Age limits on Middle Pleistocene glacial sediments from OSL dating, north Norfolk, UK.

Steven M. Pawley[1]*, Richard M. Bailey[2], James Rose[1], Brian S.P. Moorlock[1,3], Richard J.O. Hamblin[1,3], Steven J. Booth[1,3], Jonathan R. Lee[1,3].

[1]Department of Geography, Royal Holloway, University of London, Egham, Surrey, TW20 0EX, UK.
[2]School of Geography, Oxford University Centre for the Environment, University of Oxford, OX1 3QY, UK.
[3]British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK.

*correspondence to: S.M. Pawley, Department of Geography, Royal Holloway, University of London, Egham, Surrey, TW20 0EX, UK.
Email: S.M.Pawley@rhul.ac.uk

Abstract

The lowland region of north Norfolk contains some of the best preserved evidence for glacial deposition during the Middle Pleistocene in northwest Europe. Despite the importance of these deposits, there is limited chronological control and it is debated whether they belong to a single glaciation, equated to the Anglian glaciation (Marine Isotope Stage 12), or represent deposition over a number of Middle Pleistocene cold stages. In order to develop an improved chronology for glaciation in this region, we obtained 18 samples for optical stimulated luminescence (OSL) dating from glacial outwash facies. Samples of coarse-grained quartz sand were measured using the SAR (single aliquot regenerative-dose) protocol. The low radioactive isotope concentrations in sediments of this region enable the traditionally accepted age limit of luminescence dating to be extended. The form of the dose response curves, pre-heat plateaux tests, and dose recovery experiments also indicate that laboratory doses can be reliably measured in these samples. Age overestimation due to partial bleaching is thought to be insignificant. The OSL ages suggest that the glacial sediments studied were deposited during MIS 12 rather than in different post MIS 12 stages.

1. Introduction

The growth and decay of northwest European Pleistocene ice sheets is recorded in extensive terrestrial glacigenic sequences that are present around the margins of the North Sea basin (Fig. 1a). The chronology of the younger component of these deposits during the Last Glacial Maximum (LGM) is relatively well established from the application of a range of absolute and relative dating techniques (Clark et al., 2004). However, considerably less is known about the extent and timing of earlier periods of Pleistocene glaciation, despite the fact that these had considerable effects on global climate and exerted a significant geological and geomorphologic impact on the formerly glaciated regions.

In Britain, evidence of Middle Pleistocene glaciation occurs widely across lowland areas of eastern England where thick glacial sequences were preserved outside of the (LGM) ice limit (Fig. 1b). This evidence is represented by a particularly well exposed and intensely studied sequence of till and outwash sediment in north Norfolk (Fig. 1c) that has provided a detailed record of terrestrial glacial processes and glacier events in lowland Britain and in the adjacent North Sea (Ehlers and Gibbard, 1991). However, establishing the age of such glacial sequences has been difficult because they are beyond the radiocarbon timescale and geological materials suitable for other radiogenic dating methods (U-series, K-Ar, Ar-Ar) are generally absent, or destroyed by the act of glaciation (Bowen et al., 1986; Rose, 1989). Consequently, there is long standing debate into the chronology of these glaciations with most information relating to the timing of glacier expansion being inferred from the deep-marine isotope record (Shackleton et al. 1990).

Early workers attempted to derive a glacial chronology by placing the glacigenic sequence of northern East Anglia into a three-fold stratigraphic scheme with two extensive periods of glaciation occurring prior to the LGM. These glaciations were known from oldest to youngest as the Anglian and Wolstonian Stages (Fig. 1a), and were correlated with the Elsterian and Saalian glaciations of northwest Europe respectively (Mitchell et al., 1973). The view of two Middle Pleistocene lowland glaciations persisted in Britain until deposits relating to the Wolstonian Glaciation in the English Midlands (Shotton, 1986) and northern East Anglia (Baden-Powell, 1948; West and Donner, 1956; Bristow and Cox, 1973; West, 1977, Straw, 1983) were subsequently re-interpreted as Anglian in age (Perrin et al., 1979; Rose, 1987, 1989, 1991). As a result, the concept of the Wolstonian Glaciation in Britain was abandoned leaving the Anglian glaciation as the only extensive Middle Pleistocene glaciation.

