanddrift eller ett enstaka stormtillfälle men i kombination med krigsrelaterade avbrott i leveransen av stenkol påverkade det sannolikt fyrdriften.

De kompletterande resultaten av luminescensdateringarna ger generellt kronologiskt stöd, även om komplexa avlagringar med betydande inslag av antropogent material är svåra att datera med luminescens. Mer enhetliga flygsandslager ger mer tillförlitliga resultat, medan de ved- och kolrika enheterna kan vara påverkade av omrörning vid avsättningen, partiell ljuspåverkan och senare störningar. Optimal kronologisk kontroll erhålls därför genom integrerad tolkning av dateringsresultat, sedimentologi och mikroskopiska observationer, samt jämförelser med historiska källor.

Eventuella fördjupade studier i framtiden av Kolabackens tillkomst och historia skulle kunna baseras på vedanatommiska undersökningar av vedrester för att klarlägga bränslets ålder och ursprung. Förfinade luminescensdateringar av vissa av sedimentlagren i kombination med jämförelser med liknande studier inom andra delar av Falsterbonäset skulle kunna förbättra kronologin. Vidare skulle eventuella rester av vippfyren och kringliggande konstruktioner kunna kartläggas med hjälp av georadar.

Nyckelord: Falsterbohalvön, fyr, geoarkeologi, OSL-datering, radiokoldatering

Handledare: Dan Hammarlund, Helena Alexanderson, Mats Rundgren

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1 Introduction

Human societies have long used and shaped coastal environments while also responding to the natural dynamics of these landscapes (Anthony et al., 2014). As a result, coastal landforms often preserve evidence of both natural geomorphological development and human activity, including settlement, resource use, navigation, and other forms of landscape modification (Bailey & Flemming, 2008). Therefore, the sedimentary archives of historically used coastal sites can reveal not only the nature of past human activities, but also how those activities influenced environmental change and how people interacted with and adapted to the coastal environment (Nicoll & Murphy, 2014).

Across the world, geological and geochronological methods have been widely used to investigate the coastal landscape development and human activities related to environmental change. In the southern Baltic Sea area, researchers have successfully reconstructed the coastal landforms in the Świna barrier in Poland (Reimann et al., 2011) and the Darss–Zingst barrier-spit system in Germany (Reimann et al., 2010), where optically stimulated luminescence (OSL) dating has been used to establish detailed chronologies for dune and barrier development. Studies from the Mediterranean have shown how integrating geomorphology, sediment cores, OSL dating, radiocarbon dating, and archaeological evidence can be used to reconstruct changing coastlines, lagoons, beach systems, and disturbed cultural deposits in relation to past settlement and land use (Ghilardi, 2021). These studies used geological and geochronological methods directly within archaeological and geoarchaeological research where the aim is not only to reconstruct environmental change but also to understand how coastal processes affected settlement history, site preservation, and human use of the landscape. In addition, in more direct archaeological settings, luminescence dating has been applied to coastal Paleolithic sites in Shandong (Nian et al., 2015) and South China (Jin et al., 2025) to establish site chronologies and relate human occupation to late Quaternary environmental change.

The Falsterbo Peninsula in southwestern Scania, the southernmost province of Sweden, forms a suitable area for this type of approach. The peninsula is located near the entrance to the Öresund Strait, which is important for maritime traffic between the Baltic Sea and the North Sea. The peninsula consists of a low-lying sandy coastal landscape shaped by coastal deposition and ongoing geomorphological activity (Blomgren & Hanson, 2000). Previous research has established Falsterbo as both a dynamic coastal environment and a historically important maritime area (Fredriksson et al., 2016). Geological and geomorphological studies have shown that the peninsula is still evolving under the influence of shoreline dynamics, sediment transport, erosion, and human intervention (Blomgren & Hanson, 2000), while historical and archaeological work has clarified the broader importance of Falsterbo and Skanör within the Medieval Scanian Market and the Baltic trade network (Jahnke, 2021). More recent geoarchaeological research has also demonstrated how sand drift and related coastal processes affected the preservation of historical remains in the Falsterbo area

(Alexanderson et al., 2024).

This thesis focuses on Kolabacken (“the coal hill”, translated from Swedish), a small grass-covered hill near the southern tip of the Falsterbo Peninsula. In Medieval and later times, this site functioned as a beacon, guiding ships around the dangerous sandy shores. Kolabacken is of particular interest because it represents the intersection of coastal landscape development, maritime and medieval history, and long-term human-environment cooperation, which provides an opportunity to investigate how a small coastal landscape can preserve evidence of both human activities and natural processes.

Although previous research has provided important insights into the historical and geological development of the Falsterbo Peninsula, Kolabacken itself still requires more detailed investigation. Existing studies have mainly focused on the broader coastal landscape and historical setting of the peninsula (Alexanderson et al., 2024), while the internal sedimentary structure, chronology, establishment and later history of the beacon at Kolabacken remain less well understood. It is still uncertain when beacon activity first began at the site, how the beacon and its associated mound developed through time and whether the sediments preserve evidence of activities. Therefore, a more detailed study of Kolabacken is needed to understand both the internal architecture of the beacon site and its relationship to the wider development of the Falsterbo Peninsula.

1.1 Research aims

This thesis has the following aims:

- I. To make a detailed description of the sedimentary architecture of Kolabacken, including its content of material associated with beacon activity in the past.
- II. To establish a chronology of the deposits based on luminescence and radiocarbon dating, clarifying the age of establishment of the beacon, its subsequent history, and any natural or anthropogenic processes that may have affected its present configuration (sand drift, excavation, deposition of artificial material etc.).
- III. To provide an integrated description of the history of Kolabacken and the adjacent coastal environment based on comparison with historical accounts and relevant literature.

2 Background

2.1 Study area

Kolabacken (55° 23' 2" N, 12° 49' 21" E) is located in the southwestern part of Scania, southern Sweden, close to the southern tip of the Falsterbo Peninsula (Fig. 1). Based on field observations and GPS measurements, the highest point of the mound reaches approximately 5.6 m a.s.l., and it rises about 4.5 m above the surrounding relatively flat landscape. The mound is characterized by two small tops separated by a shallow saddle. Its surface is grass-covered (Fig. 2), and several rabbit burrows were observed during fieldwork. Fragments of coal slag are also present across the surface. Today, Kolabacken lies within the protect-

ed coastal landscape of the Falsterbo Peninsula, an area that includes several nature reserves. The area is fenced to the north, west, and south. To the east there is a small tree area, with a golf course beyond it, whereas paved roads and a parking area are situated outside the fences to the south and west. The new lighthouse, Falsterbo fyr, was established approximately 380 m west of Kolabacken in 1795 and replaced the earlier beacon.

The Falsterbo Peninsula is a low-elevation coastal area, mainly composed of sand deposited by currents and wave action. It was formed 6000–7000 years ago because of isostatic rebound and coastal depositional processes (Ringberg, 1975). Previous studies of the Falsterbo Peninsula have shown that its current land-forms are still undergoing dynamic changes and have not yet fully stabilized (Blomgren, 1999). The shape of the shoreline and the distribution of sediments have been influenced not only by natural coastal processes, but also by later human activities. Examples include the construction of a port at Skanör in the 1870s (Falsterbo Museum, n.d.) and the construction of the Falsterbo Canal in the early 1940s (Dellborg, 1942). These activities modified local sediment transport and coastal morphology, showing that the modern landscape of the peninsula reflects both natural processes and human intervention.

2.2 Historical development and significance of Kolabacken and Falsterbo

The historical development of Kolabacken was closely linked to the emergence and growth of Falsterbo as a medieval coastal town. In turn, the development of both Falsterbo and the neighbouring town of Skanör was strongly influenced by the rise, expansion, and eventual decline of the Scanian Market (Skånemarknaden) (Reisnert, 2021). This market was not merely a background factor in the history of the two towns; throughout much of the medieval period, it formed the basis of their economic importance and urban development (Ersgård, 1989).

The early phase of the market can be traced back to the Late Viking Age, but it expanded rapidly from the late twelfth century and especially during the thirteenth century (Ersgård, 1989). This growth was supported by the rich herring fishery in the area and by the favourable location of the Falsterbo Peninsula along one of the main maritime routes of the Baltic Sea (Sicking, 2021). What had first been a seasonal fishing market gradually developed into a large interregional and later international trading centre, attracting merchants and fishermen from across northern Europe. Skanör developed earlier, but during the thirteenth century the market area expanded southwards towards Falsterbo (Ersgård, 1989). By the late Middle Ages,

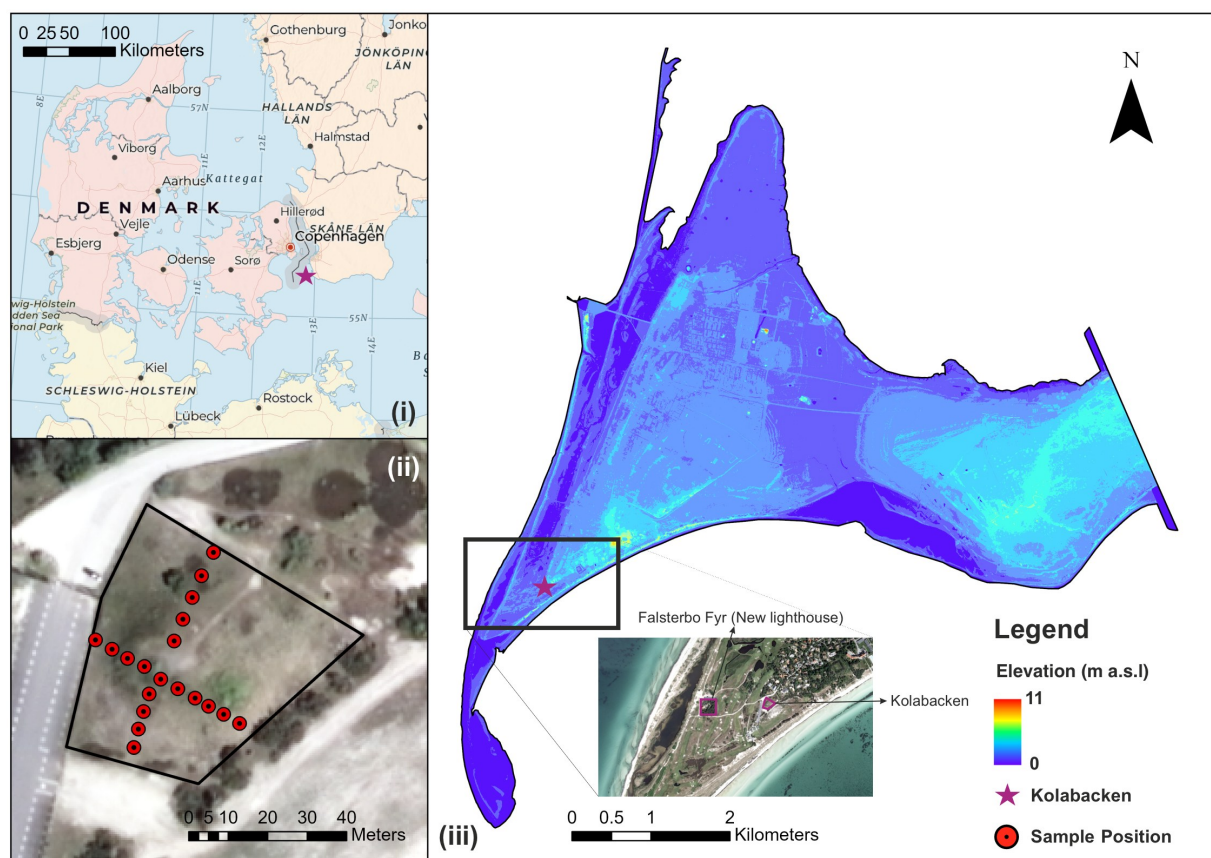


Fig. 1. Location of the study area and the sampling positions at Kolabacken. (i) Regional map showing the location of Kolabacken. (ii) Aerial photo of Kolabacken with the sampling position. (iii) Digital elevation model of the Falsterbo Peninsula with the positions of Kolabacken and the Falsterbo lighthouse indicated in purple. Map created by ArcGIS Pro 3.6.3. Data origin: SDFI, Esri, Garmin, FAO, NOAA, USGS; Lantmäteriet.



Fig. 2. Kolabacken seen from the north. Photograph by Shengliang Dong, 11 May 2025.

the centre of the herring trade seems to have shifted from Skanör to Falsterbo. Around 1500, the market began to decline, probably because of changes in the herring trade and increasing competition from North Sea herring fisheries, especially those connected to the Low Countries, which gradually reduced the earlier dominance of the Scanian herring trade (Brunmayr, 2020). As both towns were strongly dependent on the market system, their later development also changed. Skanör survived as a small town, while Falsterbo gradually lost much of its urban importance.

Maintaining safe and efficient maritime transport routes was essential for the functioning and continuity of the market system. Because of the dangerous coastal area for marine activities, a lighthouse became very important. The earliest known historical reference to the need for a lighthouse at Falsterbo is linked to the Danish king Valdemar II. A document dated between 1225 and 1241 CE (Fig. 3) states that the king granted permission for a lighthouse to be established at Falsterbo to help ships avoid shallow waters and hidden reefs. In the centuries that followed, the site appears to have continued to serve as an important navigational landmark.

The later operation of Kolabacken was closely connected to coal supply. According to Clemensson (1958), Danish beacons have been fired with coal since the early 1620s, probably using imported coal from Scotland or the Netherlands. Coal delivery prob-

lems are recorded in 1664–1665, when Nidingen, Kulen and Falsterbo were not supplied. In the late 1660s, coal from the Tinkarp mine north of Helsingborg began to be shipped to the beacons. Coal was brought to Falsterbo by ship to Höllviken Bay or Skanör and then transported by carriage to the beacon. Records from 1668 mention a small coal-storage barn near the Falsterbo beacon, built because wind-blown sand damaged the stored coal and nearby grassland. Around 1670, the beacon consumed nearly 900 barrels of coal per winter, showing the scale of its operation. Coal delivery was again disrupted during the Scanian War in 1676 (Clemensson, 1958).

The old beacon at Kolabacken remained part of Falsterbo's navigational landscape until the end of the eighteenth century. The present lighthouse was built in the 1790s and came into operation around 1795 (Fig. 4), replacing the older beacon site at Kolabacken. Before this change, Kolabacken was generally regarded as the site of the oldest lighthouse in Falsterbo. Evidence from the 1761 map of the Falsterbo area (Fig. 5), together with the description given by Carl von Linné in 1749, suggests that this early lighthouse consisted of an iron basket suspended on a wooden pole and was marked on the map as “Landtärnan” (Fig. 6). Linné also noted that coal was burned there at night to provide light for ships sailing in the surrounding waters (von Linné, 1751).



Fig. 3. Archival document referring to the establishment of a beacon at Falsterbo during the reign of King Valdemar II of Denmark. Document origin: Archive of the Hanseatic City of Lübeck, Germany.



Fig. 4. The “new” lighthouse at Falsterbo, erected in 1795. Photograph by Shengliang Dong, 11 May 2025.

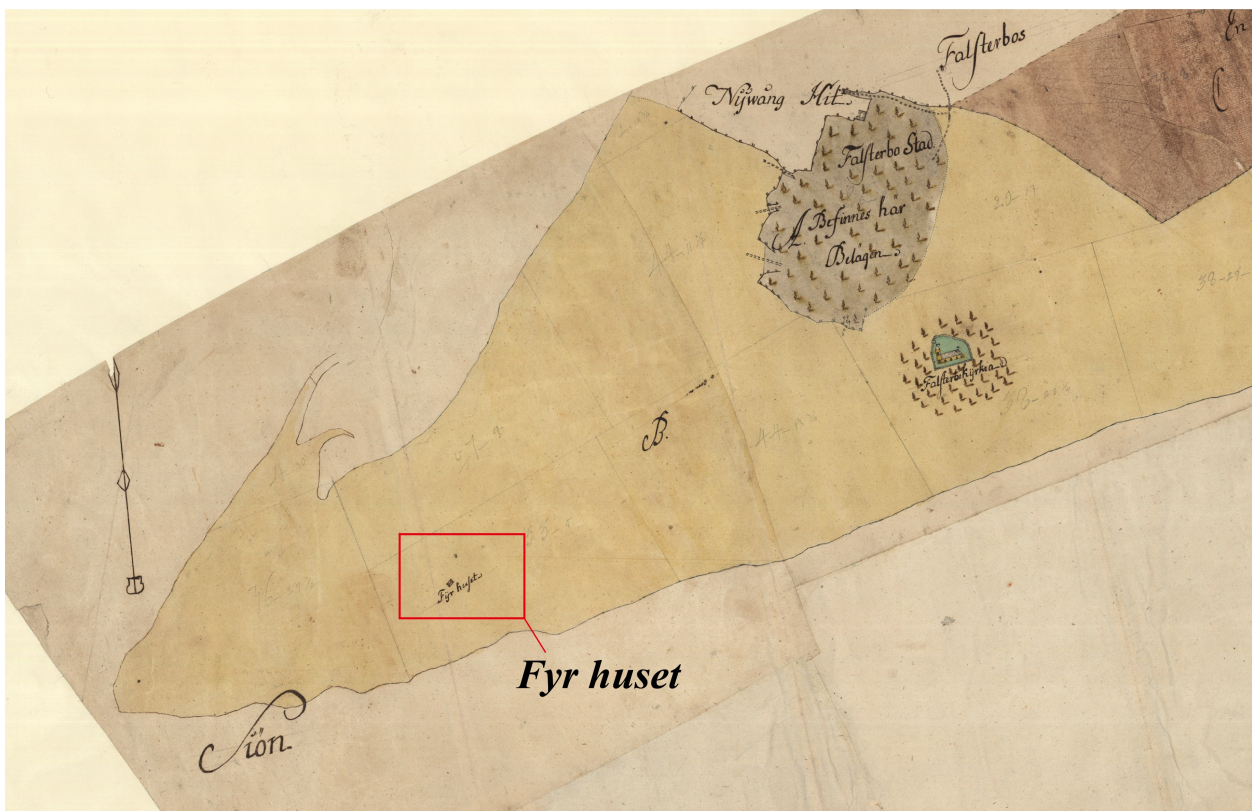


Fig. 5. Historical map evidence for the beacon site at Kolabacken in 1761. The map labels the site as “Fyr huset”, indicating the presence of a lighthouse or beacon house in this area by the mid-eighteenth century. The red box marks the location of the label on the original map. Source: Lantmäteriet, Historiska kartor, act 12-skf-1, 1761.



Fig. 6. Model of the former beacon at Kolabacken. Photograph by Shengliang Dong at Falsterbo Museum, 3 October 2025.

2.3 Age determination

Chronology is a very important part in the analysis of sedimentary archives, as it provides the temporal framework needed to investigate the formation and evolution of sedimentary sequences, as well as their relationship to environmental change and human activity (Lowe & Walker, 2015). In this way, chronological control helps us to understand the history of the sediments and the processes by which they were formed. A wide range of methods can be used to determine the age of sediments and associated depositional layers, among which radiocarbon dating, cosmogenic nuclide dating (Walker, 2013), and optically stimulated luminescence (OSL) dating have been especially widely applied in recent geological and environmental studies (Murray et al., 2021). In the present study, OSL dating and radiocarbon dating were combined to reconstruct the depositional history of Kolabacken, thereby helping to clarify its historical development and improve the archaeological record.

2.3.1 Luminescence profiling

Luminescence profiling is a rapid screening method used to examine down-core changes in the luminescence properties of sediments (Munyikwa et al., 2020; Sanderson & Murphy, 2010). Unlike conventional OSL dating, which normally requires careful preparation and measurement of purified mineral grains, portable OSL profiling can be applied to bulk sediment samples with limited preparation (Bateman et al., 2015). It measures the luminescence signals released under infrared and blue-light stimulation. The infrared signal is mainly related to feldspar components, while the blue-stimulated signal is usually associated with quartz-dominated or mixed quartz–feldspar signals. Changes in these signals and in the IR/Blue ratio can therefore help identify variations in sediment composition, bleaching conditions and depositional units. However, luminescence profiling does not completely replace full OSL dating, because the signals can also be affected by mineral composition, grain size, water content and other sediment properties.

2.3.2 Luminescence dating

Luminescence is light resulting from the release of energy stored in a crystal structure (Murray et al., 2021). The amount of stored energy increases with continued exposure to natural ionizing radiation through time. Since this signal can be reset by heating or by bleaching during exposure to sunlight, it can be used for dating sediments (Preusser et al., 2008).

2.3.2.1 Principles of luminescence dating

The development of optically stimulated luminescence (OSL) dating has gradually expanded from the dating of archaeological materials to the dating of sediments (Aitken, 1985). Early luminescence dating was mainly applied to heated archaeological materials such as pottery, burnt clay and fire-affected remains. The main method of measurement was thermoluminescence (TL) dating, in which trapped electrons accumulated within the mineral lattice are released by heating in order to obtain an age estimate (Aitken, 1998). Lat-

er, researchers recognised that the luminescence signal in mineral grains can also be reset by exposure to sunlight. This led to the development of optically stimulated luminescence (OSL) dating (Huntley et al., 1985). Unlike TL which relies on thermal stimulation, OSL uses light to release the energy stored in electron traps, making it more suitable for determining the burial time of quartz and feldspar grains since their last exposure to light. In 1985, Huntley and co-workers were the first to apply OSL to the dating of sediments from different geological settings (Huntley et al., 1985). Since then, the method has continued to develop and has expanded into different technical branches, such as Infrared Stimulated Luminescence (IRSL) and Linearly Modulated Optically Stimulated Luminescence (LM-OSL) (Murray et al., 2021). As a result, luminescence dating has developed from a method originally used for archaeological ceramics and burnt remains into an important tool for dating sediments in Quaternary geology and geoarchaeology.