Since this stratigraphic revision, the age of the Anglian/Elsterian glaciation has been widely attributed to Marine Isotope Stage (MIS) 12 (480-430 ka BP) (Bowen et al., 1986; Shackleton et al., 1990), although a correlation with MIS 10 (365-335 ka BP) has also been suggested (de Jong., 1988; Geyh and Müller, 2005). Previously in Britain, this age attribution has been inferred from: (1) stratigraphic relationships with temperate stage deposits that overlie and underlie the glacial sequence (Pike and Godwin, 1956; West, 1956, 1980; Shackleton and Turner, 1967; Turner, 1970; Hart and Peglar, 1990); and (2) the correlation of the glacial sequences with the Thames river terrace stratigraphy and the number of terrace/aggradation cycles constrained by amino-acid racemization (AAR) geochronology (Bowen et al., 1986, 1989; Bridgland, 1994). In north Norfolk, temperate deposits that underlie the tills have been assigned to the Cromerian Complex Stage and at several localities, overlying interglacial sediments have been assigned to the Hoxnian Stage on account of their pollen assemblage signatures (Rose, 1989; Hart and Peglar, 1990; Banham et al., 2001). However, the correlation of these deposits with the marine isotope record remains uncertain because climatic similarities between different interglacial stages as well as local environmental factors make it impossible to correlate patterns of vegetation development with any one particular interglacial stage (Tzedakis et al., 2001). In addition where absolute age estimates exist, different deposits with Hoxnian pollen affinities have been dated to both MIS 9 and MIS 11 (Bowen et al., 1989; Rowe et al., 1997; 1999; Grün and Schwarcz, 2000; Geyh and Müller, 2005).

More recent stratigraphical schemes have identified a greater complexity in the glaciation record of the region. Based on new lithostratigraphical and mapping-based evidence tied-in with fluvial terrace sequences, high sea level deposits, and existing absolute age estimates, it has been proposed that north Norfolk was glaciated during at least four separate cold stages prior to the LGM (Fig. 1b) (Hamblin et al., 2000, 2005; Lee et al., 2004a; Clark et al., 2004). These cold stages include evidence for an early-Middle Pleistocene glaciation during MIS 16 (Lee et al., 2004a), extensive glaciation of eastern and central England during the Anglian Stage (MIS 12), as well as post-Anglian incursions of ice correlated with MIS 10 and MIS 6 (Hamblin et al., 2000, 2005; Clark et al., 2004).

Whilst the more recent stratigraphic re-appraisal has been supported by possible evidence of glaciation during MIS 10 in the Upper Thames catchment (Sumbler, 1995, 2001), and partial age constraints on material bracketing likely MIS 6 deposits in west Norfolk (Gibbard et al., 1992; Rowe et al., 1997) and tills in East Yorkshire (Bateman and Catt, 1996), direct dating of the glacial succession itself has not been previously attempted. The divergence of views relating to the chronology of glaciation in lowland Britain also highlights the clear need for an increased use of absolute dating methods and a reduced reliance on dating based upon correlation of widely spaced and ambiguous evidence without robust age control.