Among the different methods used in OSL dating, quartz was selected in this study because the study area is mainly composed of aeolian sand, in which quartz is the main mineral. In natural environments, quartz is continuously exposed to ionizing radiation produced mainly by the radioactive decay of ^{40}K and by the ^{238}U and ^{232}Th decay series in the surrounding sediment (Preusser et al., 2008). This radiation excites electrons within the crystal lattice, some of which become trapped at metastable defects where they can remain stored over long periods of time (Murray et al., 2021). When the quartz is subsequently stimulated by light or heat, part of this stored energy is released, and some of the liberated electrons recombine at luminescence centres, producing measurable photon emission, that is, the luminescence signal. The intensity of this signal is related to the absorbed dose accumulated since the signal was last reset (Wintle, 2008). In sedimentary settings, this resetting usually occurs through exposure to daylight during erosion, transport, and deposition. After burial, the grains are shielded from further light exposure, and the luminescence signal begins to build up again as radiation dose accumulates through time (Duller, 2004). In the laboratory, the natural luminescence signal is measured by optically stimulating prepared quartz aliquots. This natural signal is then compared with signals produced by known laboratory regenerative doses to determine the equivalent dose (D_e) (Murray et al., 2021; Wintle, 2008). When combined with the environmental dose rate, derived from the radioactivity of the surrounding sediment together with the contribution from cosmic radiation, the burial age of the sediment can be calculated using the fundamental luminescence age equation (1) (Prescott & Hutton, 1994). Quartz OSL dating therefore provides a chronological basis for determining the time elapsed since sediment grains were last sufficiently exposed to sunlight (Huntley et al., 1985).

$$\text{Age (ka)} = \frac{\text{Equivalent dose (De) (Gy)}}{\text{Dose Rate (Gy/ka)}} \quad (1)$$

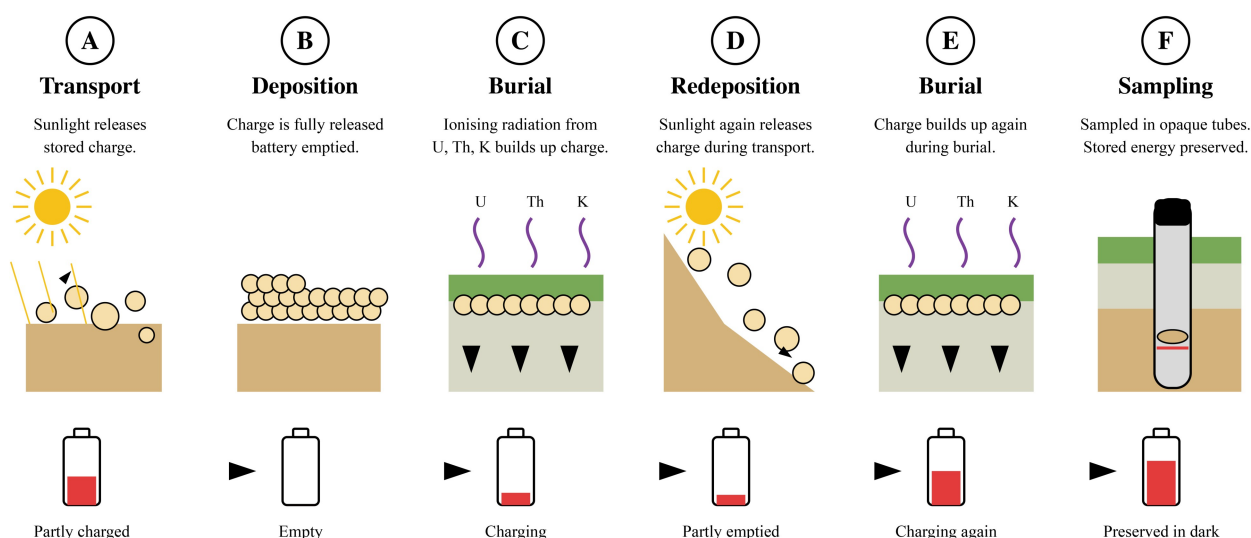


Fig. 7. Accumulation and release of charge within mineral grains (modified from Duller, 2008). (A) During transport of sediment, the accumulated charge gets released due to energy provided by natural sunlight; (B) At deposition, the charge is fully released and the “battery” is emptied; (C) Charge can accumulate within the grain during burial due to natural ionising radiation; (D) and (E) The process described before can happen multiple times over geological times scales, depending on the environment and the geological processes; (F) When a sample is taken in opaque tubes or using cores, the stored energy at that particular time is recorded and can later be released in the laboratory to obtain a luminescence age.

Before carrying out equivalent-dose measurement, it is necessary to assess whether the quartz extracts and the selected measurement settings are suitable for a reliable OSL dating. Therefore, a series of quality-control tests is usually carried out before the routine dose rate measurements. These tests are used both to evaluate the purity of quartz samples and to identify suitable parameter settings especially the thermal treatment and signal measurement settings.

2.3.2.2 Quality control tests

The IR test is first used to assess whether the quartz samples contain significant feldspar contamination (Duller, 2003). This is very important because feldspar commonly produces a stronger luminescence signal than quartz, and if the feldspar is not removed, it may influence the signal and thereby result in an erroneous age. During the measurement, the signal produced by infrared stimulation is compared with the OSL signal. In this study, an IR/B ratio below 10% was taken to indicate that feldspar contamination was sufficiently low for the samples to be considered pure quartz, whereas values above 10% were treated as a warning of possible feldspar contamination. This means that the quartz sample is not pure enough for measurement and the further purification or renewed chemical treatment may be required (Duller, 2003; Murray et al., 2021; Wintle & Murray, 2006).

The next step is the preheat plateau test. This test determines an appropriate preheat temperature range for the analytical protocol (Murray & Wintle, 2000; Wintle & Murray, 2006). In this test, multiple aliquots are measured under same SAR conditions with only the preheat temperature as the main variable. The result of equivalent dose values are then plotted against temperature (Aitken, 1998; Wintle & Murray, 2006). A suitable preheat range is indicated by a “plateau”, which means a temperature interval over which the measured D_e values remain approximately constant.

This means that unstable signal components have been removed, while no obvious thermal transfer or other measurement problems have been introduced, this temperature is the best temperature for further analytical protocol (Murray & Wintle, 2000; Wintle & Murray, 2006).

2.3.2.3 Single-aliquot regenerative-dose (SAR) protocol

Quartz OSL luminescence measurement consists of a sequence of laboratory procedures to get the equivalent dose of sediment samples and calculate the age (Duller, 2008; Murray et al., 2021; Preusser et al., 2008). The procedure generally begins with the collection of light-protected samples in the field, followed by laboratory preparation under red light conditions to isolate quartz grains for analysis. The prepared quartz aliquots are then measured in a luminescence reader, and the resulting equivalent dose is combined with the environmental dose rate to obtain the final age estimate (Murray & Wintle, 2000).

The Single-aliquot regenerative-dose (SAR) protocol has become the standard procedure for equivalent-dose determination in quartz OSL dating because it provides an effective way to correct for sensitivity changes during repeated measurement cycles (Murray & Wintle, 2000, 2003; Wintle & Murray, 2006). During measurement, the luminescence sensitivity of quartz may change after successive irradiation, heating, and optical stimulation, so a direct comparison between the natural signal and regenerative-dose signals would otherwise be unreliable. In the SAR protocol, both the natural OSL signal and a series of regenerative-dose signals are measured on the same aliquot, while a small, fixed test dose is used after each cycle to monitor and correct for these sensitivity changes (Duller, 2008; Murray & Wintle, 2000, 2003).

The luminescence response to the natural or regenerative dose (L_x) is normalized by the response to the test dose (T_x), producing a sensitivity-corrected signal expressed as L_x/T_x . The regenerated L_x/T_x values are then plotted against the corresponding laboratory doses to construct a dose-response curve, and the equivalent dose (D_e) is determined by interpolating the corrected natural signal, usually expressed as L_n/T_n onto this curve. In this way, D_e represents the laboratory dose required to reproduce the natural luminescence response of the sample (Murray et al., 2021; Preusser et al., 2008).

Because all measurements are made on the same aliquot, the SAR protocol reduces the influence of inter-aliquot variability. In addition, the sequence commonly includes a zero-dose step to assess recuperation and a repeated regenerative dose to test recycling. For quartz, preheating and cut heat are also included to remove charge from unstable traps and im-

prove measurement stability. When quartz exhibits stable luminescence behaviour and the internal quality-control tests indicate that the selected settings are appropriate, the SAR protocol can provide reliable equivalent-dose estimates and is widely used as a standard procedure in modern quartz OSL dating (Murray & Wintle, 2000; Rhodes, 2011). An example of the resulting decay curve and dose-response curve is shown in Fig. 8 for sample 25164. The decay curves illustrate the behaviour of the natural and regenerative OSL signals during stimulation, whereas the dose-response curve shows how the sensitivity-corrected signals were used to determine the equivalent dose (D_e) by interpolation of the corrected natural signal onto the regenerated growth curve.

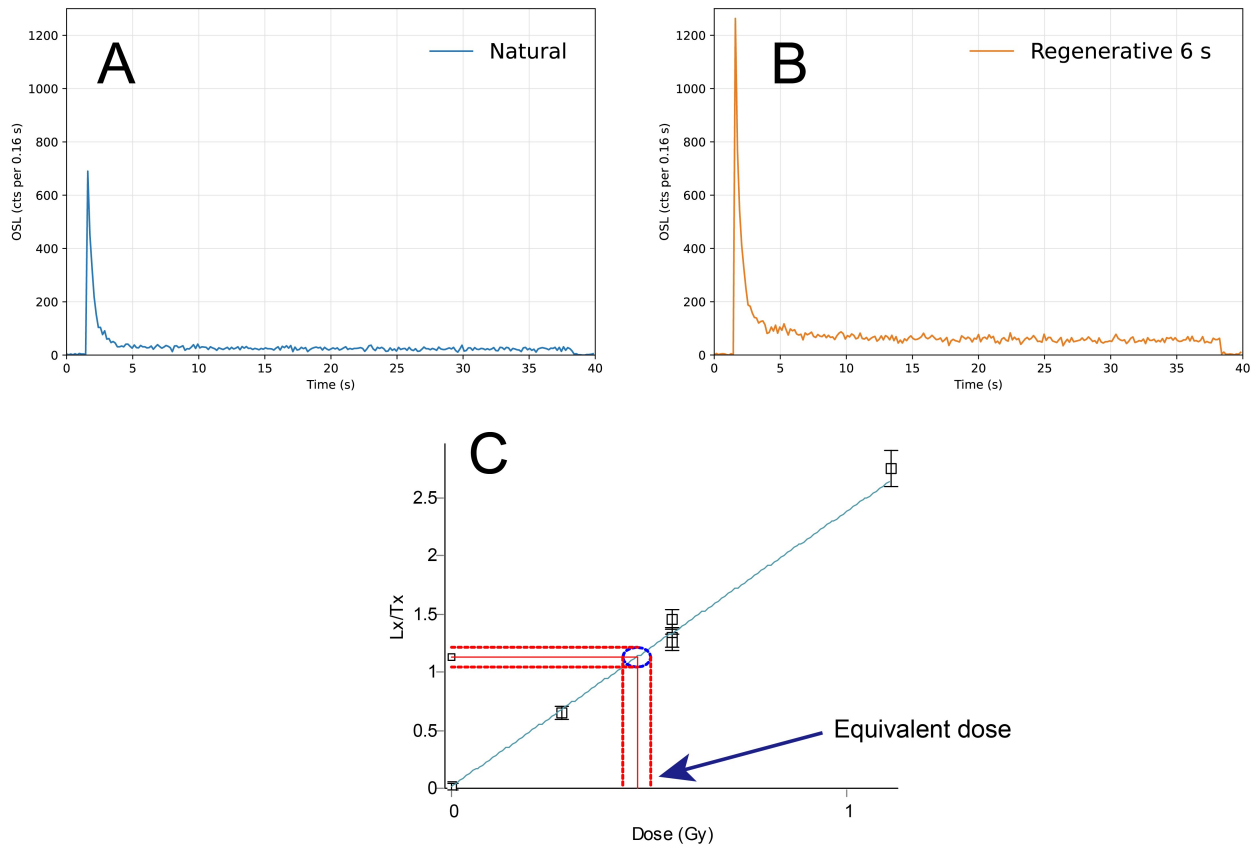


Fig. 5. Representative SAR OSL decay and dose response-curve for sample 25164. **A.** Natural OSL decay curve from one aliquot of sample 25164, showing the luminescence signal measured before any laboratory regenerative dose was added. **B.** OSL decay curve from the same aliquot after a 6 s laboratory regenerative dose. This curve illustrates the regenerated luminescence response used in the SAR sequence for comparison with the natural signal. **C.** Dose-response curve for the same aliquot. The sensitivity-corrected luminescence signals (L_x/T_x) are plotted against the regenerative doses, and the natural sensitivity-corrected signal is projected onto the fitted growth curve to determine the equivalent dose (D_e). The red dashed lines indicate the interpolation of the natural signal and its uncertainty onto the dose axis, and the arrow marks the resulting equivalent-dose estimate.

2.3.2.4 Aliquot acceptance criteria

Quality-control checks in the SAR protocol are important for identifying aliquots that produce unreliable or anomalous measurements, so that they can be excluded from further analysis. This improves the reliability and precision of the final equivalent-dose dataset. Among these checks, the recycling ratio is determined by repeating the same regenerative dose later in the measurement sequence and comparing the sensitivity-corrected signals (Roberts et al., 2015). A recycling ratio close to 1 indicates that the sensitivity correction is functioning properly. Recuperation is assessed using a zero-dose regenerative step and reflects the magnitude of any residual or procedure-induced signal carried over from previous measurement cycles. This value should remain low relative to the natural signal. Together, these checks are used to evaluate the reproducibility of the sensitivity-corrected luminescence response and to identify aliquots with abnormal behaviour.

In addition to recycling ratio and recuperation, aliquot selection can also consider the equivalent-dose uncertainty and test-dose uncertainty. Equivalent-dose uncertainty refers to the relative error associated with the equivalent dose obtained for a given aliquot, whereas test-dose uncertainty reflects the uncertainty of the test-dose response used for sensitivity correction. Aliquots with high equivalent-dose or test-dose uncertainties may be excluded to ensure that only

measurements with sufficient signal quality are included in the final D_e dataset.

3 Methods

3.1 Field sampling

To investigate the internal architecture of Kolabacken, hand-auger sampling was carried out in a cross-shaped layout centred on the top of the hill (Fig. 2; Fig. 9). The position of each auger borehole was recorded using a handheld GPS receiver (Table 1). Because hand-auger sampling produces disturbed sediment rather than continuous cores, the stratigraphy was assessed based on sediment samples recovered successively from increasing depths at each borehole (Quik et al., 2022). The sampling layout consisted of a short-axis transect, sample series A, with boreholes spaced at 5 m intervals, and a long-axis transect, sample series B, with boreholes spaced at 10 m intervals (Fig. 10). At each auger borehole, the recovered sediment samples were brought to the surface and laid out in depth order on a tarpaulin (Fig. 11). Lithology, colour and sediment texture were then described, and photographs were taken of the complete recovered sediment sequence after each auger hole had been completed.

Table 1. Location and elevation data for auger sampling points at Kolabacken, including sample ID, geographic coordinates, and altitude.

Name	Latitude	Longitude	Altitude / m	Borehole depth / m
A1	55°23'02.61" N	12°49'19.98" E	2.236	1.16
A2	55°23'02.54" N	12°49'20.23" E	3.473	3.63
A3	55°23'02.47" N	12°49'20.45" E	5.331	1.10
A4	55°23'02.40" N	12°49'20.70" E	5.462	1.10
A5	55°23'02.30" N	12°49'20.94" E	5.013	3.94
A6	55°23'02.23" N	12°49'21.19" E	4.890	1.13
A7	55°23'02.16" N	12°49'21.44" E	4.336	1.05
A8	55°23'02.09" N	12°49'21.64" E	4.230	3.83
A9	55°23'02.03" N	12°49'21.86" E	3.881	0.93
A10	55°23'01.96" N	12°49'22.09" E	2.719	2.30
B1	55°23'01.74" N	12°49'20.58" E	1.733	1.73
B2	55°23'01.89" N	12°49'20.64" E	2.625	1.21
B3	55°23'02.03" N	12°49'20.71" E	4.344	3.98
B4	55°23'02.18" N	12°49'20.78" E	5.788	3.97
B5	55°23'02.45" N	12°49'20.97" E	5.635	3.94 (A5)
B6	55°23'02.62" N	12°49'21.12" E	5.630	5.32
B7	55°23'02.80" N	12°49'21.23" E	4.723	4.15
B8	55°23'02.98" N	12°49'21.36" E	4.365	4.23
B9	55°23'03.16" N	12°49'21.48" E	4.064	1.15
B10	55°23'03.35" N	12°49'21.64" E	3.880	1.08

When stratigraphically distinct sediment layers were encountered, samples for OSL dating were collected directly from the auger with minimal exposure to light. After deciding that the next auger section should be sampled for OSL dating, a light-protection sleeve was first placed around the auger. The auger was then lowered into the borehole, and the sleeve was tightened around the auger rod to prevent light from entering the borehole or reaching the auger head. After the auger section was recovered, the auger head was kept inside the sleeve as it was brought out of the borehole. The sleeve and auger head were then transferred into a large light-tight bag. Inside the bag, the sleeve was opened and as much sediment as possible was transferred from the auger head into the bag. The auger and sleeve were then removed while the bag was kept opaqued, and the bag was sealed immediately to keep the sample protected from light.



Fig. 9. Hand Auger sampling at Kolabacken. Photograph by Dan Hammarlund, 29 September 2025.

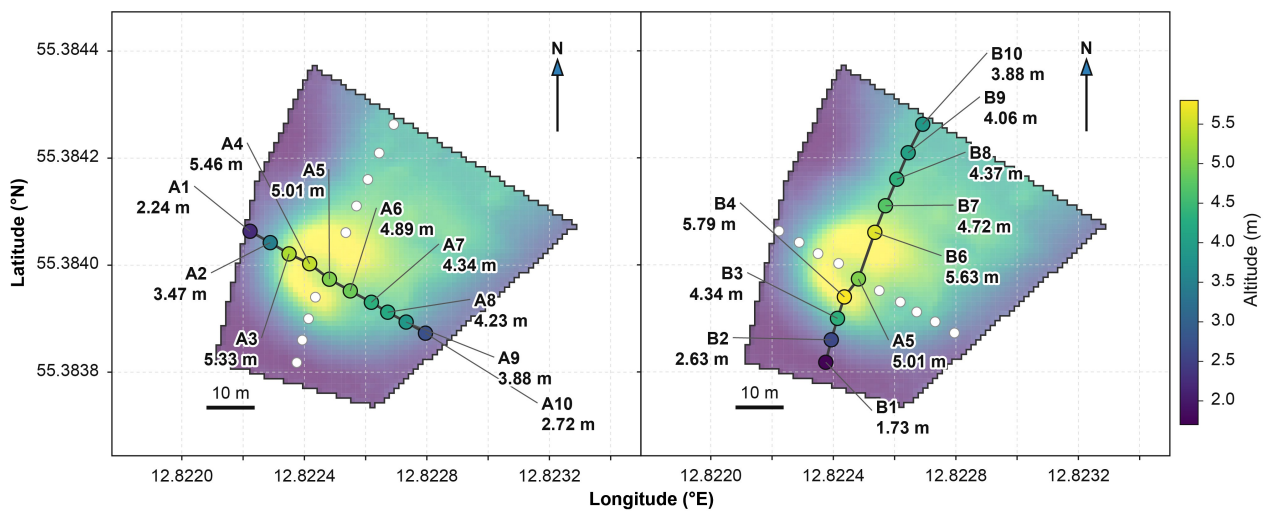


Fig. 10. Digital elevation model (DEM) of Kolabacken showing the auger sampling locations along the two sampling transects.



Fig. 11. Disturbed sediment samples recovered from auger hole A8 and laid out on a tarpaulin in stratigraphic order for field description and photographic documentation. Photograph by Shengliang Dong, 30 September 2025.

In addition, POSL samples were collected from material in the auger head using metal sampling tubes (Fig. 12). After an auger section was recovered, one end of the tube was covered by hand, and the tube was pushed into the sediments held in the auger head. The sediments were then packed into the tube, and both ends of the tube were covered by hand to limit light exposure as much as possible. The tube was immediately wrapped completely in aluminium foil and stored in a bag to keep it dark before later POSL measurements.

Samples for microscopic analysis and radiocarbon dating were selected mainly from dark-coloured units and stored in small plastic bags, while representative sand layers were collected for grain-size analysis. Once all necessary sampling had been completed, the remaining material was backfilled, and the site was restored to its original condition.



Fig. 12. Collection of POSL sample from the hand auger. Photograph by Dan Hammarlund at Kolabacken, 29 September 2025.

3.2 Sedimentary analyses

3.2.1 Microscopic analysis

After the fieldwork, sediment samples stored in small plastic bags were examined under a binocular stereomicroscope at 18-50 $\times$ magnification. The aim of this analysis was to assess the carbonaceous fractions, particularly to distinguish coal from charred wood, and to identify suitable charred wood material for radiocarbon dating (Bird, 2013). In addition, the microscopic examination was used to support the stratigraphic description and to verify the dominant components of the dark sediment layers.

To aid the differentiation between coal and charred wood in the sediment samples, reference materials were also examined. According to historical records, fuel use at Kolabacken changed over time, from an earlier reliance on wood to the later use of coal from the mining district around Helsingborg (L'Estrade, 2002). Reference samples of coal from the Helsingborg mining area and charred wood from Skåne were therefore used as comparative material. Small fragments of these reference samples were submerged in water and examined under the same microscope. Their diagnostic properties, including colour, lustre, hard-

ness, fracture behaviour, and friability, were recorded and compared with the carbonaceous fragments observed in the sediment samples.

Because the original sediment volume and weight could not be measured precisely, and because the exact composition of the wet-sieved residue was difficult to quantify, the sediment proportions were estimated visually. During microscopic observation, white grid paper was placed beneath the sample container, and the relative area occupied by each component was estimated using the grid squares as a guide. Coal and charred wood particles were first distinguished on the basis of morphology and colour, and their hardness and friability were then tested using tweezers. After large sand grains observed under the microscope had been excluded, the relative percentages of the remaining components were recorded in a table. Once the selected samples had been identified and described, samples containing relatively high proportions of charred wood fragments were chosen for further screening. Suitable charred wood fragments were then selected for radiocarbon dating.

3.2.2 Grain-size analysis

All grain-size samples were oven-dried at 105 °C for 24 h before analysis. Grain-size analysis was carried out on samples from auger holes B6 and B7 to characterize changes in sediment texture with depth. The samples were analysed by dry sieving using a vibratory sieve shaker, which separates sediment into predefined size fractions. For B6, seven samples were analysed from depths of 80, 202, 303, 360, 420, 479, and 532 cm, whereas for B7, nine samples were analysed from depths of 30, 80, 125, 153, 182, 217, 306, 365, and 415 cm. After drying, each sample was weighed and then passed through a stack of sieves with mesh sizes of 4.0, 2.8, 2.0, 1.4, 1.0, 0.710, 0.500, 0.350, 0.250, 0.180, 0.125, 0.090, and 0.063 mm. The material retained on each sieve was weighed after sieving, and the pan fraction of <0.063 mm was also collected. The sum of all retained fractions was used to check mass recovery by comparing the total post-sieving fraction weight with the initial dry sample weight.

For each sample, the weight of each size fraction was converted to a percentage of the total recovered sample weight. The grain-size distribution was then described using d₁₀, d₅₀, d₉₀, geometric mean, arithmetic mean, standard deviation and sigma log. The d₁₀, d₅₀ and d₉₀ values represent the grain sizes below which 10%, 50% and 90% of the sample material is finer, respectively. The arithmetic mean was used to describe the average grain size calculated across all size fractions, whereas the geometric mean was used to describe the central grain size on a logarithmic scale. Standard deviation was used to describe the spread of grain sizes around the mean, and sigma log was used to describe the spread of the grain-size distribution in logarithmic space.

3.3 Age determination

3.3.1 Luminescence profiling

The samples collected in tubes were used for luminescence profiling. First, all the tubes and samples were transferred to the darkroom for pre-treatment. Potentially light-exposed material from both ends of each tube was removed, and the remaining unexposed material was oven-dried at 30°C for 24 h, dry-sieved to <1 mm, and 5.00 g of each sample was placed in a petri dish for analysis (Sanderson & Murphy, 2010).

POSL measurements were carried out using a SU-ERC portable OSL reader following the CW-proxies protocol (Munyikwa et al., 2020; Sanderson & Murphy, 2010). For each sample, both infrared-stimulated (IR) and blue-stimulated (Blue) luminescence signals were recorded. Before sample measurement, an empty container was measured to determine the background signal, and measurements were only carried out when the background values were within acceptable limits (IR <200 counts; Blue <400 counts). The prepared sediment samples were then measured systematically. To monitor instrument stability and background conditions, an empty container was re-measured after every ten samples (Sanderson & Murphy, 2010).