The aim of this paper is therefore to develop an improved chronology for the glacial sediments in north Norfolk based upon optical stimulated luminescence (OSL) dating of glaciofluvial sediments that can be directly associated with major episodes of ice sheet advance. Previous applications of luminescence dating in the region have been limited to a small number of TL measurements (Lewis, 1998; West et al., 1999), or OSL and TL dating of Late Pleistocene coversand deposits (Bateman, 1995, 1998; Clarke et al., 2001). However, more recent developments in OSL measurement protocols (Murray and Roberts, 1998; Murray and Wintle, 2000, 2003) along with rigorous testing of the technique (Murray and Olley, 2002; Murray and Funder, 2003) have indicated much potential for the extension of OSL dating into the Middle Pleistocene timescale. In this paper, it is demonstrated how OSL dating can be applied to such sequences under certain conditions, and the evidence presented impacts upon: (1) the timing of the Anglian glaciation; and (2) the suggestion that several post-Anglian glacial advances reached into the area. In particular, we focus on the relative timing of glaciation in the region and place age limits on glacial sequences that have been ascribed to MIS 6, 10, and 12. This study is of more than local importance because it contributes to the debate over the timing of major lowland glaciations in the UK as well as northwest Europe (Beets et al., 2005; Geyh and Müller, 2005; Ehlers and Gibbard, 2004).

2. Stratigraphic setting

This study examines glacial sediments from the region of north and northwest Norfolk (Fig. 1c). The glacial geology of this region has been studied extensively over the past ~150 years. In general terms, the glacial succession is traditionally thought to have been deposited by a number of advances of ice lobes entering the region from the north and from the southwest (Fig. 2) (West and Donner, 1956; Perrin et al., 1979; Rose, 1992; Ehlers et al., 1987, 1991; Fish and Whiteman, 2001; Lee, 2003; Pawley, 2006). In the west of the study region, highly chalk-rich tills locally termed the Weybourne Town Till extend eastward of the chalk escarpment and form a degraded till plain across the central part of the study area (Pawley et al., 2004; Pawley, 2006). Till thicknesses vary considerably from 1-2 metres to in excess of 50 m. Glaciofluvial and glaciolacustrine facies are also present where they are complexly inter-stratified within the till sequence. Traditionally, tills within this assemblage have been referred to informally as Marly Drift and were considered to represent a chalk-rich facies of both the Lowestoft Formation (Table 1) and in places part of the North Sea Drift (Perrin et al., 1979). Two phases of ice flow are generally recognised with an early southwest-northeast movement of ice from central England and a later north-south ice movement across chalk on what is now the bed of the North Sea (Fig. 2) (Baden-Powell, 1948; West and Donner, 1956; Perrin et al., 1979; Straw, 1983; Ehlers et al., 1987, 1991; Fish and Whiteman, 2001). The source of both of these ice lobes is thought to be northern Britain. The Lowestoft Till has widely been attributed to the Anglian Glaciation which is correlated with MIS 12 (Bowen et al., 1986; Shackleton et al., 1990). However, an alternative correlation with MIS 10 has also been proposed for some of the chalk-rich till facies in this region (Hamblin et al., 2000, 2005; Clark et al., 2004).

Glacial sediments in the eastern part of the study region consist of multiple brown to grey-coloured sandy and chalky tills that are separated by glaciolacustrine and glaciofluvial sediments (Banham, 1988; Hart and Boulton, 1991; Lunkka, 1994; Lee et al., 2004b). Extensive tracts of coarse-grained glaciofluvial sediment separate the different tills and cap the sequence, the latter including outwash fan sediments that form part of an east-west striking push moraine ridge complex, known as the Cromer Ridge (between Sheringham and Trimingham) (Hart, 1990). Historically, this assemblage has been known as the North Sea Drift Formation and has been interpreted to represent subglacial till deposition followed by proglacial glaciotectonic deformation of the tills and overlying outwash plain sediments during an advance of ice moving directly off sandy North Sea bed sediments to the northeast (Perrin et al., 1979; Banham, 1988; Hart, 1990; Hart and Boulton, 1991; Hart and Roberts, 1994; Lunkka, 1994; Lee et al., 2004b; Pawley et al., 2005; Roberts and Hart, 2005). Because the sandy tills interdigitate with and are overlain by chalk-rich tills between the Glaven valley and northeast Norfolk (Fig. 1c), both the North Sea Drift and Lowestoft formations have previously been attributed to a single glacial event reflecting ice lobe movements over differing bed materials (Perrin et al., 1979; Banham, 1988; Hart and Boulton, 1991; Lunkka, 1994). Recent investigations have recognised a more complex stratigraphy for the glacial deposits of the region (Hamblin et al., 2000, 2005; Lee, 2003, Lee et al., 2004a), which is the basis of a more complex glacial history involving ice sheet advances over several Middle Pleistocene glacial cycles (MIS 16, 12, 10, and 6) (Hamblin et al., 2000, 2005; Clark et al., 2004). The local names for these units are detailed in Table 1.