3.3.2 Luminescence dating

Sediment samples collected for luminescence dating were transported to the Lund Luminescence Laboratory (LLL) and processed in the darkroom with red-light conditions to prevent unconscious signal resetting. The samples were registered as 25163-25175 and 25198 according to the LLL lab code assignment. All the sample preparations strictly followed established protocols as described below.

To separate the required grain-size fractions for analysis, each sediment sample was transferred to a 100 ml beaker and processed in an automated wet-sieving machine. Five different sieve meshes were used: 355, 250, 180, 90 and 63 μm . Each sample was processed for 10 minutes under pulse vibration with water flow to ensure the separation of the fractions.

After sieving, subsamples from different meshes were collected in separate containers and dried at 30°C until completely dry.

Among the separated fractions, the 180–250 μm fraction was selected for further luminescence sample preparation and measurement. This fraction was chosen for both practical and sedimentological reasons. First, it was sufficiently abundant in most samples and was relatively easy to handle during the following chemical pre-treatment steps, as the grains settled rapidly during washing and chemical reaction. Second, the 180–250 μm fraction represents the fine to medium sand component of the deposits, which is suitable for quartz OSL dating and is likely to have experienced better light exposure during aeolian or shallow coastal transport than finer particles transported in suspension (RITTENOUR, 2008). In addition, the samples contained a considerable amount of coal and charred wood fragments, which needed to be removed during pre-treatment. Microscopic inspection of the sieved fractions showed that the 63–90 μm fraction contained abundant black charred wood particles, which were difficult to remove during chemical pre-treatment. The 180–250 μm fraction therefore provided a better balance between sample abundance, sedimentological representativeness, bleaching potential and practical laboratory preparation.

Following grain-size separation, the 180–250 μm fraction was selected for quartz OSL preparation before the IR test, preheat plateau test, dose recovery test, and final equivalent-dose estimation. The chemical pretreatment followed the procedure illustrated in Fig. 15. Carbonates and organic matter were first removed, after which quartz grains were isolated by density separation. The quartz-rich fraction was then etched with HF to remove the outer alpha-irradiated layer of the grains and to dissolve remaining mineral impurities. HCl was subsequently used to remove any fluoride precipitates formed during HF treatment. The samples were then rinsed, dried, and further purified by magnetic separation. Finally, the prepared quartz fractions were labelled and stored in the darkroom until measurement.

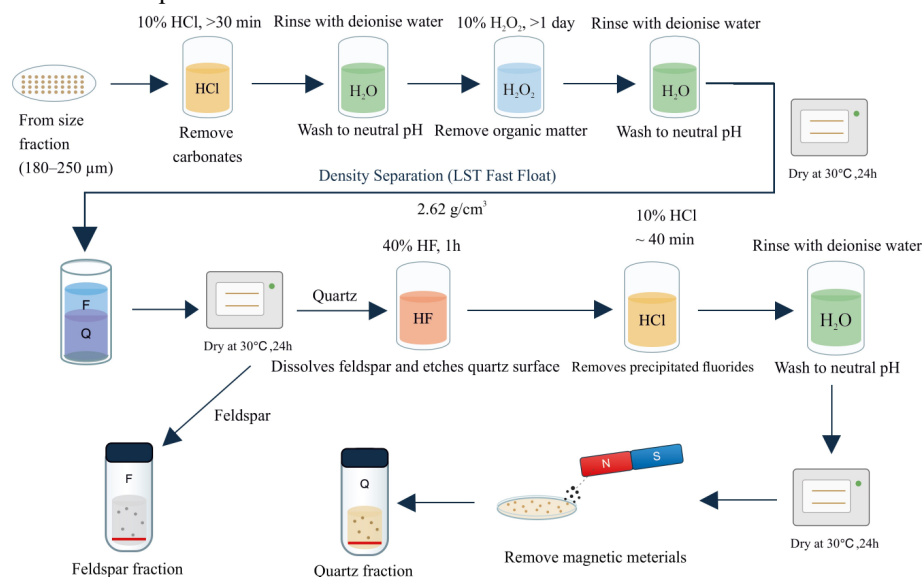


Fig. 13. Pretreatment procedure for quartz extraction prior to OSL measurement. The figure was redrawn and modified based on the laboratory procedure and the schematic workflow presented in (Murray et al., 2021).

Following sample pretreatment, all the OSL measurements were performed using a Risø TL/OSL DA-22 reader and the purified quartz grains were mounted as 2 mm aliquots on stainless-steel discs for analysis.

First, an infrared (IR) test was conducted to check the purity of the extracted quartz fraction. Samples with an IR/Blue ratio above 10% were further purified by repeated density separation and additional HF etching. The measurement sequence and settings used for the IR test are presented in Fig. 14.

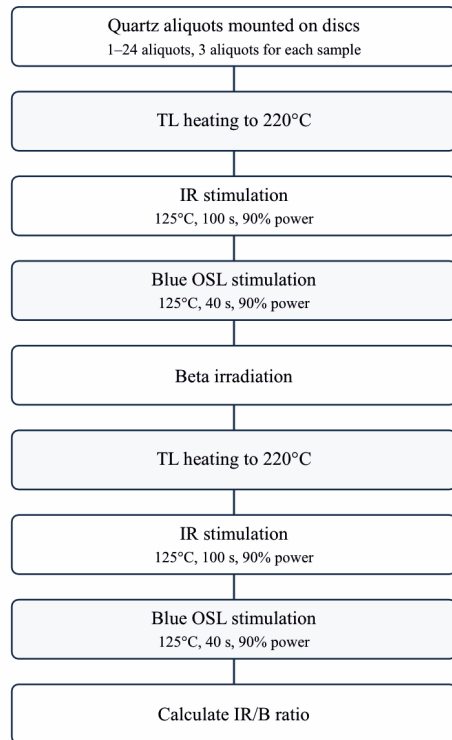


Fig. 14. Generalized procedure for IR test.

The next step was the preheat plateau test. Sample 25168 was selected for this test because it showed the best IR test result among the measured samples, with an IR/B ratio of only 0.78%, indicating a low level of feldspar contamination. This sample was taken from 292 cm depth in auger hole B6, immediately below the black coal-rich layer. Its stratigraphic position is closely related to one of the main sedimentary units investigated in this study and provides a good link between the luminescence measurements and the observed lithological sequence. This sample was therefore considered a suitable quartz-rich sample for testing the SAR measurement settings. Repeated SAR measurements were carried out on quartz aliquots from this sample using different preheat temperatures. The final preheat and cutheat conditions were selected from the temperature interval where D_e values remained stable and the SAR performance indicators stayed within acceptable limits. The measurement sequence and settings are presented in Fig. 15.

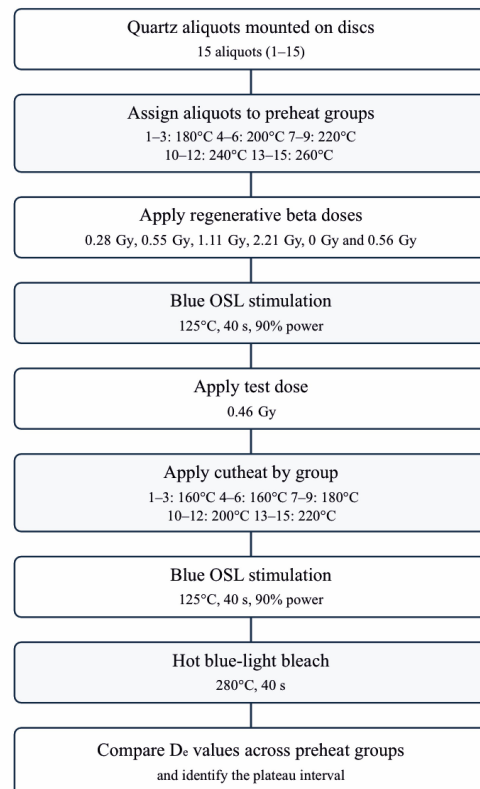


Fig. 15. Generalized procedure for preheat plateau test.

A dose recovery test was carried out in two stages before final equivalent dose determination. First, sample 25168 was used to test dose recovery under different preheat conditions, in order to support selection of the final SAR settings (Fig. 16, stage 1). A second dose-recovery test was then performed on aliquots from all samples using the selected protocol, to check whether a known laboratory dose could be reproduced consistently across the sample set (Fig. 16, Stage 2).

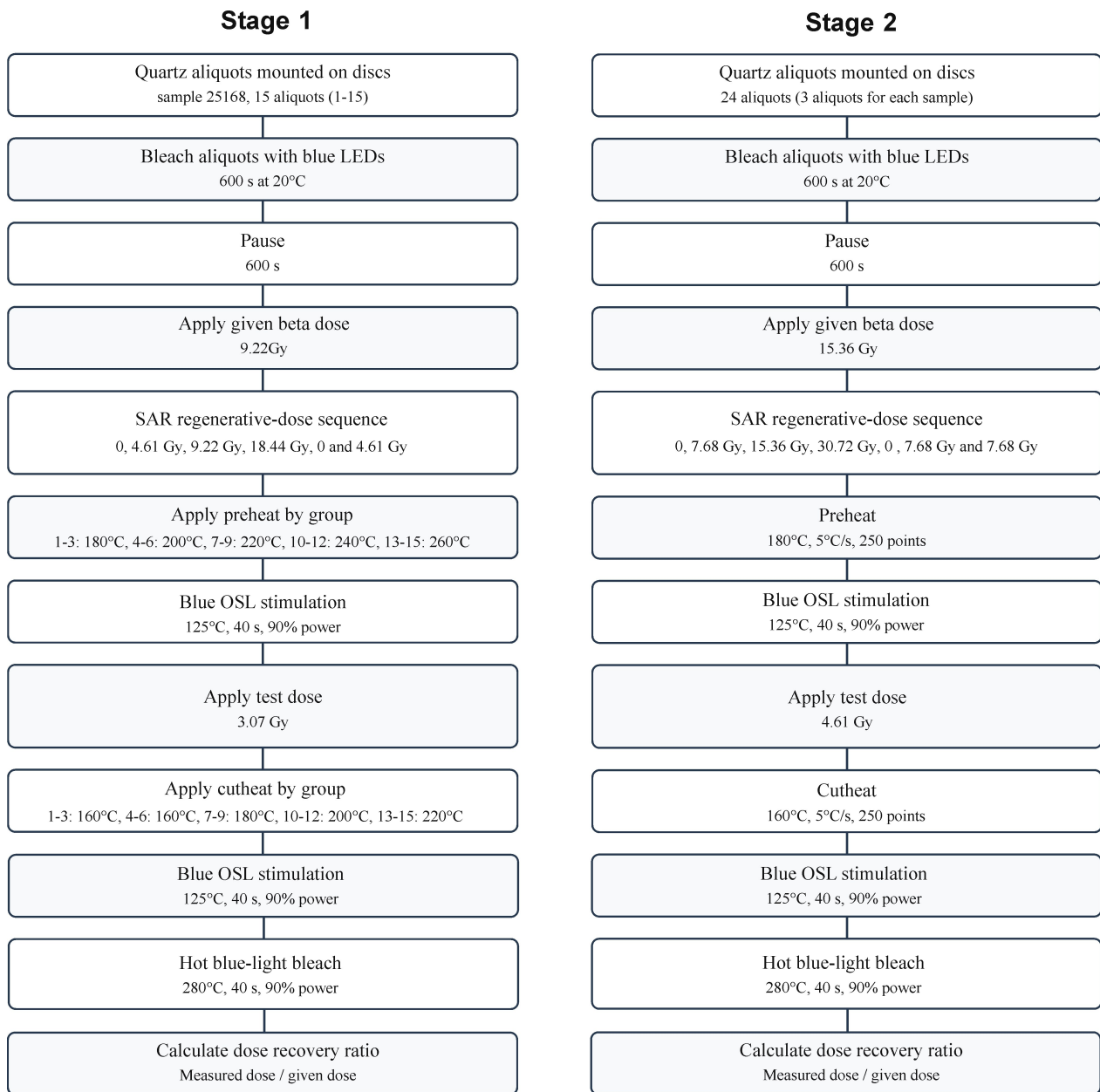


Fig. 16. Generalized procedure for dose recovery test.

For dose estimate, all samples were measured using the SAR sequence shown in Fig. 17. The measurement sequence included the natural OSL signal, a series of regenerative beta doses, and test-dose measurements for sensitivity correction. The final equivalent dose was calculated from the sensitivity-corrected dose-response curve. Fig. 18 shows the aliquots on discs in the OSL reader.

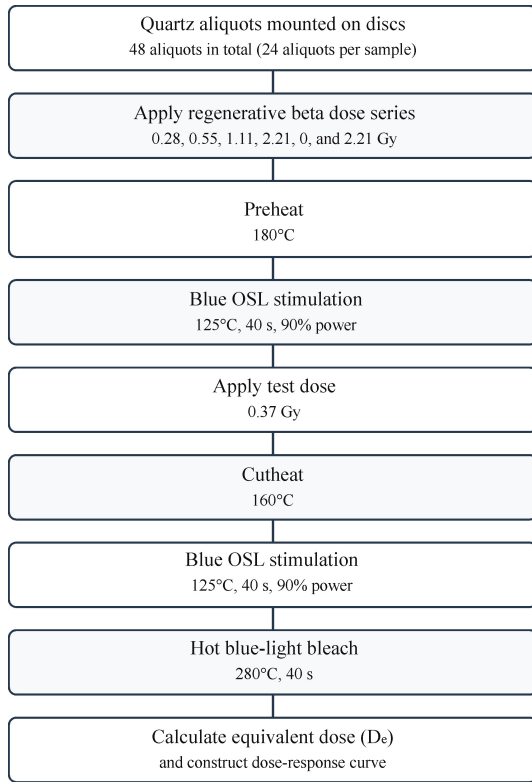


Fig. 17. Generalized procedure for dose estimate.

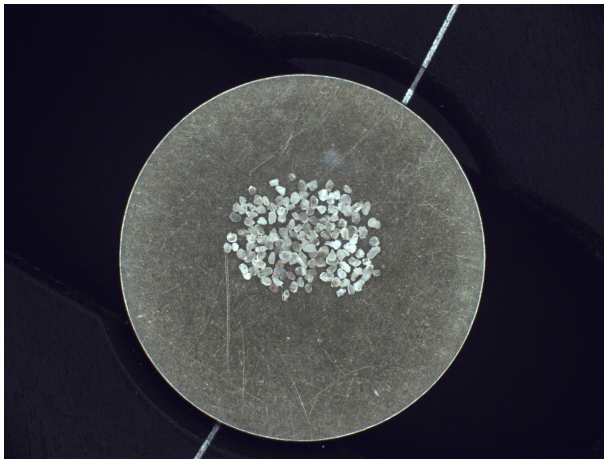


Fig. 18. Prepared quartz aliquot from sample 25175 for equivalent-dose measurement.

Accepted aliquot D_e values were analysed using the R package Luminescence (Kreutzer et al., 2012). Both the central age model (CAM) and three-parameter minimum age model (MAM-3) were calculated for each sample (Galbraith & Roberts, 2012; Galbraith et al., 1999). Model selection was based on the structure of the D_e distribution, including KDE and Abanico plots, skewness, scatter and sedimentological context. CAM was used where the accepted aliquots formed a relatively compact or broadly symmetrical distribution and where no clearly separated low-dose population could be identified. MAM-3 was applied where the D_e distributions showed positive skewness or a distinct high-dose tail, suggesting that some ali-

quots may have retained residual signal before burial. In these cases, MAM-3 was considered more appropriate because it estimates the lower-dose population that is most likely to represent the best-bleached grains and the final burial event. For samples without clear evidence of partial bleaching or a sedimentologically meaningful low-dose component, CAM was used because applying MAM-3 could underestimate the burial age.

The environmental dose rate was determined from the natural radioactivity of the sediment surrounding each OSL sample. Environment dose rate subsamples were dried and ground using a ball mill, then mixed to ensure uniformity before being measured using the μ DOSE system (Tudyka et al., 2018).

After equivalent-dose determination, the environmental dose rate and the water content of the original sediment samples were determined in order to calculate the final OSL ages. Water content measurement was carried out to estimate both the natural water content at the time of sampling and the maximum possible (saturated) water content of the sediment. A subsample from each sediment sample was first weighed in its container to obtain the field sample weight (S_n). Water was then carefully added until the sediment was fully covered, and the sample was left for at least 24 hours to allow complete infiltration of the pore spaces. After excess water had been poured off and the sediment reached saturated conditions, the sample was weighed again to obtain the saturated sample weight (S_s). The subsample was then dried in an oven at 105°C for 24 hours and weighed again to obtain the dry sample weight (S_d). Using the tare weight of the container (t), the natural water content (W_n), and the saturated water content (W_s) were calculated as (2) and (3):

$$W_n = \frac{S_n - S_d}{S_d - t} \quad (2)$$

$$W_s = \frac{S_s - S_d}{S_d - t} \quad (3)$$

The total environmental dose rate and final OSL ages were calculated using DRAC v1.3 (Durcan et al., 2015). For each sample, the U, Th and K concentrations measured with the μ Dose system were entered together with the selected long-term water content, sample depth, grain-size fraction, HF etching information, altitude, latitude and longitude. The corrected total environmental dose rate for each sample was obtained from DRAC v1.3 (Guérin et al., 2011; Prescott & Hutton, 1994). The final OSL age was calculated by dividing the selected equivalent dose (D_e) by this total environmental dose rate.

3.3.3 Radiocarbon dating

Following the microscopic analysis, all samples identified as charred wood were separated and re-examined. Based on sample preservation, fragment size, sampling depth, and stratigraphic comparison with the OSL sample positions, nine samples were selected for radiocarbon dating. Before measurement, the charred wood samples were pretreated with HCl and NaOH, except for sample LuS 21357, which was treated with HCl only. Sample weights and the main pretreatment steps are presented in Table 2.

The radiocarbon analyses were carried out at the Lund University Radiocarbon Dating Laboratory. The resulting radiocarbon dates were subsequently calibrated and incorporated into the age-depth model using OxCal v4.4.4 (Ramsey, 2009a, 2009b) and the IntCal20 radiocarbon calibration dataset (Reimer et al., 2020).

Table 2. Details of the samples selected for radiocarbon dating.

Sample ID	Lab Number	Sample Weight (mg)	Pretreatment
A8_220 cm	Lus 21357	1.6	HCl
B6_495 cm	Lus 21358	1.6	HCl, NaOH
B6_410 cm	Lus 21359	1.7	HCl, NaOH
B6_303 cm	Lus 21360	0.9	HCl, NaOH
B7_380 cm	Lus 21361	1.4	HCl, NaOH
B7_250 cm	Lus 21362	1.5	HCl, NaOH
B8_400 cm	Lus 21363	1.3	HCl, NaOH
B8_371 cm	Lus 21364	1.5	HCl, NaOH
B8_325 cm	Lus 21365	1.5	HCl, NaOH

4 Results

4.1 Sedimentology and stratigraphy

After summarizing the field records and inspecting the collected samples in the laboratory, the sediments were grouped into six lithological units based on sediment composition, texture, colour and other visible sedimentological features. From bottom to top, these units were identified: Unit 1: Brown sand; Unit 2: Grey sand with charred wood and brick fragments; Unit 3: Black sand with coal particles; Unit 4: Yellowish white sand; Unit 5: Grey sand with burnt coal; Unit 6: Whitish grey sand. The sampling locations and lithological distribution are shown in Fig. 19, and the cross-section diagrams are shown in Fig. 20. Grain-size distribution plots were produced for all measured grain-size samples and are presented in Appendix 1. In the unit descriptions below, only the summarized grain-size characteristics are included.

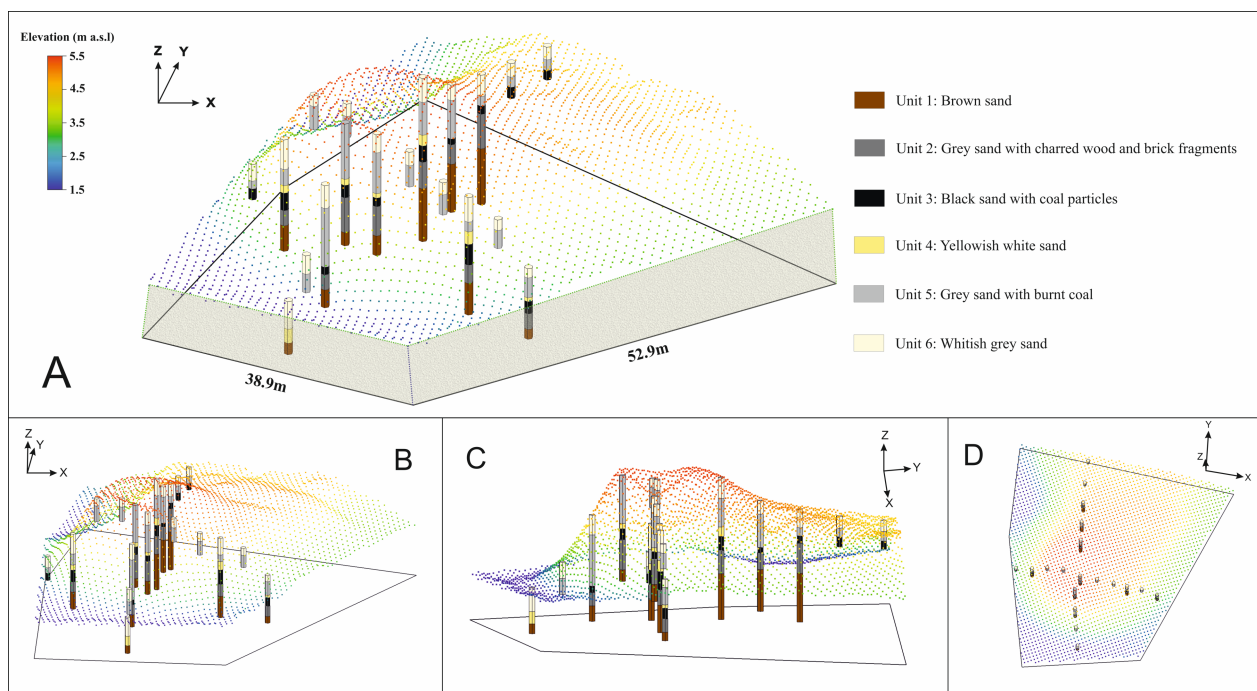


Fig. 19. Three-dimensional model of stratigraphy based on auger-hole observation at Kolabacken. A: the 3D stratigraphic model with interpreted sediment units. B-D: the same model from three different view angles to illustrate the spatial relationship between the auger holes and stratigraphic units. The point grid is based on DEM data from Lantmäteriet. The 3D auger-hole model and DEM data calculation were made by Groundwater Modeling System 10.4 and ArcGIS Pro 3.6.3.

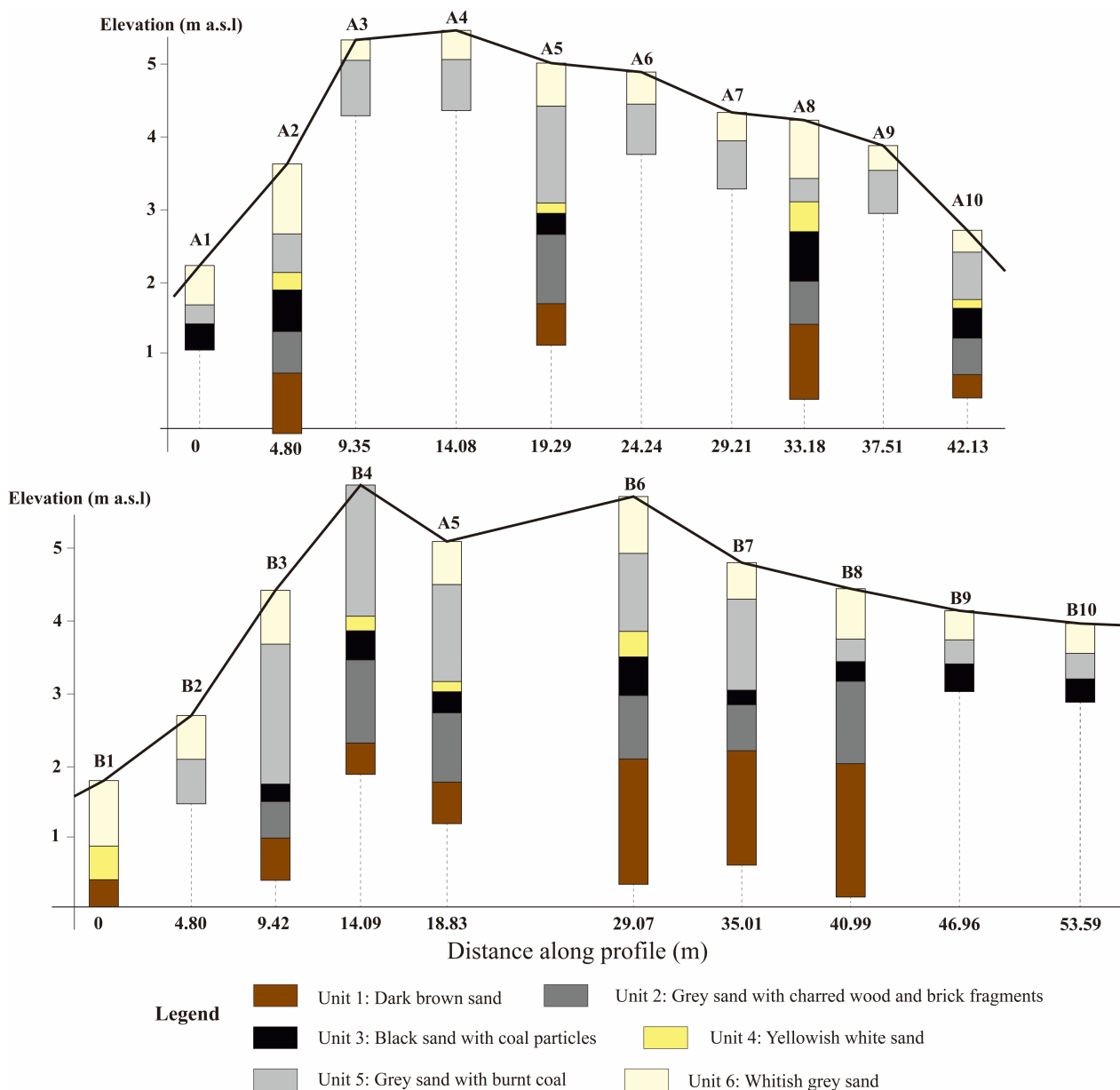


Fig. 20. Sedimentological cross-section of Kolabacken. The lithological sequence is based on borehole observations. Borehole positions are plotted by distance along the profile, and the vertical axis shows elevation in meters above sea level. A shows the short-axis profile through auger holes A1-A10, whereas B shows the long-axis profile through auger holes B1-B10, with A5 included because this position was used as the corresponding point on the B profile.

Unit 1: Brown sand. This unit is the lowermost sediment unit at Kolabacken. The unit is brown in colour (Fig. 21) and generally becomes darker with increasing depth. It consists mainly of dark brown sand with small amounts of charred wood fragments. Close to the groundwater level, the sediment water content increased markedly, and at these depths it became difficult to continue sampling with the hand auger. A peat fragment was found at the bottom of borehole A8; this material was collected and later used for radiocarbon dating.

Grain-size analysis of Unit 1 is based on seven samples from boreholes B6 and B7. The unit consists mainly of medium sand, with the 0.25-0.50 mm fraction forming the dominant part of the distribution. The median grain size is 0.283 mm. The grain-size curve shows a moderate spread, with only limited fine mate-

rial and a small coarse component. (Fig. 22).



Fig. 21. Material from Unit 1: Brown sand. Sample position: A8, 350 cm.

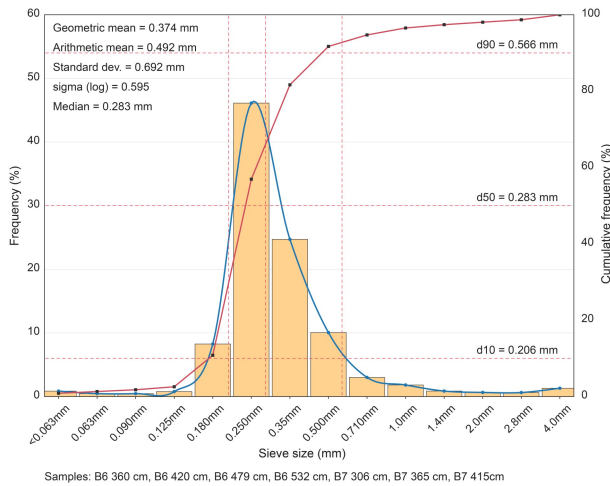


Fig. 22. Average grain-size distribution of Unit 1. The orange bars show the mean frequency of each sieve-size fraction for Unit 1. The blue curve represents the fitted grain-size distribution, and the red curve shows the cumulative frequency. Red dash lines indicate the d10, d50 and d90 values.

Unit 2: Grey sand with charred wood and brick fragments. Unit 2 is grey in colour and contains black fragments (Fig. 23 and Fig. 24). The unit was recorded thicknesses ranging from 0.50 to 1.14 m in the auger holes. Its average observed thickness is approximately 0.76 m. In the central part of the hill, red brick fragments were also found in this unit. Two grain-size samples from B6 and B7 were analysed for Unit 2 (Fig. 25). The distribution is concentrated in the fine-to medium-sand range, with a median grain size of 0.245 mm. Coarse material is limited, giving the unit a relatively narrow grain-size distribution.



Fig. 23. Material from Unit 2: Grey sand with charred wood and brick fragments. This picture shows the grey sand and charred wood part. Sample position: B3, 290 cm.



Fig. 24. Material from Unit 2: Grey sand with charred wood and brick fragments. Sample position: B3, 312 cm.

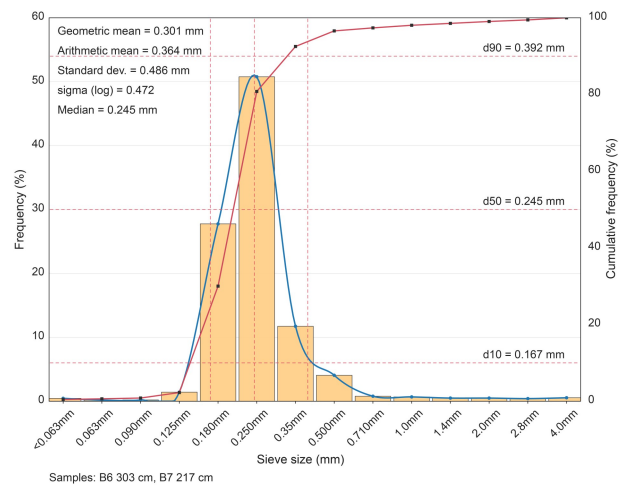


Fig. 25. Average grain-size distribution of Unit 2. The orange bars show the mean frequency of each sieve-size fraction for Unit 2. The blue curve represents the fitted grain-size distribution, and the red curve shows the cumulative frequency. Red dash lines indicate the d10, d50 and d90 values.

Unit 3: Black sand with coal particles. This unit is black colour and contains hard black fragments, interpreted in the field as coal particles (Fig. 26). For Unit 3, the grain-size result is based on one sample from B7 (Fig. 27). Although the median grain size is still within the medium-sand range, the distribution is broader than in most other units and has a clear coarse tail. This is reflected by the higher d90 value and the larger proportion of material above 2 mm.



Fig. 26. Material from Unit 3: Black sand with coal particles. Sample position: A5, 201 cm.

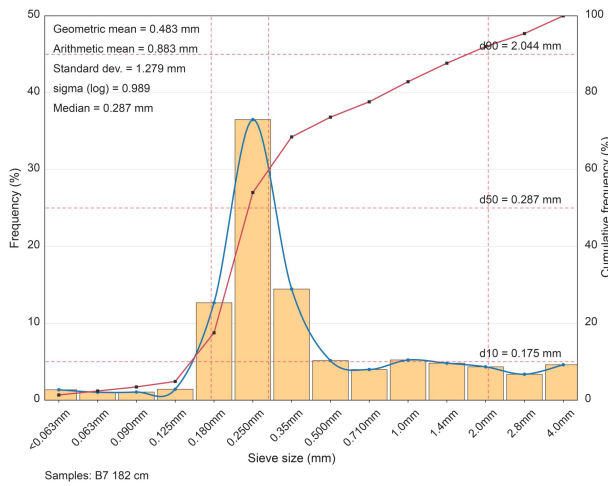


Fig. 27. Average grain-size distribution of Unit 3. The orange bars show the mean frequency of each sieve-size fraction for Unit 3. The blue curve represents the fitted grain-size distribution, and the red curve shows the cumulative frequency. Red dash lines indicate the d10, d50 and d90 values.

Unit 4. Yellowish white sand. Unit 4 consists mainly of light yellow to whitish sand with a fine texture and little visible mixed material (Fig. 28). Its observed thickness ranges from 0.12 to 0.46 m, with an average thickness of about 0.27 m. This unit was mainly found in boreholes near the top of the mound and from the southern and eastern slopes. The analysed sample from Unit 4 (Fig. 29) shows a grain-size distribution dominated by fine- to medium sand. The median grain size is 0.248 mm, and the coarse fraction is small. The distribution is relatively narrow compared with the darker units that contain more coarse fragments.



Fig. 28. Material from Unit 4: Yellowish white sand. Sample position: A2, 173 cm.

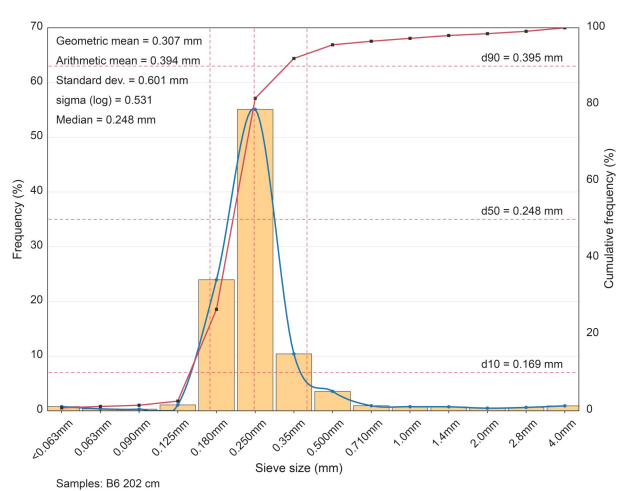


Fig. 29. Average grain-size distribution of Unit 4. The orange bars show the mean frequency of each sieve-size fraction for Unit 4. The blue curve represents the fitted grain-size distribution, and the red curve shows the cumulative frequency. Red dash lines indicate the d10, d50 and d90 values.

Unit 5: Grey sand with burnt coal. Unit 5 occurs below the upper whitish grey sand and its observed thickness ranges from 0.26 to 1.92 m, with an average thickness of 0.79 m. Compared with the overlying unit, Unit 5 is darker in colour and appears grey to dark grey. The unit is still mainly composed of sand but contains abundant burnt coal fragments (Fig. 30). Some black fragments show no clear signs of burning, whereas others are partly burnt and have grey or whitish edges.



Fig. 30. Material from Unit 5: Grey sand with burnt coal. Sample position: A8, 112 cm.

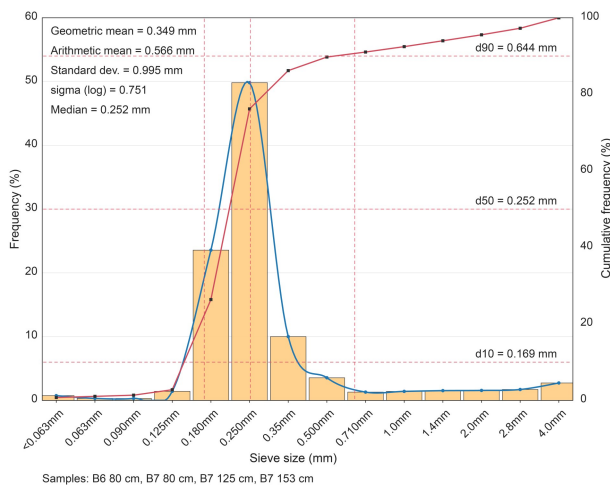


Fig. 31. Average grain-size distribution of Unit 5. The orange bars show the mean frequency of each sieve-size fraction for Unit 5. The blue curve represents the fitted grain-size distribution, and the red curve shows the cumulative frequency. Red dash lines indicate the d10, d50 and d90 values.

Unit 6: Whitish grey sand. Unit 6 forms the uppermost sediment unit and is less than about 1 meter thick in most parts of the hill. It represents the surface sand layer between Kolabacken. The sand is light grey to white in colour and has a fine, soft texture (Fig. 32). The grain-size of unit 6 is represented by one grain-size sample from B7 (Fig. 33). The sample is dominated by fine- to medium sand, with a median grain size of 0.250 mm. The coarse fraction is small, and the distribution is concentrated mainly around the 0.25-0.50 mm fraction.



Fig. 32. Material from Unit 6: Whitish grey sand. Sample position: A10, 30 cm.

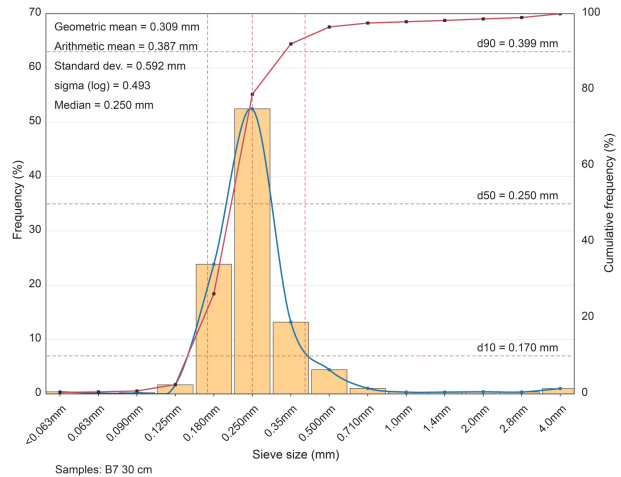


Fig. 33. Average grain-size distribution of Unit 6. The orange bars show the mean frequency of each sieve-size fraction for Unit 6. The blue curve represents the fitted grain-size distribution, and the red curve shows the cumulative frequency. Red dash lines indicate the d10, d50 and d90 values.

4.2 Microscopic analysis

Based on microscopic analysis of selected samples, the main components of the sediments of Kolabacken were classified into the following categories:

1. Coal (Fig. 34-a)
2. Coal slag (burnt coal) (Fig. 34-b)
3. Charred wood (Fig. 34-c)
4. Brick fragments (Fig. 34-d)
5. Peat fragments with plant remains (Fig. 34-e)
6. Other materials (bone fragments, etc.) (Fig. 34-f)

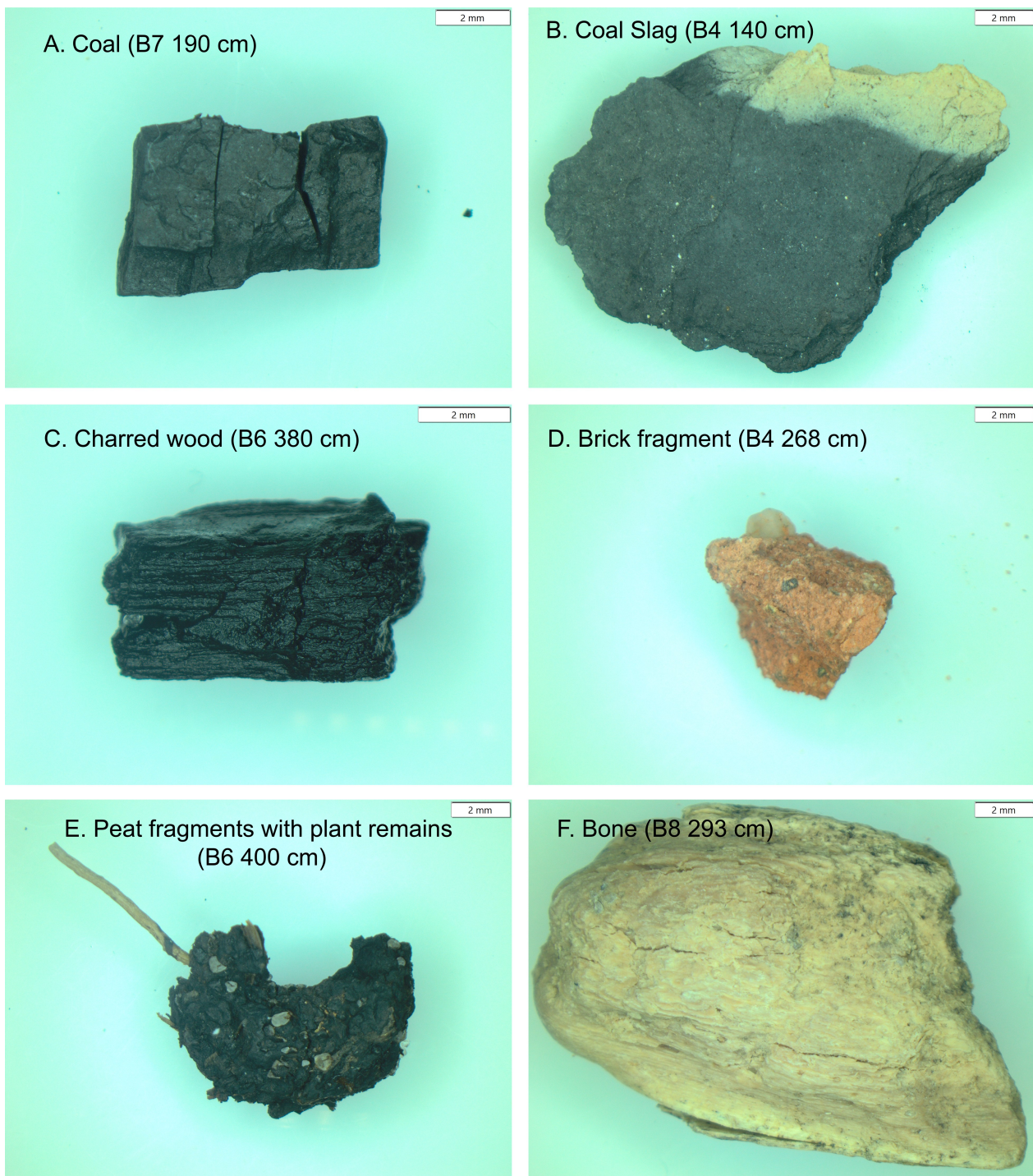


Fig. 34. Microscopic examples of sediment components identified in the Kolabacken samples. **A.** Coal fragment from B7 at 190 cm depth. **B.** Coal slag or burnt coal from B4 at 140 cm depth. **C.** Fragment of charred wood from B6 at 380 cm depth. **D.** Orange brick fragment from B4 at 268 cm depth. **E.** Peat fragment with plant remains from B6 at 400 cm depth. **F.** Bone fragment from B8 at 293 cm depth. Scale bars are 2 mm.

4.3 Chronology

4.3.1 Luminescence profiling

Fig. 35 presents the portable OSL profiles from boreholes B6 and B7, which were selected to illustrate the main down-core patterns in the luminescence signals.

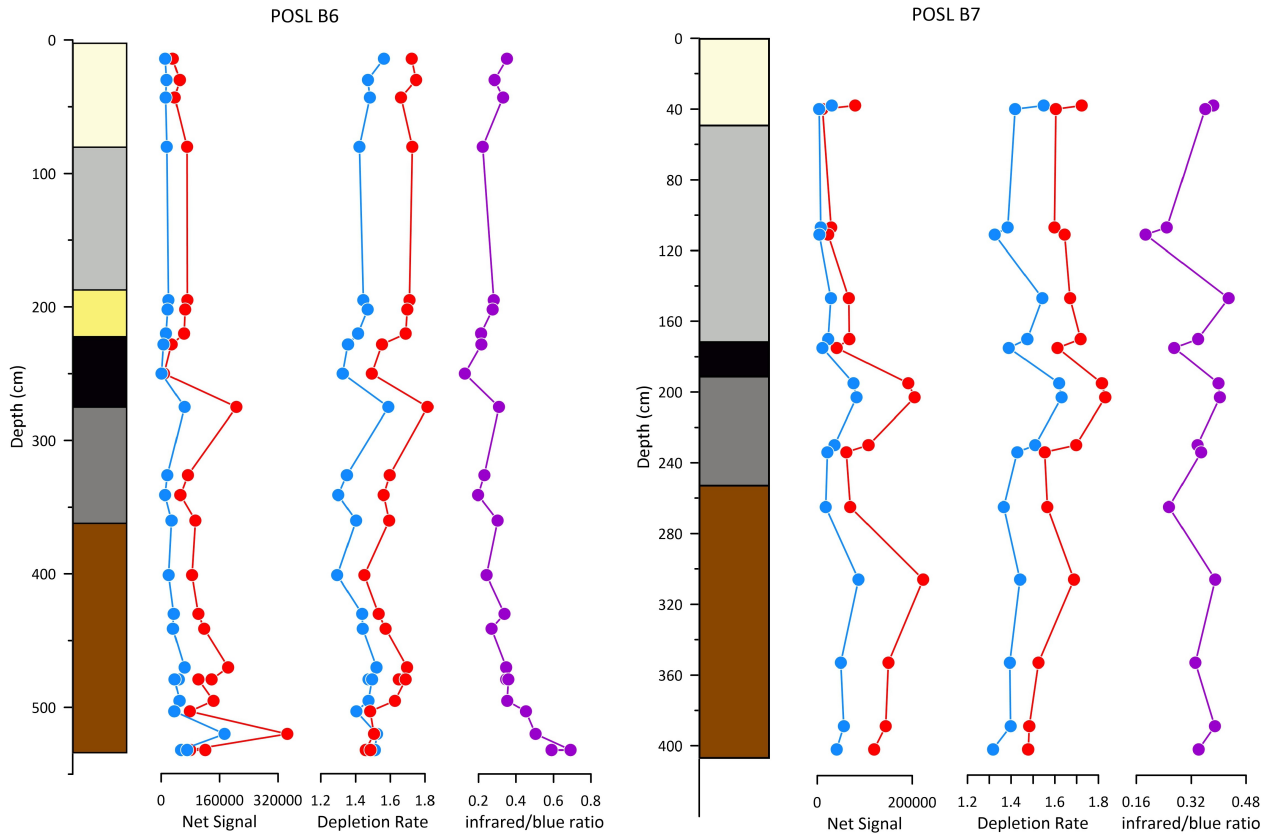


Fig. 35. Portable OSL profiles from boreholes B6 and B7 at Kolabacken plotted against depth. The figure shows down-core variations in the blue-stimulated net signal, IR-stimulated net signal, depletion ratio and IR/Blue ratio. The red line represents the blue-stimulated POSL signal, and the blue line represents the IR-stimulated signal. Depth is shown in centimetres, and each panel represents one borehole.