3. Methods

3.1. Site locations and sediment description

This paper reports on the results of field investigation and luminescence sampling at five sites in the study area (Fig. 1c). The sites consist of exposures in quarry sections, farm cuttings and trial pit excavations into the deposits of ice lobes that flowed from both the north and southwest directions. Extensive field investigation was undertaken at these sites, including sedimentological logging, clast macrofabric analysis, measurement of glaciotectonic structures, as well as clast lithology, allochthonous palynomorph and heavy mineral provenancing (Pawley, 2006). Additional geological data were provided through regional mapping by the British Geological Survey. Shear plane and fold surfaces were excavated with a trowel and measured by recording the dip angle and dip direction of the surface. Clast macrofabrics were taken to provide an estimate of strain and infer local ice-flow direction by recording the dip and direction of 30-50 elongate clasts. Palaeocurrent directions were inferred from measuring the direction of the maximum dip angle of planar cross-bedded foresets. A summary of the sedimentary data is given in this paper in the form of vertical sedimentary logs using modified lithofacies schemes of Eyles et al. (1983) and Miall (1985).

3.2. Optical stimulated luminescence (OSL) dating

OSL samples were collected in opaque plastic tubes hammered into the face of a cleaned section. Samples were processed under subdued orange light in the luminescence laboratories at the Department of Geography, RHUL. For OSL dating, quartz was extracted from the bulk sample using standard laboratory techniques.

Briefly, carbonate and organic matter was removed using HCl and H_2O_2 washes respectively. The samples were then wet sieved to either 125-180 or 180-250µm. Heavy mineral grains were removed by density separation and the remaining grains were etched in 40% HF solution for 50 minutes. All samples were subsequently placed in flurosilicic acid for 5 days to dissolve any remaining feldspar grains, followed by an HCl wash for 1 hour to dissolve any fluorides. External dose rates were calculated from the concentration of radioactive isotopes (U, Th, K) determined by ICP-MS (inductively coupled plasma mass spectrometry) (Department of Geology, RHUL) and/or *in situ* dose rate measurements using an Ortec MicroNomad γ-spectrometer. The internal alpha and beta quartz dose was also estimated from the concentration of radioactive isotopes measured in four (~500 mg) samples of etched quartz by NAA (neutron activation analysis) undertaken by Becquerel Laboratories. The absence of heavy mineral grains and feldspars in the etched quartz samples was confirmed by the analysis of grain mounts under a petrological microscope and an absence of IR signal during OSL measurement. The dose rate conversion factors of Adamiec and Aitken (1998) were used throughout and the internal alpha dose contribution assumed an *a*-value of 0.03 ± 0.01 in the dose rate conversion (Mauz et al., 2006). The beta dose attenuation/absorption was accounted for using the factors of Mejdahl (1979). Cosmic ray contributions were calculated from the altitude, latitude and longitude of the section as well as the thickness and density of the overburden (Prescott and Hutton, 1994). *In situ* and saturated water contents were assessed from undisturbed sediment samples with dose rates being corrected for water attenuation as described by Aitken (1985).

Luminescence measurements were performed on two Risø OSL/TL-DA-15 systems using blue light LED stimulation (470 nm, ~40 mW/cm^3) and a U-340 detection filter. Laboratory irradiation used a ^{90}Sr/^{90}Y beta source which was calibrated against quartz which had been γ-irradiated quartz at the National Physical Laboratory (Teddington, UK). Prepared quartz grains were mounted onto 10 mm sized steel discs with the inner 2 or 9 mm part of the disc covered with a monolayer of grains using viscous silicone oil. The initial equivalent dose data presented in Pawley (2006) was subsequently corrected for a dose rate difference (9.8% Risø B; 5.8% Risø C) found to occur following machine calibration when using small aliquot sizes, and more stringent quality assessment criteria were also adopted (see below).