4.3.2 OSL data quality control

4.3.2.1 IR test

The first quality-control step was the IR test. The results are shown in Table 3. Only a few measurements exceeded the 10% rejection threshold. Therefore, these samples were considered acceptable, and the batch was retained for further measurement and analysis.

Table 3. The results of IR test of OSL samples.

Sample No.	IR/B Ratio	Sample No.	IR/B Ratio
25162	3.1%	25170	0.6%
25163	6.3%	25171	0.4%
25164	2.2%	25172	1.0%
25165	6.2%	25173	2.6%
25166	6.7%	25174	1.5%
25167	8.7%	25175	13.9%
25168	0.8%	25198	3.7%
25169	4.0%		

4.3.2.2 Preheat plateau test

For sample 25168, the equivalent-dose estimates vary with preheat temperature rather than forming a clear plateau. The mean D_e is lowest at 180 °C (0.18 Gy), increases at 200–220 °C (0.55–0.57 Gy), reaches a maximum at 240 °C (0.93 Gy), and then decreases at 260 °C (0.67 Gy). The accepted aliquots are also scat-

tered across most temperature groups, so the preheat test alone does not identify a single stable temperature interval. It was therefore evaluated together with the dose-recovery results (Fig. 36).

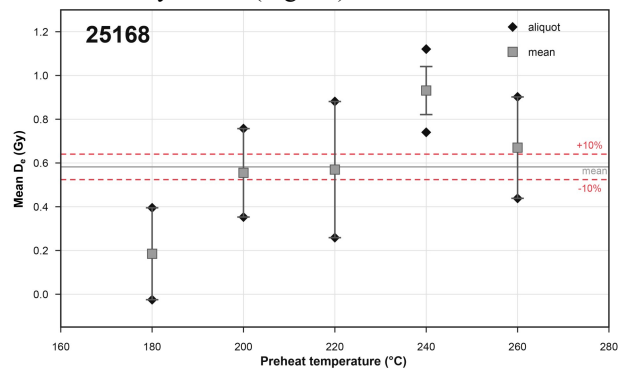


Fig.36. Preheat plateau test results for sample 25168. Black diamonds represent accepted aliquots, and grey squares represent the mean values.

4.3.2.3 Dose recovery tests

No clear systematic trend in dose recovery ratio is observed across the temperature range for sample 25168, but the 240°C group shows a slightly lower mean value than the other temperature groups (Fig. 37). Based on these results, 180°C was selected for the final SAR protocol because it produced ratios close to unity while using the lowest tested preheat temperature, thereby reducing the risk of thermally induced signal transfer or sensitivity change during measurement.

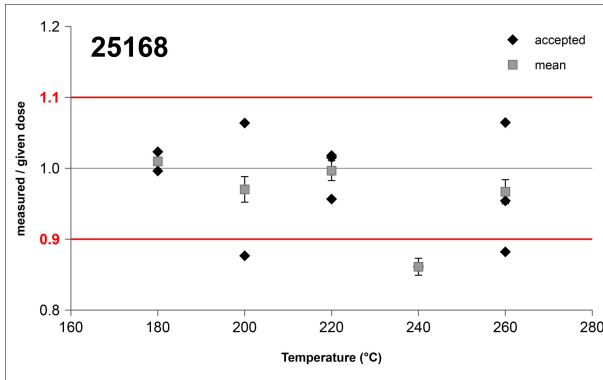


Fig. 37. Dose recovery test results for sample 25168 measured using different preheat temperatures. Black diamonds represent accepted aliquots and grey squares represent the mean values. The red horizontal lines indicate the acceptable range of 0.9–1.1.

these outliers do not dominate the dataset and were considered during subsequent aliquot quality control (Fig. 38).

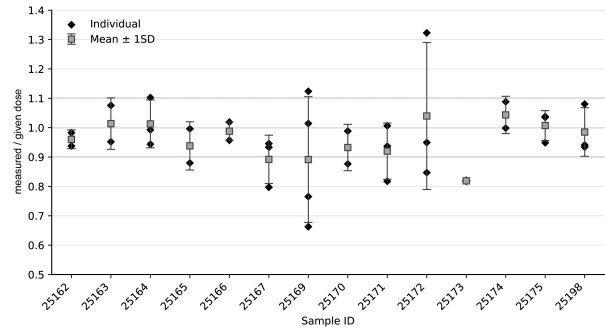


Fig. 38. Dose recovery test results for the OSL samples measured using the selected SAR protocol. The red horizontal lines indicate the accepted range of 0.9–1.1.

4.3.3 OSL ages

4.3.3.1 Environmental dose rate

The radionuclide concentrations for the OSL samples are presented in Table 4.

4.3.3.2 Dose estimates

Equivalent dose estimates were obtained for 15 OSL samples from Kolabacken. In total, 681 aliquots were measured, of which 270 aliquots were accepted after quality-control screening. The overall acceptance rate is approximately 40%. The equivalent doses range from 0.28 ± 0.02 Gy to 1.26 ± 0.07 Gy, indicating gen-

Table 4. The result of the concentrations of uranium, thorium and potassium measured by μ DOSE system and the cosmic dose rate from DRAC v1.3.

Sample ID	U-238 (ppm)	Th-232 (ppm)	K-40 (%)	Cosmic dose rate (Gy / ka)
25162	0.311 ± 0.187	2.716 ± 0.600	1.373 ± 0.056	0.144 ± 0.014
25163	0.494 ± 0.282	4.461 ± 0.918	1.658 ± 0.064	0.147 ± 0.015
25164	0.351 ± 0.275	2.501 ± 0.884	0.960 ± 0.057	0.168 ± 0.017
25165	0.483 ± 0.240	1.783 ± 0.766	1.447 ± 0.061	0.197 ± 0.02
25166	1.338 ± 0.361	6.551 ± 1.173	1.336 ± 0.064	0.164 ± 0.016
25167	0.330 ± 0.279	8.569 ± 0.917	1.415 ± 0.060	0.122 ± 0.012
25168	0.217 ± 0.232	2.412 ± 0.746	1.474 ± 0.059	0.147 ± 0.015
25169	0.000 ± 0.224	1.944 ± 0.724	1.364 ± 0.061	0.161 ± 0.016
25170	0.081 ± 0.246	3.167 ± 0.801	1.451 ± 0.060	0.163 ± 0.016
25171	0.519 ± 0.245	4.551 ± 0.795	1.160 ± 0.056	0.18 ± 0.018
25172	0.847 ± 0.272	3.154 ± 0.874	1.481 ± 0.062	0.128 ± 0.013
25173	0.437 ± 0.218	4.382 ± 0.701	1.444 ± 0.058	0.155 ± 0.016
25174	0.485 ± 0.228	1.050 ± 0.718	1.415 ± 0.061	0.149 ± 0.015
25175	0.224 ± 0.266	3.328 ± 0.865	1.745 ± 0.064	0.136 ± 0.014
25198	0.503 ± 0.255	4.222 ± 0.830	1.372 ± 0.061	0.156 ± 0.016

The dose-recovery ratios obtained with the selected SAR protocol range from 0.66 to 1.32, with an overall mean of 0.96 ± 0.12 . Most aliquots are close to unity, indicating that the protocol generally recovered the given laboratory dose well. A small number of aliquots deviate more strongly from the expected value, but

erally low D_e values and young burial ages for the analysed sediments (Table 5).

Table 5. Equivalent dose estimates, age-model results and OSL age estimates for the Kolabacken samples.

Sample ID	Stratigraphic Unit	Age (CE)	Age Model	p Value	Accepted aliquots	Dose (Gy)	Relative Standard Error D _e (%)	Skewness (c)	Dose rate (Gy/ka)	Water Content (%)
25162	Unit 2	1190 ± 60	CAM	/	22/47	1.26 ± 0.07	6%	0.89	1.50 ± 0.08	15 ± 5
25163	Unit 2	1430 ± 50	CAM	/	16/32	1.11 ± 0.08	8%	-0.47	1.88 ± 0.10	15 ± 5
25164	Unit 5	1660 ± 30	CAM	/	29/48	0.43 ± 0.02	4%	0.70	1.18 ± 0.08	15 ± 5
25165	Unit 5	1810 ± 20	MAM-3	0.47	16/56	0.36 ± 0.03	9%	0.52	1.67 ± 0.09	10 ± 5
25166	Unit 4	1740 ± 20	CAM	/	17/30	0.55 ± 0.03	5%	0.59	1.91 ± 0.11	15 ± 5
25167	Unit 1	1480 ± 50	MAM-3	0.70	18/52	0.85 ± 0.06	7%	0.73	1.56 ± 0.07	35 ± 5
25168	Unit 2	1700 ± 30	CAM	/	19/56	0.50 ± 0.03	6%	0.98	1.55 ± 0.09	15 ± 5
25169	Unit 4	1790 ± 20	CAM	/	17/56	0.33 ± 0.01	4%	0.05	1.41 ± 0.08	15 ± 5
25170	Unit 4	1830 ± 20	MAM-3	0.14	18/55	0.30 ± 0.03	10%	0.82	1.57 ± 0.09	15 ± 5
25171	Unit 5	1820 ± 20	MAM-3	0.32	28/56	0.28 ± 0.02	6%	0.54	1.38 ± 0.07	25 ± 5
25172	Unit 1	1370 ± 60	CAM	/	15/24	0.94 ± 0.07	7%	0.18	1.43 ± 0.07	35 ± 5
25173	Unit 2	1680 ± 30	CAM	/	15/45	0.59 ± 0.03	5%	0.11	1.69 ± 0.09	15 ± 5
25174	Unit 1	1690 ± 20	CAM	/	14/32	0.50 ± 0.02	4%	0.71	1.48 ± 0.08	15 ± 5
25175	Unit 1	1720 ± 20	CAM	/	26/71	0.49 ± 0.03	6%	-0.24	1.60 ± 0.08	30 ± 5
25198	Unit 1	1760 ± 20	CAM	/	20/69	0.42 ± 0.02	4%	-0.64	1.56 ± 0.08	20 ± 5

4.3.4 Radiocarbon dating

Radiocarbon dating was carried out on nine selected samples from Kolabacken and the results are presented in Table 6 and Fig. 39. Seven samples produced usable radiocarbon ages, ranging from 645–775 AD to 1300–1435 AD at 95.4% probability. Two samples, A8_220 cm and B6_303 cm, gave very old and infinite ages of >44,000 BP and >42,500 BP, which excluded from the radiocarbon chronology dataset. All the single plot are shown in Appendix 2.

Table 6. Radiocarbon dating results for selected samples from Kolabacken. The radiocarbon ages were measured at the Lund Radiocarbon Dating Laboratory.

Sample ID	Lab Number	¹⁴ C age (BP)
A8_220cm	Lus 21357	>44000
B6_495cm	Lus 21358	880 ± 35
B6_410cm	Lus 21359	935 ± 35
B6_303cm	Lus 21360	>42500
B7_380cm	Lus 21361	895 ± 30
B7_250cm	Lus 21362	605 ± 30
B8_400cm	Lus 21363	1325 ± 35
B8_371cm	Lus 21364	885 ± 35
B8_325cm	Lus 21365	565 ± 40

5 Discussion

5.1 Sedimentary architecture of Kolabacken

The field observations and auger sampling data indicate that Kolabacken comprises six sedimentary units that reflect different stages of its development. To understand the internal architecture, lithological descriptions, grain-size analysis and POSL measurements are considered together. This sedimentological interpretation provides an important framework for integrating dating results and historical records and helps explain how natural processes and human activity together have contributed to the formation and development of Kolabacken. The following section discusses these units from the base upwards, focusing on their lithological characteristics, sedimentary structures and possible roles in the development of the mound.

Unit 1: Brown sand

Unit 1 is the lowermost lithological unit identified in this study and forms the basal sand layer of the mound. The sediments consist of dark brown slightly gravelly medium sand with scattered charred wood fragments in the middle to upper part, and the sediment generally becomes darker with depth. Only a small number of charred wood fragments were observed in the upper part of this unit. These fragments may have been mixed into the top of Unit 1 when early human activities began, for example, through digging and cleaning the fireplaces to keep the beacon burning.

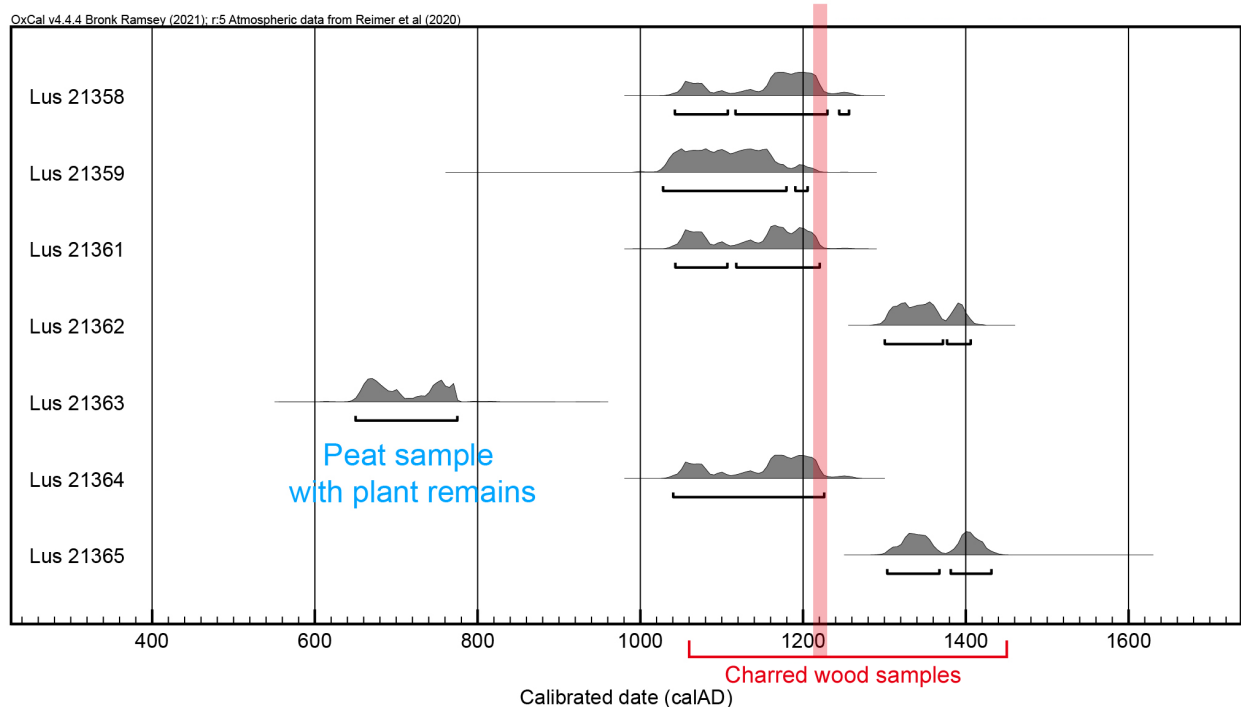


Fig. 39. Calibrated radiocarbon age distributions for selected Kolabacken samples. The probability distributions were produced in OxCal v4.4.4 using the IntCal20 calibration curve. Horizontal bars indicate the calibrated age ranges for each sample, plotted in calendar years AD, showing the relationship between dated charred wood samples and the historical record of the Falsterbo beacon during the reign of Danish king Valdemar II (1225 – 1241 CE).

Some charred wood may also have entered this unit during augering, via fall-in from upper deposits. In the deeper part of this unit, no materials related to human activity were detected.

Fragments of peat containing plant remains were found near the base of several boreholes, generally when approaching the groundwater level (Fig. 34-E). This indicates that Kolabacken was established near the coastline, where organic deposits accumulated in adjacent lagoons. The grain-size data support this interpretation by characterising the sandy matrix of this unit as beach deposits (Fig. 22). Unit 1 is dominated by medium sand, but the sand is less uniform than in several of the overlying units and contains a substantial coarse-grained component. This suggests a variable depositional environment in which changes in coastal energy, water level, and local sediment movement influenced the development of the basal sand layer (Jiang et al., 2015). This sediment pattern is consistent with a low-lying coastal sandy environment, where wave action and shoreline change produced variable sorting and occasional coarse sand and even gravel-sized particles (Bujan et al., 2019).

Unit 2: Grey sand with charred wood and brick fragments.

Above the basal dark brown sand of Unit 1, the sediment changes into grey medium sand with charred wood fragments, locally with beds rich in orange-coloured brick fragments. This marks the first clear lithological evidence of human activity at Kolabacken. In Unit 1, charred wood occurs only in small amounts near the top, whereas in Unit 2 it becomes a more characteristic component of the sediments. The black fragments in this unit are smaller, softer and more easily crushed than the hard coal fragments observed in the overlying units. Microscopic analysis shows that these fragments consist of charred wood (Fig. 34-C).

The grain-size data are useful for distinguishing the sandy sediment character from visible material mixed into the unit. Although Unit 2 contains charred wood fragments and some brick fragments, its grain-size distribution is largely similar to those of Units 4 and 6 but clearly different from Unit 1 (Fig. 22). Units 6, 4 and 2 exhibit similar median grain sizes and weak coarse-grained tails, suggesting consistent aeolian depositional processes (Lancaster, 2005). This suggests that the grey colour of Unit 2 is more likely related to the incorporation of charred wood fragments from beacon activities than to a change in mineralogy compared with Unit 1. The weak coarse tail in Unit 2 is partly explained by the presence of charred wood fragments.

Unit 3: Black sand with coal particles.

Above unit 2, the sediments grade into black medium sand containing coal particles and a minor gravel-sized component. The colour of this unit is much darker than the grey sand with charred wood below and also darker than Unit 5, which mainly contains grey sand and burnt coal fragments. The black colour and the hard coal fragments suggest that coal had become the main fuel of the beacon. The apparent age of >44000 BP of A8 220 cm (Table 6) indicates that the dated material was ancient coal rather than charred

wood. The same applies to the sample from B6 303 cm. In both cases, the fragments exhibited wood-like textures under the microscope, leading to their initial misidentification as charred wood.

The grain-size data help to distinguish the anthropogenic component of Unit 3 from the cleaner sandy units (Fig. 27). The grain-size distribution shows that this unit is dominated by medium sand, but it has a much more substantial coarse tail than Units 2, 4 and 6, which is most likely caused by its higher proportion of coal particles mixed into the sand. After sieving, numerous coal particles of different sizes remained on the largest 4.00 mm sieve, while no mineral grains were observed. This indicates that these hard and resistant coal particles strongly influence the coarse fraction of the sample.

Unit 4: Yellowish white sand.

Above the coal-rich unit, Unit 4 is a yellowish-white sand unit with few visible coal fragments and is generally lighter in colour. This unit is interpreted as wind-blown sand based on its lithology, spatial occurrence and grain-size characteristics. Visual observation shows that the sediment is relatively clean compared with the coal-rich unit below. The grain-size distribution is also relatively uniform and does not have a coarse-grained tail, which is consistent with wind-sorted sand (Zhang et al., 2018). Unit 4 occurs in the upper part of several boreholes, especially in the higher parts of the mound, suggesting intense and widespread aeolian activity, although its temporal representation cannot be determined.

Unit 5: Grey sand with burnt coal.

Unit 5 is a grey, sandy unit containing burnt coal fragments. Compared with the darker, coal-rich Unit 3, Unit 5 is greyer in colour and contains more clearly burnt material, including grey-white slag fragments (Fig. 40). By contrast, Unit 3 contains a larger proportion of hard, black, less completely burnt coal particles. This difference suggests that Unit 5 represents a later phase of coal use at Kolabacken, when coal was combusted more efficiently, possibly at higher temperatures than before, leaving residues dominated by slag with less distinguishable coal structures.

The interpretation is based on the character of the material in the unit. Burnt coal slag are typical residues of coal combustion, whereas larger unburnt coal pieces indicate incomplete combustion or discarded fuel. The dominance of burnt material in Unit 5 therefore suggests that the deposit formed mainly from combustion waste rather than from unused coal.

The grain-size data also support the interpretation that Unit 5 is a sandy unit modified by the addition of burnt coal. The median grain size is similar to that of the other sandy units, indicating that the main sediment matrix is composed of aeolian sand. However, Unit 5 has a stronger coarse-grained tail than Units 2, 4 and 6. This coarse fraction is most likely due to mixture with fragments of burnt coal and slag. The coarse tail is weaker than in Unit 3, which is consistent with the smaller and more fragmented character of the burnt material in Unit 5. Thus, the grain-size distribution reflects both the sandy matrix and the addition of anthropogenic combustion residues.

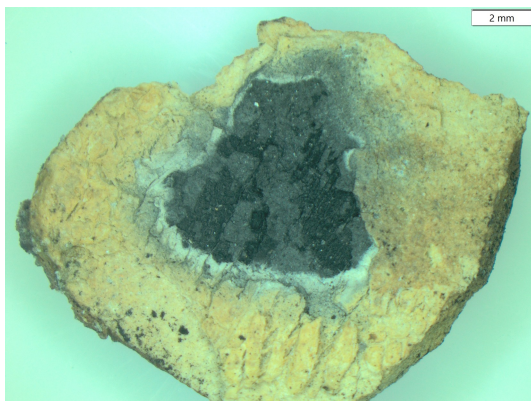


Fig. 40. Coal slag particle found in a sample from 140 cm depth in borehole B4.

Unit 6: Whitish grey sand.

In most boreholes at Kolabacken, Unit 6 forms the uppermost white to whitish-grey sand unit. This unit is relatively thin compared with other units, with an average thickness of 0.56 m, and is interpreted as a sand cover that accumulated after the period of beacon-related activity had ended. Its similar lithology and grain-size compared to Units 2 and 4, and the presence of a small amounts of visible coal slag are all consistent with wind-blown sand accumulation and later stabilisation of the surface by vegetation. However, Unit 6 is not continuous across the whole mound. At borehole B4, the uppermost sediment is grey in colour and contains many visible coal and burnt coal fragments, making the surface sediment more similar to Unit 5 (Fig. 41). According to historical evidence, the former beacon basket was located above this area, which was likely the most-used part of the site (Ersgård, 1989). Coal-rich deposits would therefore have been more concentrated in this area, and cleaning, maintenance and surface disturbance during the beacon activity probably mixed the surface sand with coal fragments, explaining why Unit 6 is poorly preserved at Site B4.



Fig. 41. Borehole B4 and the hand auger equipment used. Grey sand and coal fragments dug from the surface layer are visible around the borehole. To prevent collapse of the poorly consolidated sediments of Unit 1, a steel pipe was lowered into the borehole during augering. Photograph by Shengliang Dong, 29 September 2025.

5.2 The establishment of Kolabacken and its subsequent history

The sedimentological and chronological data provide clear evidence of several well-defined stages in the development of Kolabacken. (Fig. 42, 43). The sedimentary sequence suggests that the site first developed as a natural coastal sand deposit, most likely a beach ridge, which was later modified by beacon activity. Fuel-related residues, including charred wood, coal fragments and burnt coal slag, were mixed with brick fragments (Fig. 34-D) and other evidence of human activity, such as cattle bones (Fig. 44). Through repeated phases of deposition and disturbance, as well as aeolian sand deposition events, these materials gradually raised the mound and formed Kolabacken as an isolated hill. Its development can therefore be divided into the following succession as schematically illustrated in Fig. 45: deposition of beach sand (Unit 1); the establishment of wood burning in the first half of the 1200s (Unit 2); the transition to coal burning in the 1620s (Unit 3); aeolian sand deposition (Unit 4); more efficient coal combustion during the later period of beacon operation from the late 1600s (Unit 5); and finally abandonment and surface stabilisation following the construction of the new lighthouse in 1795 (Unit 6). The following discussion focuses mainly on the history of beacon-related human activity at the site.

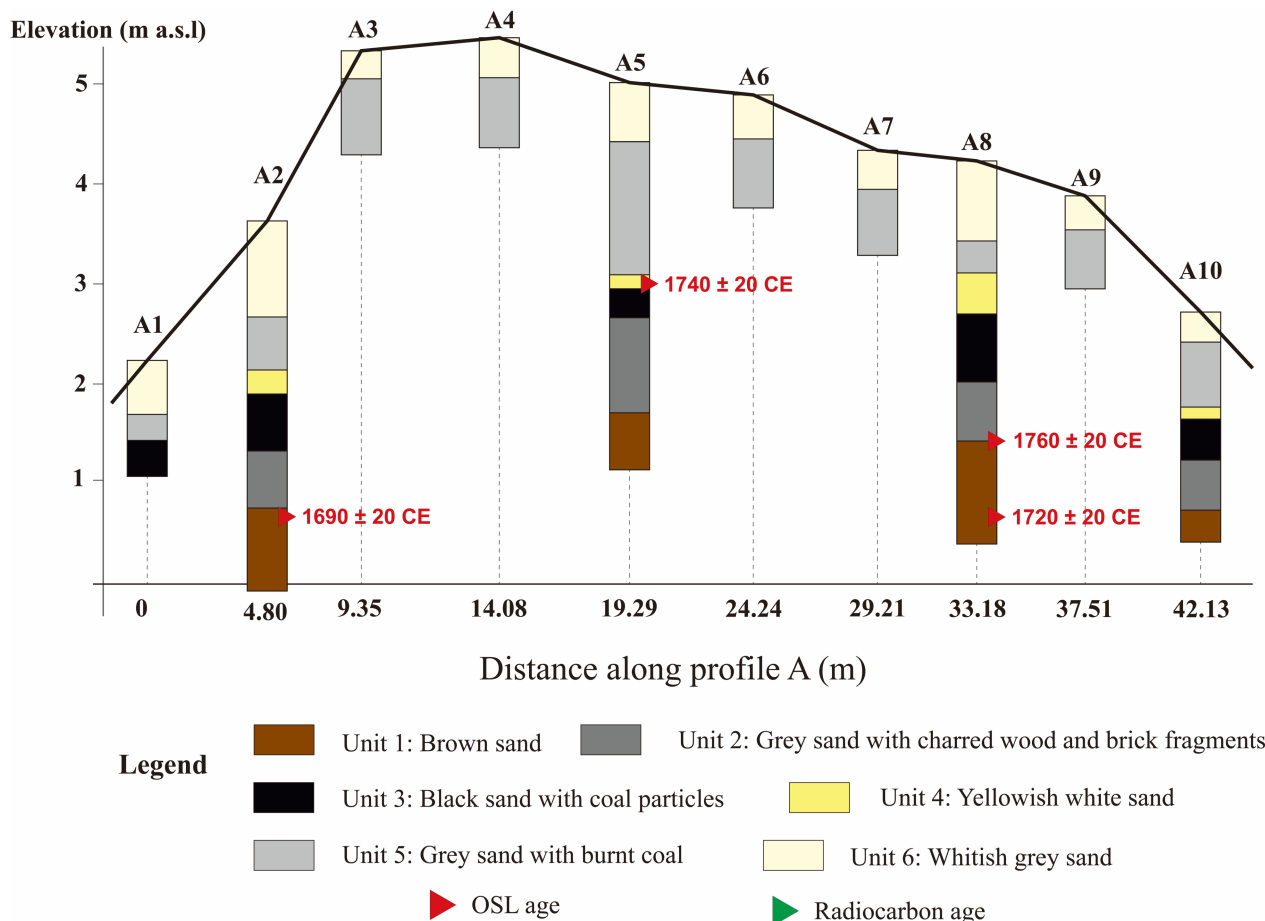


Fig. 42. Chronostratigraphic interpretation of Profile A at Kolabacken, showing the lithological units, OSL ages and calibrated radiocarbon ages used to reconstruct the historical development of the mound.

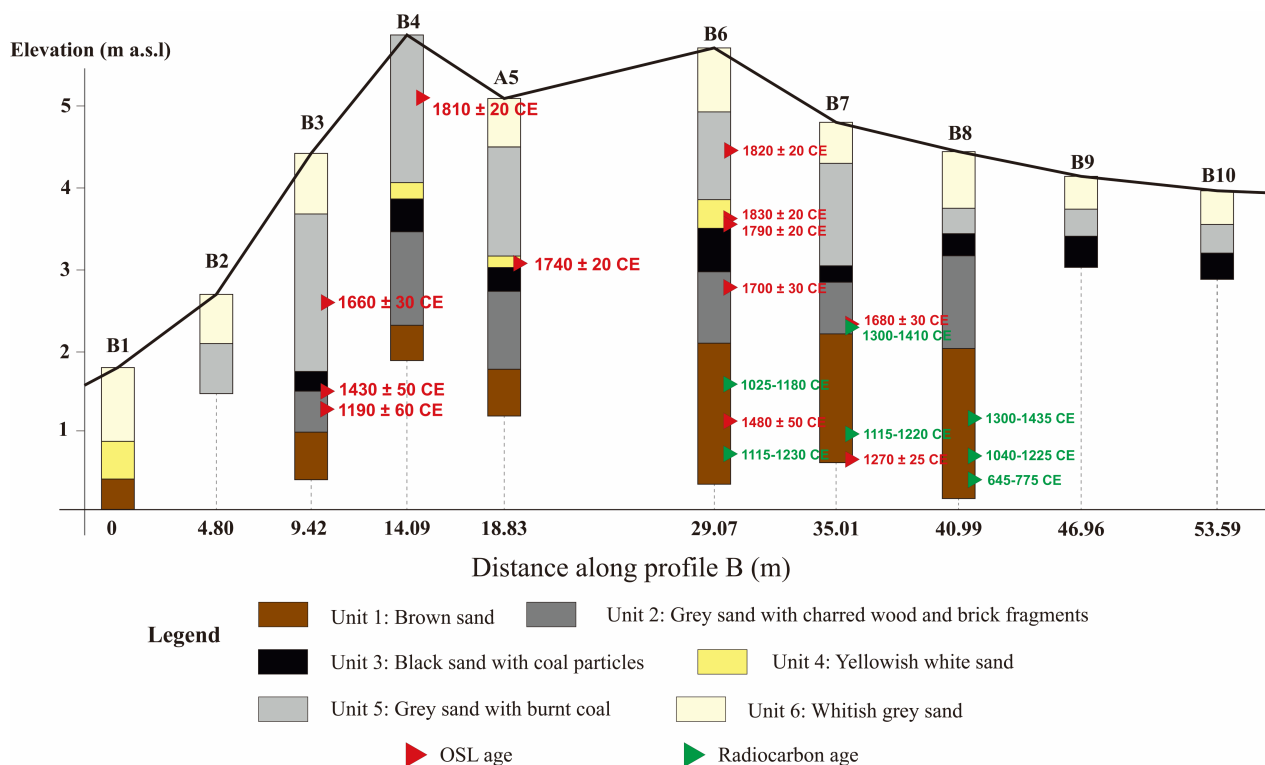


Fig. 43. Chronostratigraphic interpretation of Profile B at Kolabacken, showing the lithological units, OSL ages and calibrated radiocarbon ages used to reconstruct the historical development of the mound.



Fig. 44. Cattle bone fragments from B8 at 293 cm depth.

The earliest clear evidence of burning activity comes from charred wood deposits above the basal sand in Unit 2. Radiocarbon dating of charred wood from these layers yields ages mainly between the 11th and early 13th centuries, indicating that fire-related activity had begun in Medieval times at Falsterbo. These dates are in general agreement with the period of 1225–1241 CE when the Danish king Valdemar II issued a command of establishing a beacon at Falsterbo (Fig. 3 and Fig. 46), hence confirming the onset of beacon activity.

At this stage, the beacon probably relied mainly on local or regional wood as fuel (Fig. 45-B). The beacon may initially have been relatively simple, but repeated use would have required regular maintenance. Burnt material had to be cleared, new fuel supplied, and the burning area kept stable and visible for navigation. Based on historical sources, it cannot be established with certainty whether a beacon was in operation at this early stage (Dufberg, 1994). Some kind of construction to raise the fire above the ground surface may have been in place, but burning of wood on the ground cannot be excluded. The brick fragments found in the middle part of Unit 2 may therefore represent construction or reinforcement material associated with the early beacon structure. The cattle bone fragments from the same activity layer also suggest that the site was not only a place where fire was lit but also a working area that was visited and maintained repeatedly by beacon personnel. Fuel handling, cleaning, repair and everyday activity around the beacon all contributed to the gradual build-up of the mound.

The continuity of beacon operation between the decline of the Medieval Falsterbo Market and the early 1600s remains uncertain. The stratigraphic and chronological data obtained in this study do not have sufficient temporal resolution to determine whether firing was continuous, intermittent, or absent during this period. Literature suggested that the beacon may have been abandoned, partly because no beacon is marked on two maps dating from the 1500s (Dufberg, 1994). However, the absence of the beacon from these maps is not conclusive evidence of abandonment. Therefore, a possible interruption in beacon activity must be acknowledged, although its timing and duration cannot be established from the available evidence.

One of the most important changes in the history of Kolabacken was the shift from wood to coal as the main light source of the beacon (Fig. 45-C). This change was not merely a change of fuel but also a shift in the system of supply, storage and maintenance.

While the earliest evidence of burning at Kolabacken consists of charred wood fragments, probably linked to wood-based beacon activity, historical records show that coal was already used for Danish beacons from the early 1620s, most likely imported from Scotland or the Netherlands (Clemensson, 1958). From this period onward, historical accounts indicate that a classical beacon (Swedish: “vippfy”) was present at Kolabacken (Dufberg, 1994). The introduction of coal changed the practical operation of the beacon at Falsterbo. Coal had to be mined or imported, transported by ship, carried over land and stored close to the beacon. Historical records from the 1660s show how demanding this system was. The early coal supplies to Falsterbo, Kullen and Nidingen were interrupted in 1665 due to the Second Anglo-Dutch War. As a consequence of this, coal mining began at Tinkarp north of Helsingborg, the first production of which was shipped to Falsterbo and Nidingen. In the autumn of 1667, 300 barrels of coal were mined at Tinkarp, and between then and April 1668 about 700 barrels were shipped to the beacons at Falsterbo, Kullen and Nidingen. The coal was usually brought by ships anchoring in Höllviken Bay or near Skanör, and then transported by carriage to the beacon (Clemensson, 1958).

This historical background helps explain the black sand containing coal particles (Unit 3). This unit marks the beginning or early development of coal use at the site. The abundance of relatively soft black coal fragments suggests that early coal-burning was not always complete or efficient. Coal requires higher combustion temperatures than wood and typically needs firewood to ignite. It is likely that coal was first used in a beacon system that was originally adapted to wood burning. Such a system may not have provided the combustion conditions needed for complete coal burning, which resulted in the relatively large fragments of unburnt or partly burnt coal recorded in Unit 3. These fragments were later cleared from the burning area and mixed with the surrounding sand during beacon maintenance.

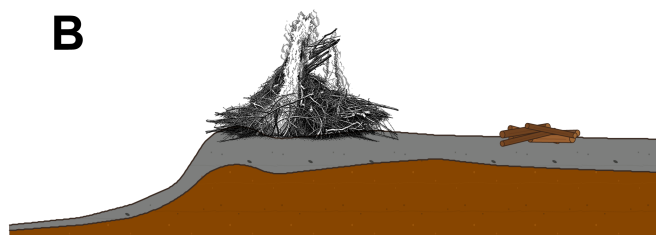
The yellowish-white aeolian sand of Unit 4 contains fewer visible coal particles than the coal-rich units below and above, and its cleaner sandy character suggests less direct incorporation of burning residues. It is therefore interpreted as wind-blown sand that temporarily covered the beacon surface (Fig. 45-D). This aeolian deposition may have occurred either during a short-lived event, such as a strong storm, or during a short interval of increased aeolian activity. This change may be linked to two historical factors. First, during the Scanian War in 1676, coal deliveries to the beacons, including Falsterbo, failed, and the beacon could not be properly maintained (Clemensson, 1958). If fuel supply and regular maintenance were interrupted, the working surface would have been cleaned, trampled and renewed by burning activity less frequently. This would have allowed wind-blown sand to accumulate across the coal-rich surface of the mound. Second, historical records also show that wind-blown sand was already a practical problem at Falsterbo. In the winter of 1668, a small barn was built beside the beacon to store coal after the fire personnel complained that sand blowing from the beach damaged both the coal and the surrounding grasslands. This record directly links beacon operation with strong aeolian activity at the site.



Before 1220ies

Natural beach-ridge sand deposition

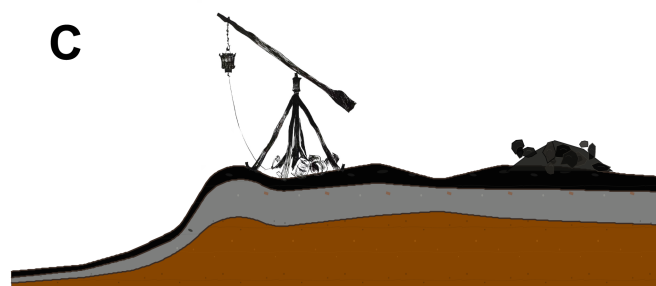
Basal brown sand accumulated in a coastal setting before beacon activity began.



After the 1220ies

Establishment of wood-burning beacon activity

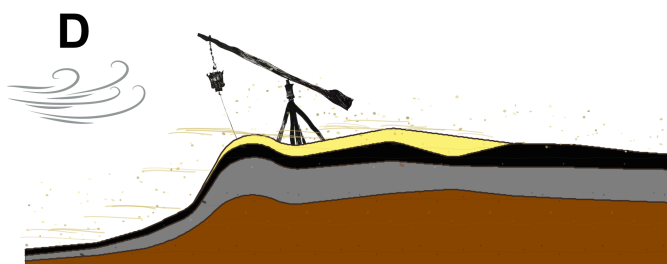
Charred wood fragments and brick particles mark the first clear human activity at Kolabacken.



From the 1620ies

Transition to coal as the main beacon fuel

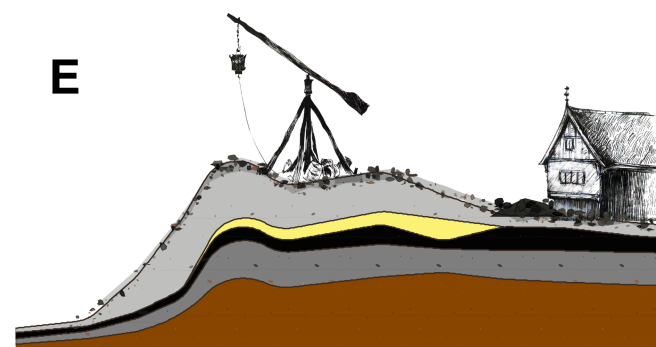
Black sand with abundant coal particles records early coal use and incomplete combustion around the beacon.



Late 1600s

Aeolian sand temporarily covers the surface

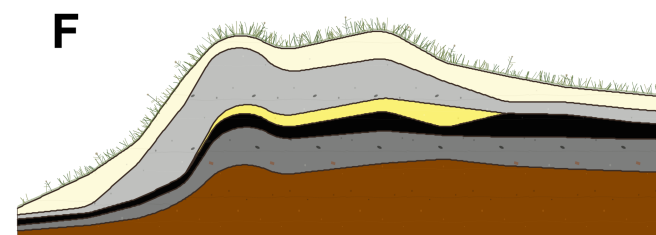
Yellowish-white aeolian sand accumulated during a period of increased sand drift and reduced maintenance.



After the late 1600s

More efficient coal burning and site maintenance

More efficient coal combustion produced burnt coal slag which were mixed into the grey sand around the beacon.



After 1795

Abandonment and surface stabilisation

After the new lighthouse was built in 1795, the old beacon site was abandoned and gradually covered by wind-blown sand and vegetation.

Fig. 45. Schematic reconstruction of the geological and historical development of Kolabacken, the former beacon site at Falsterbo.

The OSL ages from Unit 4 mainly fall within the 18th century, supporting the interpretation that this unit formed during a sand movement event. This aligns with the pattern described at Falsterbo Church, where a thick aeolian sand unit was deposited above beach sand and cultural layers from the mid-16th century to the early 19th century (Alexanderson et al., 2024). Their luminescence profiling data suggest that this aeolian sand was not formed continuously but by several short-lasting storm events.

After an event of interrupted maintenance and wind-blown sand accumulation, the Falsterbo beacon appears to have entered a more organised and efficient coal-burning phase (Fig. 45-E). This stage is represented by the grey sand containing abundant burnt coal slag. Compared with the underlying black coal-rich layer, this unit contains more ash-like material and coal slag, but fewer large fragments of incompletely combusted coal. This difference suggests that coal was burned more efficiently, probably in a better-maintained beacon structure from the late 1600s onward. The combustion residues were likely cleared from the burning area and mixed with surrounding sand during repeated cleaning and maintenance. Unit 5 can therefore be interpreted as a maintained working surface or activity layer, where burnt coal slag, ash and sand were repeatedly moved, spread and mixed during the continued use of the beacon.

This interpretation aligns well with the historical evidence of beacon activity in the 18th century. The description of the site by Carl Linnaeus in 1749 is significant because it directly links Falsterbo to coal burning (von Sydow, 1977). The 1761 map, which marks the beacon as “Fyr huset” (the beacon house), also shows that it was a recognised feature in the landscape at this time (Fig. 5). The 1765 map provides further support, marking the site as “Falsterbo Lyckta” in Swedish, meaning “The lantern at Falsterbo”, and showing the beacon beside a small building (Fig. 47). The accompanying text indicates that the light was intended for seafarers at night, confirming its function as a navigation light.



Fig. 46. Falsterbo beacon on the 1765 historical map. Source: Lantmäteriet, Historiska kartor, act 12-skf-2, 1765.

The OSL chronology supports this interpretation. Several OSL ages from the middle and upper sediment units of Kolabacken fall within the seventeenth and eighteenth centuries, including ages in the range of

1660–1820 CE. These ages show that sand in this unit was exposed, moved and buried during the same broad period of intensified beacon activity as described in the historical records. This means that the ground surface was still open to disturbance related to the daily work around the beacon during the main period of coal-fired operation. Before being added to the fire, the coal had to be stored nearby, most likely in the building depicted on the historical maps (Fig. 47). After burning, the residues had to be cleared away to facilitate continued beacon activity. Such activities likely led to the distribution of coal-burning residues widely across different parts of Kolabacken and mixed them with the surrounding sand.

After regular beacon activity and associated maintenance ended following the erection of Falsterbo lighthouse in 1795, natural surface processes became more important in shaping the mound. Wind-blown sand could move across Kolabacken, cover older layers and form the sand-dominated surface deposits. Rain, small-scale erosion, establishment of vegetation, burrowing rabbits and limited human disturbance may also have affected the uppermost layers of the mound. As the former working surface was no longer repeatedly cleared, trampled and renewed by beacon activity, the mound gradually stabilized. This post-beacon stabilization formed the present-day appearance of Kolabacken as an isolated sandy hill with older combustion residues preserved beneath the surface (Fig. 2, Fig. 45-F).

The reconstructed shoreline pattern in Fig. 47 provides additional spatial context for understanding the historical development of the Falsterbo beacon. Although the shoreline positions are schematic, they indicate that Kolabacken was originally situated in a much more coastal setting than today. The estimated 1200s shoreline, inferred from sedimentary evidence at Kolabacken and the position of nearby beach ridges, suggests that the site lay close to an active coastal zone during the Medieval period. This supports the interpretation that the beacon was established at a strategically visible position near the southern coast of the Falsterbo Peninsula, where it could guide ships approaching the shallow and hazardous waters around Falsterbo.

Later shoreline reconstructions based on historical maps from the eighteenth and nineteenth centuries indicate ongoing coastal change after the beacon's establishment. The approximate 1765 shoreline lies closer to Kolabacken than the modern coastline, while the 1860 shoreline shows further modification of the coastal outline. These changes reflect the dynamic character of the Falsterbo Peninsula, where shoreline migration, beach-ridge development, sand drift and coastal deposition have repeatedly reshaped the landscape. In this context, the replacement of the old beacon at Kolabacken by the new Falsterbo lighthouse in 1795 can be understood not only as a technological change in navigation, but also as part of a changing coastal landscape. As the coastline shifted and the navigation system became more formalised, the new lighthouse was placed farther west, closer to the exposed coastal margin. Kolabacken was then gradually abandoned as an active beacon site, while its sediments preserved evidence of earlier burning, maintenance and sand accumulation.

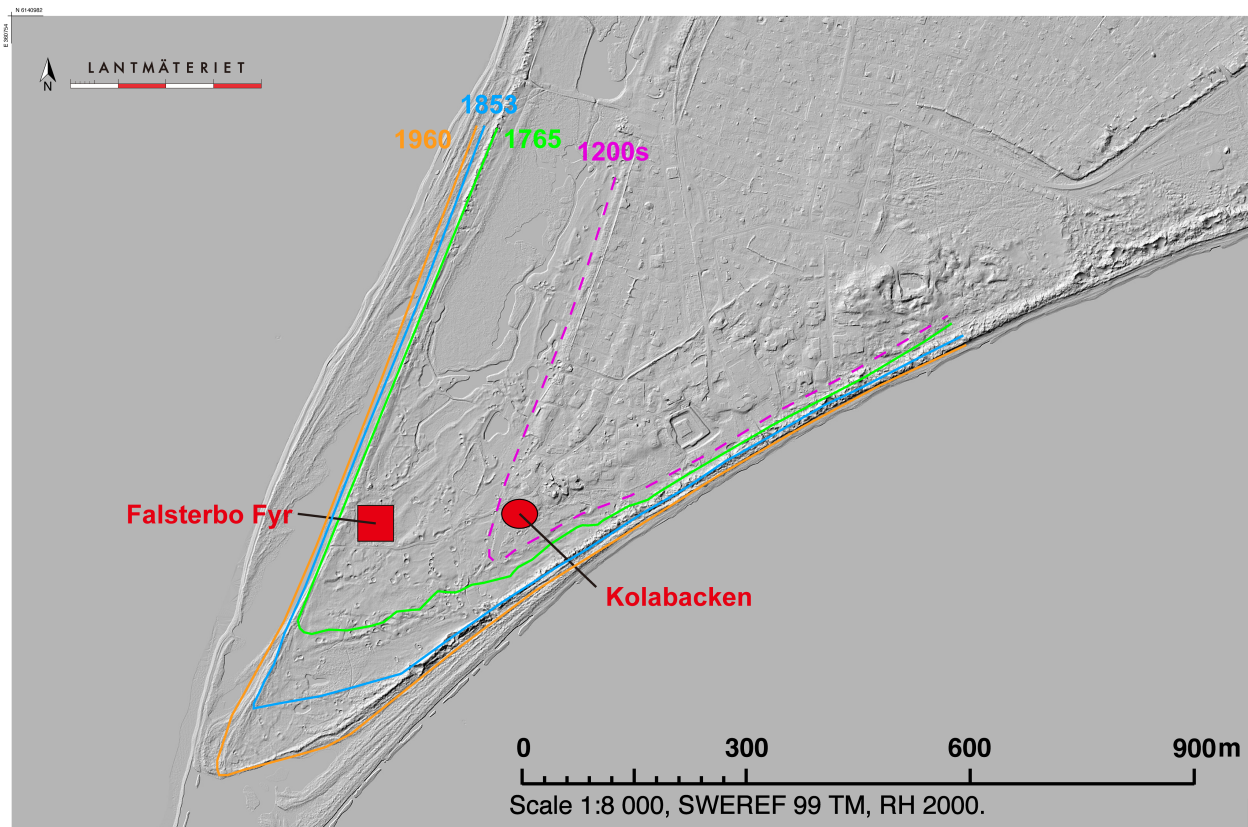


Fig. 47. Schematic reconstruction of shoreline changes around Kolabacken and Falsterbo Fyr. The magenta line shows the estimated shoreline during the 1200s, inferred from the sedimentary characteristics of Unit 1 at Kolabacken and the position of the historical beach ridge. The green and blue lines show the approximate shoreline positions interpreted from historical maps of the area from 1765 and 1860, respectively, in combination with the modern topography. The background radar-derived terrain model is from Lantmäteriet.