The single aliquot regeneration (SAR) protocol (Table 2) was used to estimate sample D_e values and all luminescence measurements were performed for 50s whilst the sample was held at 130°C to prevent re-trapping in 110°C TL trap (Murray and Roberts, 1998; Murray and Wintle, 2000, 2003). Four or five regenerative doses up to 380 Gy were used to bracket the D_e of each sample and either a 10 or 50 Gy test dose was used. The luminescence signal was integrated from only the initial part (0.3 or 0.6s) of the decay curve to increase the signal to noise ratio (Bannerjee et al., 2000) and to enhance the sampling of the most bleachable and thermally stable 'fast' component signal which dominates the start of the OSL decay curve. A background was subtracted from the last 10 s of the stimulation with the test dose background taken from the previous natural or regenerative measurement (Murray and Wintle, 2000).

Equivalent doses were calculated using a saturating exponential plus linear function in Analyst v3.07. In order to ensure sufficient quality and precision during each measurement aliquots were rejected from the analysis if: (1) the errors on their natural test dose exceeded 5%; (2) the difference between a repeated data point and the first regenerative measurement (the recycling ratio) exceeded 5%; (3) the OSL signal was depleted by >5% during a second repeat point following an IR rinse at the end of the measurement cycle (Duller, 2003); (4) the natural signal levels were less that 3 standard deviations of the background signal; (5) the natural signal was significantly greater than the highest regenerative dose; and (6) the relative error on the D_e was >30%. The unweighted mean D_e of these aliquots was used in the age calculations. Reported errors on each OSL date include systematic uncertainties from beta source calibration (3%, Armitage and Bailey, 2005), dose rate conversion (3%, Murray and Olley, 2002), and gamma-ray spectrometry calibration (3%) (Murray and Funder, 2003). Site-specific systematic uncertainties also include water content estimation (20%) and cosmic-ray contribution (calculated from Prescott and Hutton, 1994 using the density/thickness of overburden). Random uncertainties on each date include uncertainties from ICP-MS measurement (estimated at 5%) and the standard error of the D_e estimates. In the final age calculations, the overall uncertainty is based on the standard error of the OSL age distribution combined in quadrature with the shared-systematic uncertainties.

4. Site stratigraphy and OSL sample details

West Norfolk region - Glaciofluvial sediments associated with the highly chalk-rich tills were sampled for luminescence dating at three sites (Fig. 1c). In the west of the region, the site at Docking (TF 765357) is situated within an outwash tract interpreted as sandur plain deposited as the British Ice Sheet retreated westward (Straw, 1973; Pawley, 2006). Chalk-rich diamicton forms the basal unit and contains discontinuous clayey stingers. A clast fabric measurement produced a polymodal pattern with the strongest mode dipping towards the WNW (Fig. 3a). The diamicton is overlain by 4 metres of chalky planar-laminated sand and silt which are folded and tilted steeply towards the WSW and are truncated/unconformably overlain by a unit of crudely bedded, coarse gravel containing a raft of chalky diamict. The sands/silts and gravels are separated by a deformed zone where a thin bed of brown, faintly laminated clayey silt acted as a ductile shear zone and is drawn-out into the overlying gravel sheet as sock-folds and stringers. The sequence is interpreted to reflect subglacial till and glaciofluvial deposition followed by proglacial compressive deformation with the outwash sediments glaciotectonically folded and emplaced as inclined slabs of sediment. The orientation of glaciotectonic folds and clast macrofabrics indicate an ice movement direction broadly from the west, consistent with the early movement of British ice out from the region of the Wash and Fen basin (Fig. 2). Four luminescence samples were taken from planar-laminated sand beds within the sequence (Fig. 3a)