5.3 Chronological precision and accuracy

Establishing the chronology of the sediments is the most important part to know the historical development of Kolabacken. In this study, two different methods are used to identify the chronology of sedimentary sequence: Optically Stimulated Luminescence (OSL) dating and Radiocarbon dating. OSL dating estimates the time elapsed since quartz grains were last exposed to sufficient daylight before burial, whereas radiocarbon dating provides ages for organic materials, in this case peat and charred wood. Both methods are generally considered reliable, but their results must be interpreted in relation to sample material, depositional context, and method-specific uncertainties before they can be used to build a chronological framework for the site.

5.3.1 OSL age reliability

Kolabacken has a complex depositional history, with both natural sedimentary units and deposits strongly influenced by human activity. This complex lithology has a clear effect on OSL measurement and calculation. After all dose measurements were completed, the Kolabacken samples were found to have generally low dose values, ranging from 0.28 ± 0.02 Gy to 1.26 ± 0.07 Gy (Table 5). This indicates that all the samples are young, and even small residual sig-

nals, thermal transfer, water content, or differences in age model selection can have a significant influence on the final OSL calculation age (Aitken, 1985; Murray et al., 2021). When the OSL measurement results were summarised and compared with different lithological units, clear differences in data quality were observed. More sandy units with lower human-activity impact and more consistent material show more scatter and more internally consistent D_e distributions, whereas units with stronger human-activity influence and higher sediment mixing show more scattered distributions of equivalent doses. This means the reliability of the OSL ages is closely linked to the sedimentological characteristics of each unit. In complex units, additional aliquot measurements are needed to obtain more accurate age information.

Before discussing the age model choice, the quality of the measured equivalent dose results was assessed using summary statistics from the OSL dataset and visualised with Abanico plots (Fig. 48). The Abanico plots show the shape and structure of D_e distributions, while the relative standard error of the mean dose indicates the precision of the dose estimate. Skewness, considered together with the standard error, helps to show whether the distribution is scattered or not. These indicators were compared with lithological units to evaluate which stratigraphic unit provides more stable OSL measurement results and which units contain complex luminescence information and need to be explained more carefully.

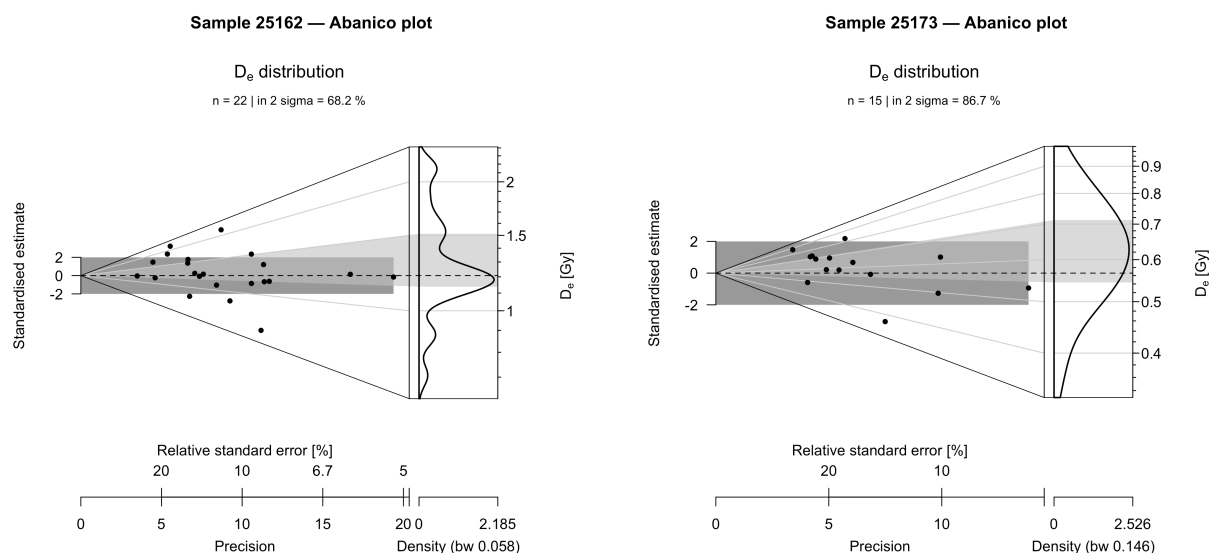


Fig. 48. Abanico plots of the equivalent dose distribution for samples 25162 and 25173. Sample 25173 shows a relatively compact distribution, with most aliquots close to the central dose estimate, whereas sample 25162 shows a more dispersed distribution and a wider range of D_e values. The Abanico plots for the remaining 13 samples are presented in Appendix 3.

The OSL results from Units 1 and 2 show more variable D_e distributions. In Unit 2, the Relative Standard Error (RSE) D_e values range from 5 to 8%, with skewness values from -0.47 to 0.98 (Table 5). Sample 25173 has the most compact and weakly skewed D_e distribution in this unit (RSE = 5%; skewness = 0.11), whereas samples 25162 and 25168 show more positively skewed distributions (RSE = 6% for both samples; skewness = 0.89 and 0.98, respectively; Fig. 48; Table 5). Sample 25163 has the highest RSE in Unit 2 (8%) but is negatively skewed (skewness = -0.47), showing that the samples from this unit did not behave in the same way during OSL measurement. This is consistent with the mixed lithology of Unit 2, where grey sand with charred wood and brick fragments may contain quartz grains with different daylight-exposure and burial histories.

Unit 1 shows a similar problem and therefore also requires cautious chronological interpretation. The OSL samples from this unit are 25167, 25172, 25175 and 25198 (Table 5). Samples 25175 and 25198 had many aliquots measured, with 26 of 71 and 20 of 69 aliquots accepted, respectively (Table 5), but the accepted dose distributions still show some scatter (Appendix 3). This is consistent with the interpretation of Unit 1 as a coastal sand deposit, where grains may have been repeatedly exposed, buried, reworked and redeposited before final burial (Bailey & Arnold, 2006; Murray et al., 2021). When the OSL results are considered together with the stratigraphic context and historical records, some OSL ages from these lower units appear anomalously young for their position (Fig. 42, 43). This may reflect post-depositional reworking or mixing with younger sand rather than the original timing of deposition. Therefore, the chronology of Units 1 and 2 should rely mainly on the radiocarbon results, while the OSL ages are used more cautiously as supporting evidence.

Units 4 and 5 show relatively stable OSL measurement patterns compared with the lower, more mixed units. The accepted aliquot numbers, RSE values and

D_e distribution parameters indicate relatively limited spread and low to moderate skewness, without strong one-sided tails (Table 5; Appendix 3). These results suggest that the quartz grains in these two units record relatively consistent burial signals. This fits the lithological interpretation of Unit 4 as a relatively pure aeolian sand layer and of Unit 5 as grey sand with burnt coal particles, with the sandy matrix less mixed than in the lower disturbed units. For Unit 4, wind transport and daylight exposure before final deposition may have promoted more complete bleaching and produced a more consistent OSL signal (Mo et al., 2022; Murray et al., 2021).

Age model selection is a key step in producing reliable OSL ages. In this study, the central age model (CAM) and the minimum age model (MAM-3) were used to select the equivalent dose for age calculation (Galbraith et al., 1999). Model selection depends on the structure of the D_e distribution and whether it is significantly skewed (Bailey & Arnold, 2006). If the distribution is positively skewed and the plot shows a high-dose tail in some aliquots, this may indicate incomplete bleaching, and MAM-3 should be used to estimate the lower-dose population and represent the final burial event. If the distribution is not strongly skewed and the low-dose component is not sedimentologically meaningful, CAM remains the more appropriate model (Bailey & Arnold, 2006; Galbraith & Roberts, 2012). In this study, four measurements were obtained using the MAM-3 (25165, 25167, 25170, 25171), and the other samples were obtained using the CAM (Table 6). The samples that used the MAM-3 show evidence of a high-dose tail in the D_e distribution with acceptable p-values, suggesting that some aliquots may have retained signal before burial. The MAM-3 was used to focus on the lower-dose component, which can represent the best-bleached grains and the final burial event. Using the CAM for these samples would pull the central dose higher and overestimate the calculated age. The other samples were calculated using CAM. For these samples, the Abanico

plots do not show a clearly separated, sedimentologically meaningful low-dose group. In these cases, using MAM-3 would risk underestimating the burial history and producing ages that are too young.

In OSL dating, the age is calculated by dividing the equivalent dose by the dose rate, so the uncertainty in the dose rate directly affects the final age calculation (Aitken, 1998; Wintle & Murray, 2006). Water content has a direct effect on the environmental dose rate. As water content increases, water absorbs and reduces the ionising radiation received by the mineral grains, especially the beta component of the dose rate (Aitken, 1985; Guérin et al., 2011), thereby lowering the dose rate. So, if the equivalent dose remains the same, a lower dose rate yields an older calculated age. This means that assuming higher water content can yield an older age. Water-content uncertainty has different importance for the two example samples shown in Fig. 49. Higher water content lowers the environmental dose rate and therefore gives an older calculated OSL age if the equivalent dose remains unchanged (Aitken, 1985; Guérin et al., 2011). The sensitivity test was evaluated from 0% to 35% water content, because 35% is the highest selected water content used in the final age calculations (Table 5; Fig. 49). For the upper-unit sample 25170, increasing water content from 0% to 35% changes the calculated age from 0.17 ka to 0.23 ka, while the selected final age at 15% water content is 1830 ± 20 CE. Around the selected value, the effect of water-content uncertainty is broadly comparable to the quoted age uncertainty. For the lower-unit sample 25167, however, the calculated age changes from 0.39 ka at 0% water content to 0.55 ka at 35% water content, while the selected final age at 35% water content is 1480 ± 50 CE. This total shift is larger than the quoted age uncertainty, showing that the choice of water content has a clearer effect on the low-

er OSL age. Therefore, water-content uncertainty has only a limited effect on the interpretation of the upper Units 4 and 5, but it is more important for assessing the reliability of the lower samples.

For the final age calculation, the selected water content were chosen to represent the long-term average water content (Preusser et al., 2008). The selected water contents used for the final age calculations range from 10% to 35%, with an uncertainty of $\pm 5\%$. These values were guided by the laboratory water-content records in Appendix 5, which include the wet, saturated and dry weights of the OSL sediment samples. Sample 25165, from the upper sandy unit, was assigned 10% because it comes from a relatively dry and well-drained part of the sequence. Most middle samples were assigned 15%, which is slightly higher than many measured field values and allows for longer-term moisture variability in sandy sediment. Deeper samples in the lower units were assigned higher values of 30–35%, because they occur closer to the ground-water-influenced part of the sequence and because their potential saturated water contents indicate that substantially wetter conditions were possible (Table 5). This approach makes the dose-rate calculations more representative of the burial environment rather than the short-term moisture condition on the day of sampling (Aitken, 1985; Guérin et al., 2011; Preusser et al., 2008).

Based on these considerations, samples 25164, 25165, 25166, 25169, 25170, 25171, 25174 and 25198 are considered the more reliable OSL ages and should have greater weight in the chronological interpretation. Samples 25167 and 25172 should be treated with more caution because their ages are more strongly affected by the selected water content of 35%. Sample 25175 should also be used cautiously because it has the highest IR/B ratio, indicating a higher risk of feldspar contamination. These samples are not rejected, but they should have less weight than the more stable OSL ages.

5.3.2 Radiocarbon dating reliability

Radiocarbon dating was used to date organic material (peat) and charred wood pieces at Kolabacken to provide ages that could be compared with the OSL ages obtained. The main difference between these two chronology methods is the type of material measured. Radiocarbon dating gives the age of organic materials, while OSL dating provides information on when quartz grains were last exposed to light and then buried. Nine samples were selected for radiocarbon dating, of which seven yielded usable calibrated ages, ranging from 645–775 AD to 1300–1435 AD.

The oldest radiocarbon age is from B6 400 cm, with a calibrated age of 645–775 AD, obtained from a peat sample taken from the basal part of Kolabacken, close to sea level. This age is interpreted as dating a natural organic deposit in the lower part of the hill, formed before clear evidence of beacon-related fire activity. It therefore suggests that human activity at this part of the site began after this age, and that organic-rich, low-lying coastal conditions, probably in a depression between beach ridges, were preserved at the base of Kolabacken before the beacon was established.

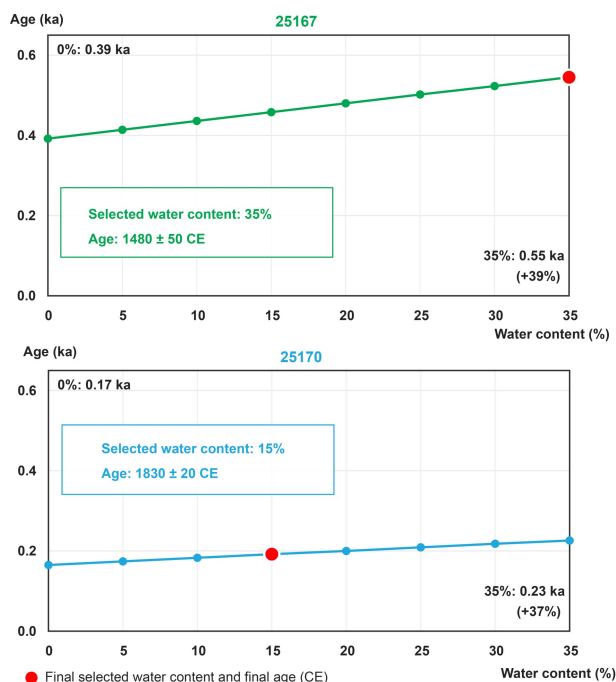


Fig. 49. Water content sensitivity for OSL age measurements of 25167 and 25170 from Unit 1 and Unit 4. The red points show the selected water contents used in the final age calculations, respectively. Figure was created in Python.

All the other radiocarbon samples providing results relevant to the development of Kolabacken consist of charred wood. For charred wood samples, the main dating uncertainty originates in the possible age difference between the charred wood material and the burning event, the so-called old-wood effect. A radiocarbon age obtained from charred wood dates the growth of the sampled wood, not the event of wood burning. If the charred wood is derived from mature wood, especially from the inner part of a long-lived tree, the dated material may be decades or even centuries older than the burning event. However, this uncertainty may be significantly reduced by selecting charred wood fragments representing short-lived tree species and including rings formed in the outer part of the trunk or in thin branches. Because the charred wood fragments from Kolabacken were not identified to species or analysed for their wood anatomy, it is not possible to evaluate the magnitude of the old-wood effect on the obtained ages. However, the local vegetation history provides a useful context. The Falsterbo Peninsula formerly included oak woodland, which was largely cut down during the Middle Ages for fuel and timber (Länsstyrelsen Skåne, n.d.), and oak is still one of the most common noble broadleaved trees in southern Sweden. It is therefore possible that wood of oak was used as fuel at Kolabacken, which implies that an old-wood effect of the magnitude of several centuries should be considered when interpreting the obtained ages.

A second uncertainty is post-burning movement of charred wood within the site. The charred wood fragments are generally small, light and fragile, and may have been moved after burning by cleaning of the fireplace, wind, runoff or disturbance of the surface (Théry-Parisot et al., 2010). Therefore, a charred wood fragment found at a particular depth does not necessarily date the exact formation of that sediment layer. This means that the charred wood dates provide important chronological evidence, but they must be considered together with stratigraphy, sedimentology and the OSL results.

6 Conclusions

This thesis shows that Kolabacken is a complex archive of coastal sedimentary processes and anthropogenic activity. The mound was formed through the interaction of natural coastal processes, aeolian sand deposition and more than five centuries of aggradation of residues from burning of wood and coal at the former Falsterbo beacon. Field observations and auger sampling identified six distinct sedimentary units.

A basal unit of beach sand with embedded organic matter, which was radiocarbon dated to around 700 CE, represents the coastal setting where the beacon was later constructed. An overlying unit, rich in charred wood remains and brick fragments, yielded ages supporting the establishment of the beacon in the 13th century as evidenced by historical accounts.

The first clear evidence of human activity is represented by grey sand containing charred wood and brick fragments. This unit indicates that burning activity and structural or maintenance-related material had begun to affect the site. The charred wood dates sug-

gest Medieval fire-related activity, and these results are broadly consistent with the historical record indicating the establishment of a beacon at Falsterbo during the reign of Valdemar II in the early thirteenth century. However, the available stratigraphic and chronological evidence does not allow us to determine with certainty whether, or to what extent, beacon activity continued without interruption from the thirteenth to the seventeenth century.

A major change in the history of Kolabacken was the transition from wood burning to coal burning from the 1620ies. This is recorded by the black sand with coal particles and later by grey sand containing burnt coal and coal slag. The lower coal-rich unit probably represents an early phase of coal use, when combustion was less complete and larger fragments of unburnt or partly burnt coal were incorporated into the sediment. The overlying unit with more burnt coal and slag suggests a later and more efficient phase of coal combustion, linked to a better-organised beacon operation during the seventeenth and eighteenth centuries.

The yellowish-white sand layer between the coal-rich units is interpreted as wind-blown sand. This unit shows that aeolian activity affected the beacon surface during its history. It may reflect a short interval of increased sand movement, possibly connected with reduced maintenance or storm-related deposition. Historical records describing wind-blown sand problems near the beacon support this interpretation. After the old beacon was replaced by the new Falsterbo lighthouse in 1795, regular burning and maintenance ended, and natural surface processes and vegetation gradually stabilised the mound.

The chronological results demonstrate the value of combining OSL and radiocarbon dating but also show the limitations of both methods in a mixed coastal and anthropogenic setting. OSL ages from cleaner sandy and upper units are more consistent and help constrain the early modern development of the site. In contrast, OSL ages from the lower mixed units are more difficult to interpret because of sediment reworking, partial bleaching and post-depositional mixing. Radiocarbon dating provides important evidence for the medieval and pre-beacon history of the site, but charred wood samples do not necessarily date the exact time of burning or deposition. Therefore, the most reliable interpretation is obtained by integrating dating results with stratigraphy, sediment composition, microscopic observations and historical records.

7 Future research

Several uncertainties remain and should be further solved in future research.

1. The charred wood fragments have not been identified anatomically. Future charred wood analysis could determine the taxa represented and, where preservation allows, assess growth-ring position, ring curvature and the possible presence of bark or outer wood. This would improve the interpretation of fuel use at the beacon and provide a better basis for evaluating possible old-wood offsets in the radiocarbon ages.

2. The age of the onset of beacon activity remains somewhat uncertain. Additional radiocarbon dating of carefully selected plant remains or other organic remains from human activity would provide stronger chronological control than dating of charred wood alone. Additional OSL samples, especially from clearly defined sedimentary contexts, could also help test whether the young OSL ages of the lower units reflect reworking, partial bleaching or later sediment mixing.

3. The physical structure of the former beacon is still poorly constrained. The sedimentary evidence indicates repeated burning, cleaning and maintenance, but it cannot fully reconstruct the exact form and position of the beacon structure. Future work could combine small-scale archaeological excavation with non-invasive geophysical methods such as ground-penetrating radar (GPR). GPR could help identify continuous internal boundaries, buried surfaces, disturbed zones, construction-related features or remaining structural elements of the former beacon without disturbing the protected site. This would provide an important bridge between the point-based borehole data and the broader three-dimensional architecture of the mound.

4. Kolabacken warrants further study in relation to the wider coastal development of the Falsterbo Peninsula. More detailed comparisons with shoreline change, storm events, sand drift and groundwater conditions would help clarify how natural coastal processes influenced the preservation and development of the beacon site. In the present study, the POSL results were used mainly as supporting information and were not discussed in detail because their relationship to the sedimentological units and the independent chronological results could not be clearly demonstrated. Future research could compare POSL signal patterns from Kolabacken with POSL and OSL data from nearby sites (Alexanderson et al., 2024). By combining and comparing these datasets, it may be possible to establish a stronger relationship between POSL signals, sedimentary units and OSL chronology in the Falsterbo area. This would improve the interpretation of sand movement, sediment reworking, and the broader development history of Kolabacken within the coastal landscape of the Falsterbo Peninsula.

8 Acknowledgements

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methods and scientific reasoning involved in geochronology and geoarchaeology. It has also strengthened my enthusiasm for geology and confirmed my determination to continue working in this field. I would particularly like to thank Zoran Perić, who taught me the routine procedures used in the OSL laboratory and provided invaluable guidance and assistance with the practical details of the laboratory work.