Glaven valley area - Two sites were sampled for luminescence dating in the Glaven valley of northwest Norfolk (Fig. 1c). The area surrounding the sites contains a glaciofluvial landform assemblage with outwash fans, kames and outwash terraces, and a sinuous northeast-southwest striking esker ridge (Sparks and West, 1964). The landform assemblage has been interpreted as ice decay topography (Sparks and West, 1964) which formed during the retreat of the North Sea ice lobe that entered the region from the northwest (Pawley, 2006). Outwash deposits that occur in between two units of chalk-rich diamicton were sampled at Risinghill Plantation (TG 033403) which is situated on the western flank of the valley. Former quarry sections located 500 m to the south at Smoker’s Hole were described by Ehlers et al. (1987) as containing chalky till overlying coarse-grained outwash facies. The diamictons and outwash sediments exposed in the current quarry sections are disturbed by large-scale compressive glaciotectonic structures including overturned folds and kink-folding of gravel beds (Fig. 3b). Fold orientations indicate ice flow from a southwest direction typical of the early British ice flow similar to that found at Docking. Two luminescence samples were taken from chalky and pebble sand beds beneath the diamicton at the site.

A second site was sampled in the Glaven valley at Glandford quarry (TG 055415) which contains a more complex sedimentary succession (Fig. 4a). Glaciofluvial deposits occur at the base of the sequence and comprise metre-thick gravel sheets that fine upwards into thin sand-gravel alternations. Two diamicton units are present in overlying sections, the lower of these consisting of a matrix-dominated, yellowish brown coloured, sandy facies. This unit forms part of a glaciotectonised sequence along with slabs of chalky silt and sand that truncate underlying sands and gravels with a prominent northwest-dipping thrust fault (Fig. 4b). Shear planes and compressive folding of the sequence demonstrate that slabs of the diamicton and glaciolacustrine sediment were vertically stacked by glaciotectonic thrusting (Fig. 4b). Clast fabric measurements, shear plane and fold orientations indicate that ice moved directly off sandy North Sea bed sediments from a location to the north or northwest. The upper diamicton has a matrix-dominated texture with a white to pale yellow colour and a highly chalky, silt-rich matrix composition. The diamicton is deformed by folds which verge towards the northeast. The succession is interpreted to have formed as deposits of the North Sea ice lobe were overridden by southwest to northeast flowing mainland British ice (Pawley, 2006). Four luminescence samples were taken from gravels at the base of the sequence and two additional samples were obtained from glaciolacustrine sandy silt rafts that were thrust along with the lower diamicton deposit (Fig. 4a).

Sheringham region - In the eastern part of the study region, four luminescence samples were taken from the Briton's Lane Quarry (TG 170414), situated on the edge of the north face of the Cromer Ridge (Fig. 1c). The quarry dissects a 40 m thick sequence of glaciofluvial outwash which has been interpreted as an ice-marginal fan (Fig. 5) (Lee et al., 2004b; Pawley et al., 2005). The gravels are known to contain rare Scandinavian indicator rocks and either represent outwash from a Scandinavian ice sheet (Moorlock et al., 2000), or represent the reworking of Scandinavian lithologies from the North Sea bed (Pawley et al., 2005). A 57 metre thick deformed sequence of till and glacial lake sediment underlies the outwash sediments and these units overlie shallow-marine sediments of the early Middle Pleistocene Wroxham Crag Formation

(Fig.5) (Pawley et al., 2005). The outwash sediments represent the uppermost stratigraphic unit in the study region and form the present day land surface. They are interpreted as being deposited following a final ice advance from the North Sea basin which formed the Cromer Ridge as a push moraine complex. Therefore, the dates from this locality should place a minimum age limit on the underlying glacial sequence. Four luminescence dates were taken at this site from shallow-water glaciofluvial facies (Fig. 5) including planar laminated sand sheets interpreted as falling flow stage deposits, or sandy channel cut-fill structures developed on the surface of thick gravel bars.