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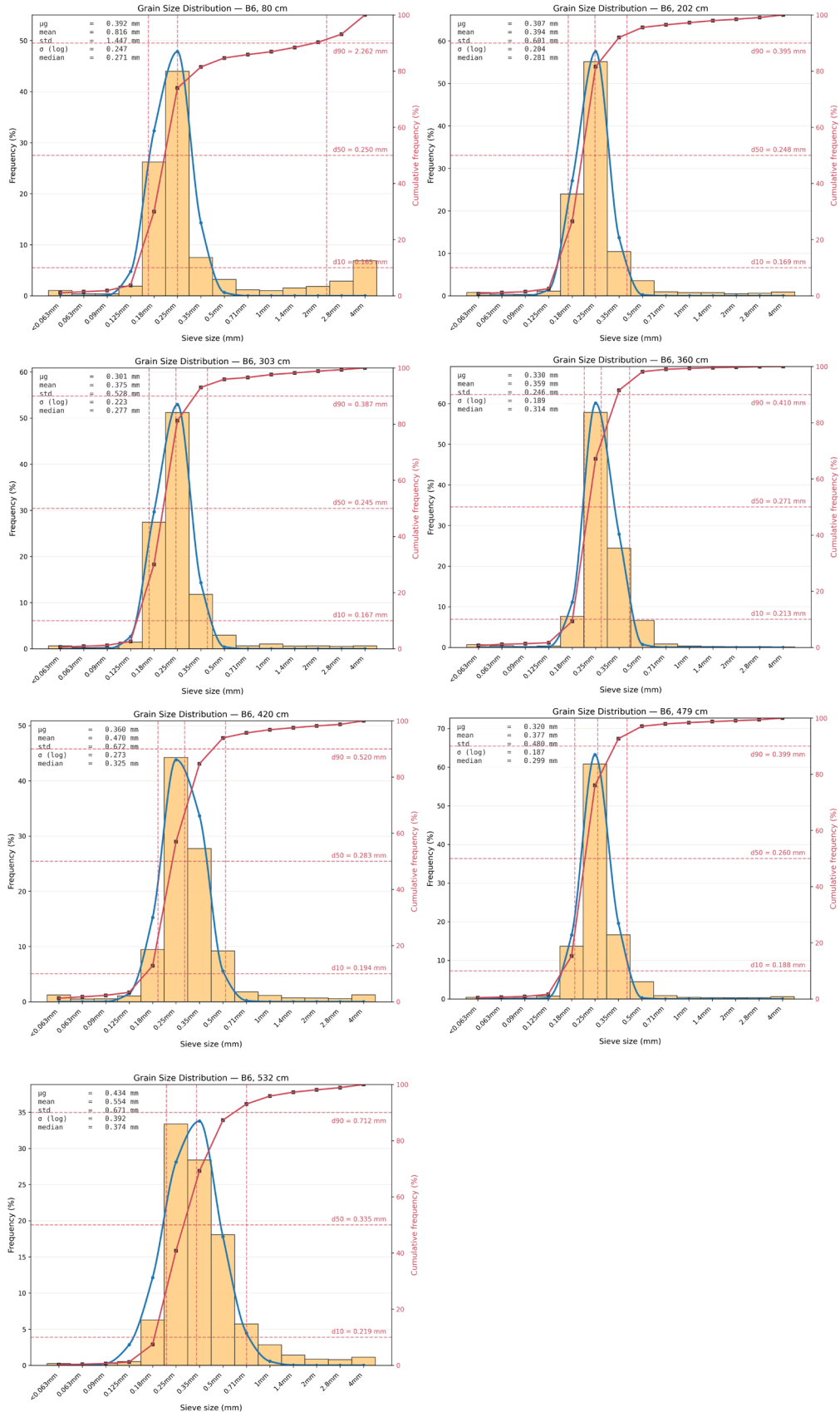
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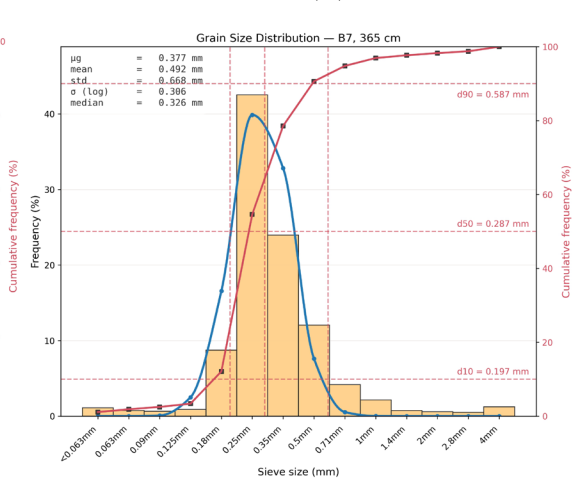
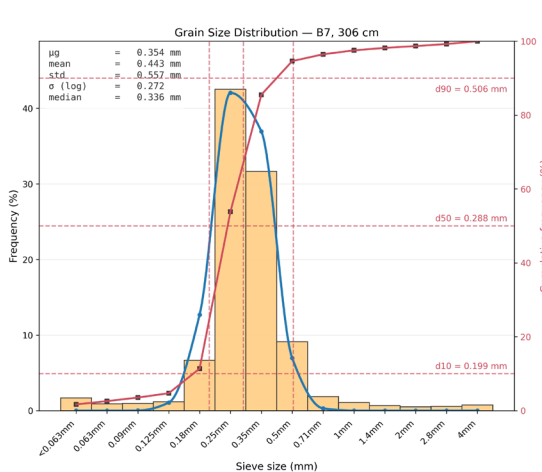
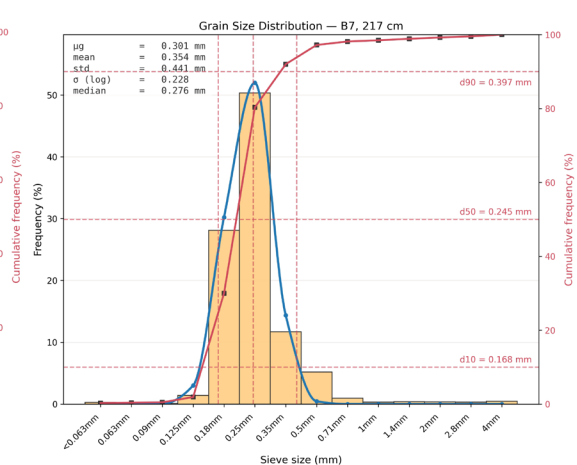
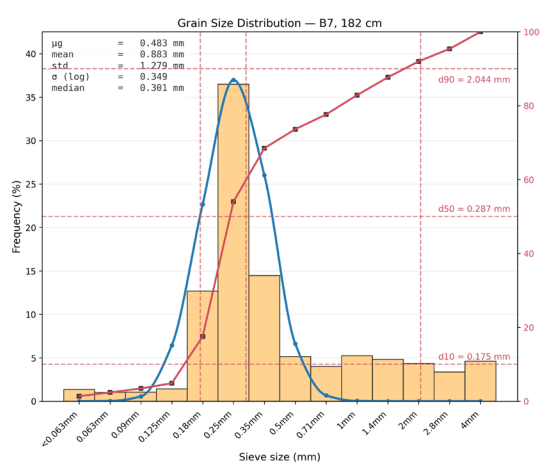
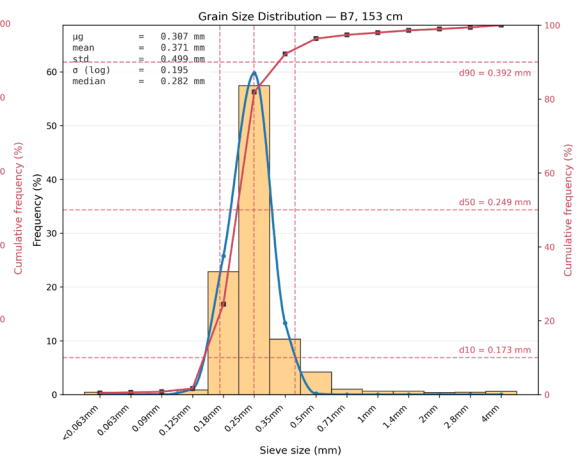
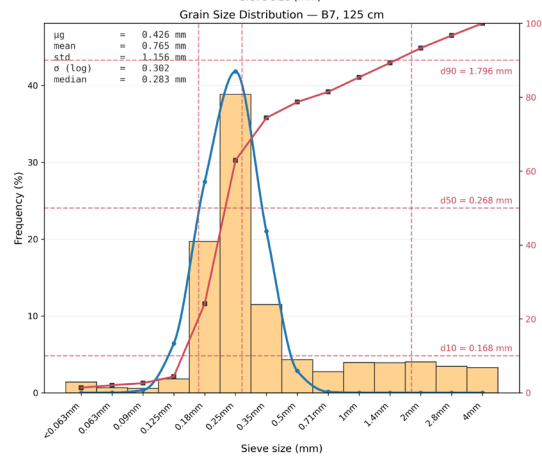
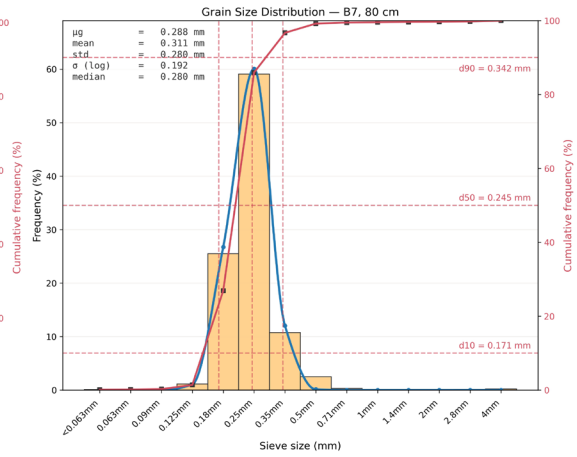
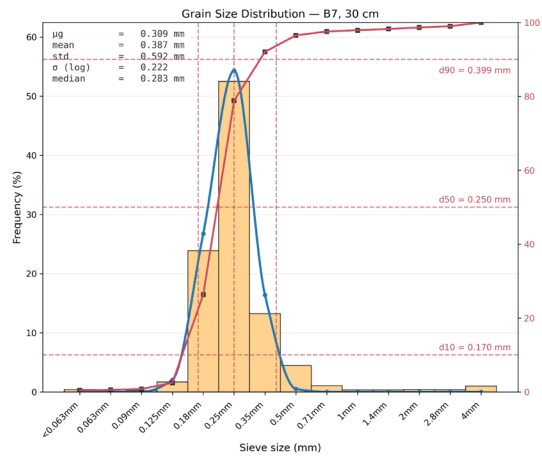
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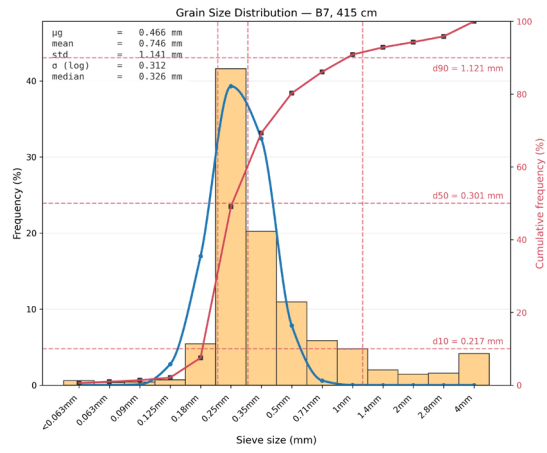
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10 Appendices

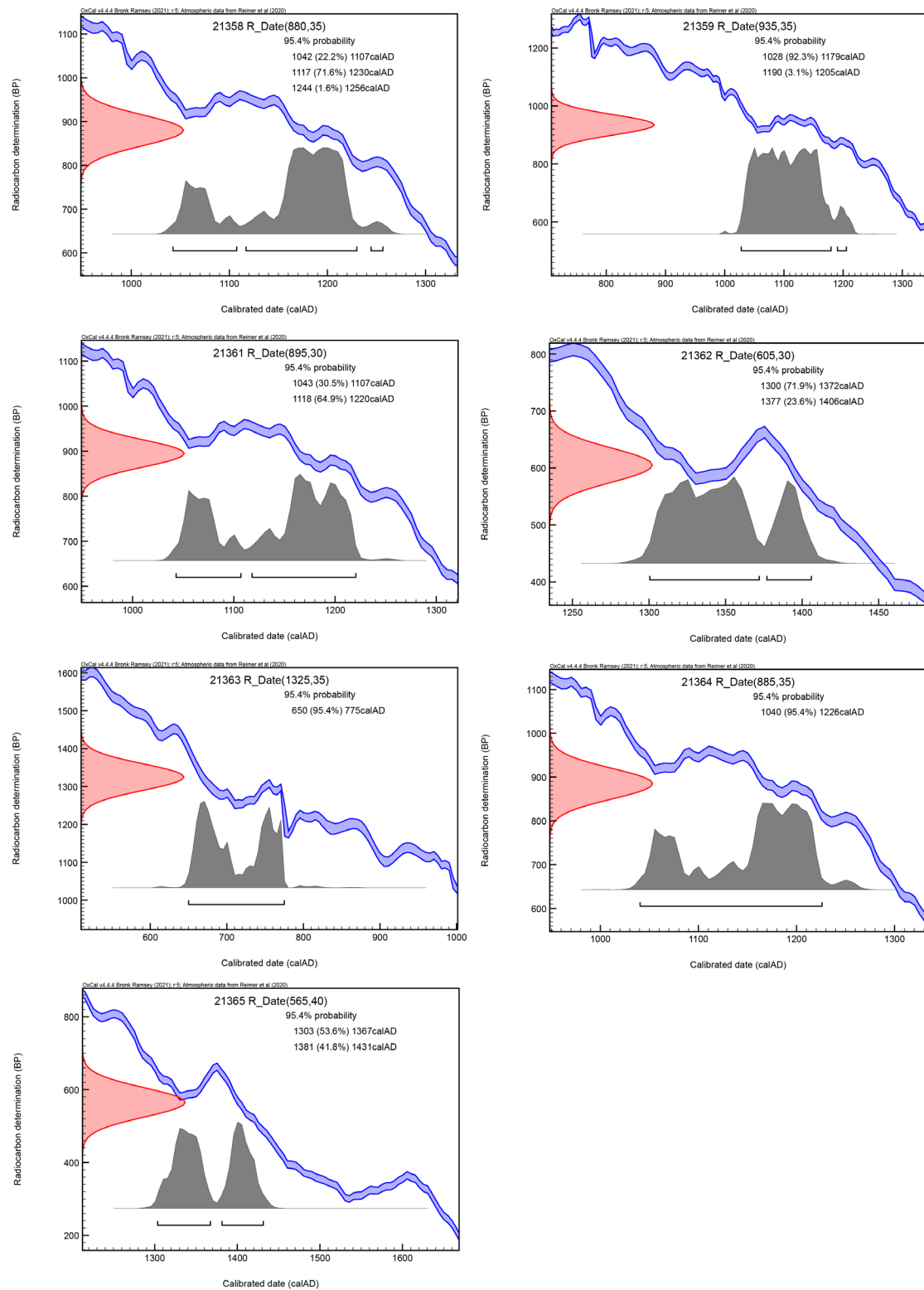
Appendix 1: All grain-size samples distribution:



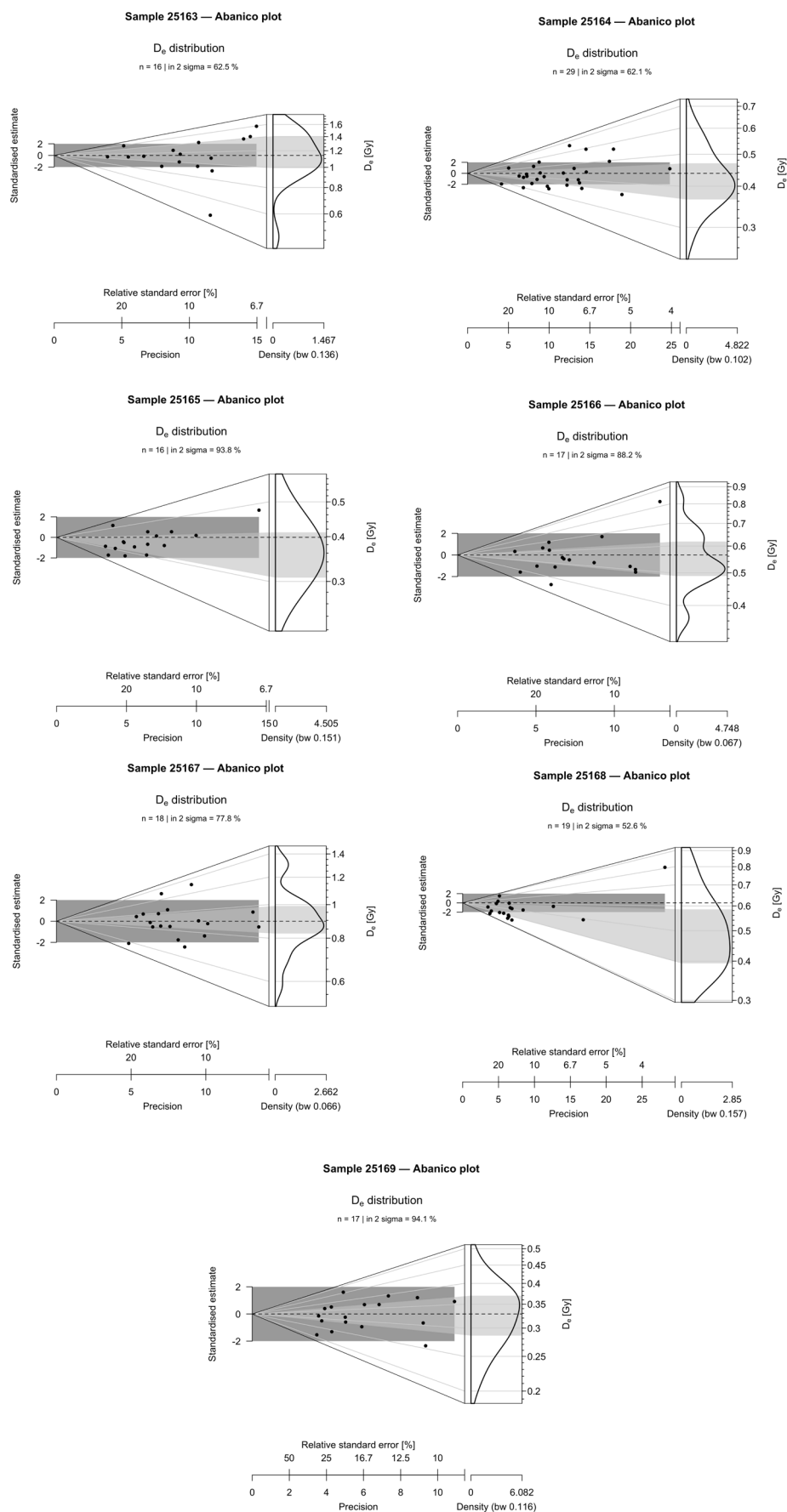




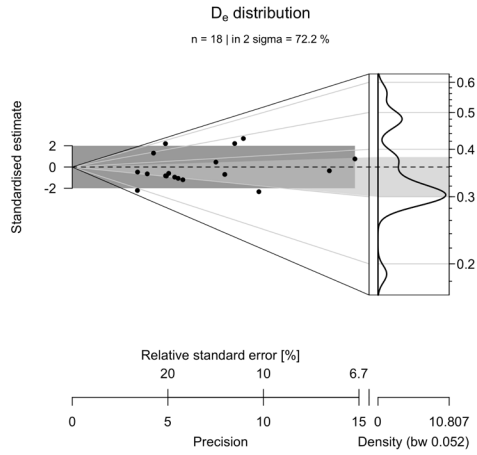
Appendix 2: All the single plot for radiocarbon dating:



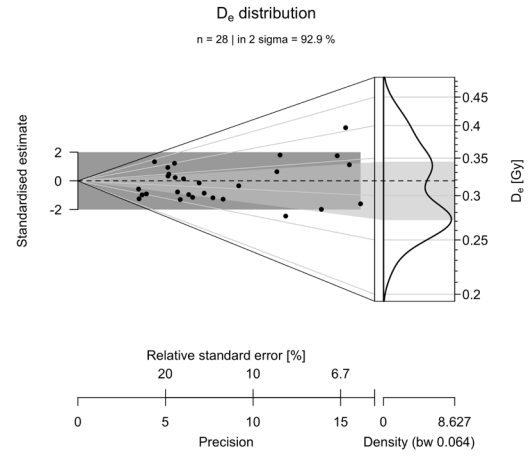
Appendix 3: The Abanico plots for the remaining 13 samples



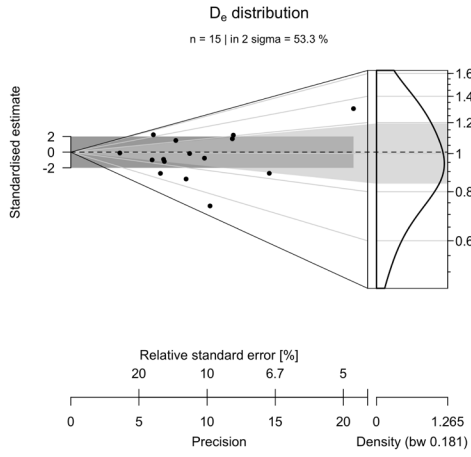
Sample 25170 — Abanico plot



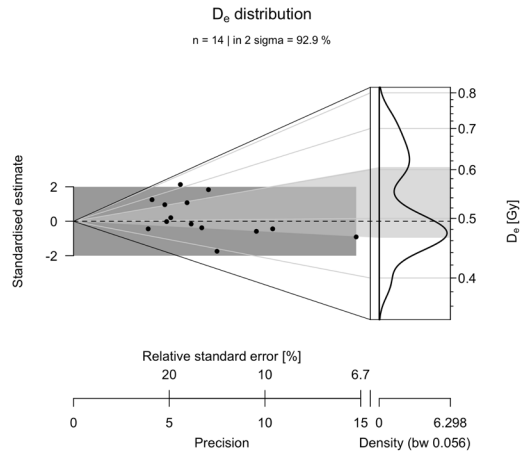
Sample 25171 — Abanico plot



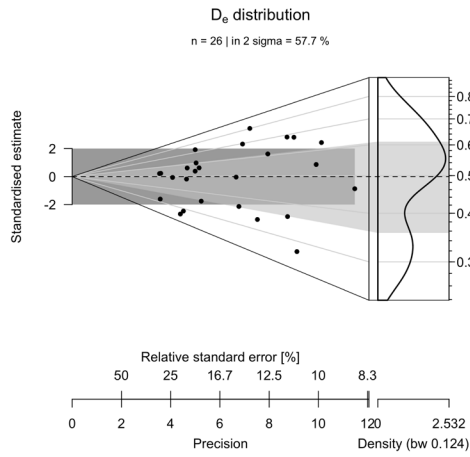
Sample 25172 — Abanico plot



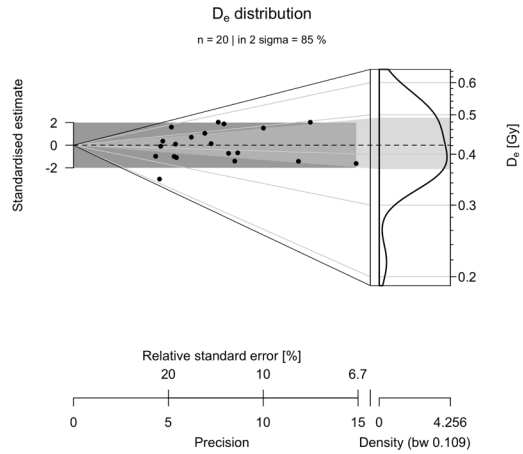
Sample 25174 — Abanico plot



Sample 25175 — Abanico plot



Sample 25198 — Abanico plot



Appendix 5: Table of measured water contents of OSL samples

Sample ID	Tare (g)	Field sample (g)	Saturated sample (g)	Dry sample (g)	Field water content (g)	Saturated water content (g)
25162	79.91	188.22	206.13	184.03	4.02%	21.23%
25163	86.56	241.61	271.50	234.26	4.98%	25.21%
25164	85.45	183.39	205.80	177.22	6.72%	31.14%
25165	94.92	207.50	230.34	193.52	14.18%	37.34%
25166	88.45	182.07	203.00	176.28	6.59%	30.42%
25167	81.11	192.16	212.84	187.97	3.92%	23.27%
25168	83.66	182.98	203.49	178.18	5.08%	26.78%
25169	87.06	182.39	202.18	176.56	6.51%	28.63%
25170	89.14	188.70	209.84	181.03	8.35%	31.35%
25171	79.30	184.78	208.41	161.13	28.90%	57.78%
25172	82.00	190.53	205.80	180.66	10.00%	25.48%
25173	89.97	199.76	217.60	192.14	7.46%	24.92%
25174	87.79	215.94	244.80	211.49	3.60%	26.93%
25175	83.68	204.66	228.80	198.07	5.76%	26.86%
25198	81.17	188.45	211.90	179.38	9.24%	33.11%

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