Age control samples - Two luminescence samples were taken from Late Devensian (MIS 2) glaciofluvial sediments near Hunstanton (Fig. 1c). The stratigraphical position of these sediments is constrained by the relationship of the Late Devensian Holkham Till which overlies a Last Interglacial (MIS 5e) raised beach at Morston (Gale et al., 1988), and radiocarbon dates on the sediments of Glacial Lake Sparks, dammed by an ice-lobe situated in The Wash at *c*. 22 cal ka BP (West et al. 1999). The Holkham Till is also ascribed to the Late Devensian on the basis of a correlation with the Skipsea Till of Holderness (Madgett and Catt 1978), which was deposited after 18.5 ^{14}C years BP (Penny et al. 1969). The samples obtained in this study were taken from the Ringstead valley (TF 725405) which is infilled with till and glaciofluvial sediments, including an esker ridge and a meltwater channel that forms a drainage exit to the valley. The sediment-landform association has been interpreted as a proglacial lake and ice-marginal drainage channel following the encroachment of an ice lobe into the valley. Sand and gravel sheets that line the valley floor were interpreted by Straw (1960) to represent marginal deposits of a proglacial lake which drained westwards parallel to the ice margin and cut a deep gorge through an interfluve at Ringstead Downs. The luminescence samples were taken from mechanically dug trenches into the proglacial lake sediments. The geomorphic position of the samples, which were taken from a low-lying terrace on the northern valley side, and their sedimentology, composed of fine silty sands, climbing ripple lamination, and clayey silt drapes confirms that deposition occurred in a glaciofluvial/lacustrine deltaic/lake marginal environment.

These control samples are from a sedimentological and glaciological setting which is similar to that expected from some of the older samples with the depositional environment most closely matching that which is associated with the rafts of glaciolacustrine sandy silt that were thrust with sandy diamicton at Glandford. They may therefore serve to broadly assess the propensity for partial bleaching that may be expected in the older samples.

5. Chronology

5.1. Luminescence measurements

For older sediments, it is important to assess whether laboratory radiation doses in quartz can be measured reliably up to the maximum expected age of the deposits. The external dose rates were found to be low across the region (0.61 ± 0.09 Gy/ka^{-1}) which is particularly advantageous for dating sediments of Middle Pleistocene age because saturation of the luminescence signal occurs more slowly. The average internal dose to quartz (Table 3), calculated to be 0.02 ± 0.01 Gy/ka is in the range of that previously reported from northwest European quartz (Mejdahl, 1987; Vandenberghe et al., 2003) and this forms only a minor contribution (2.0 – 4.3%) to the overall dose rate. Using these dose rates, the maximum expected age of the deposits (late MIS 12 or ~430 ka BP, Shackleton et al., 1990) can be expected to equate to a dose of ~250 Gy. Initial measurements showed that the luminescence signal continued to grow with increasing radiation dose to >400 Gy before signal saturation occurs (Fig. 6).

It is well known that prior to each OSL measurement pre-heating of each aliquot is needed to ensure that charge from light-sensitive, thermally-unstable traps is emptied (Aitken, 1998). To assess whether the measured doses are dependent on the preheat conditions, a pre-heat plateau test was performed on sample RH06-143. Groups of 8 aliquots were measured using the SAR protocol but the pre-heat temperature (PH1) was increased in 20°C increments from 180 to 280°C. No dependence of D_e relative to pre-heat temperature was observed (Fig. 7a) although inter-aliquot scatter was significantly reduced when pre-heat temperatures of 240 or 260°C were used. Recycling ratios showed no dependence on pre-heat temperate (Fig. 7b) and levels of signal recuperation remained low at <2% (Fig. 7c). All subsequent measurements therefore used a pre-heat temperature of 260°C.

Dose recovery tests were also used to assess the reliability of the laboratory-induced dose response curve and adequacy of the pre-heat conditions. Seven samples with at least six aliquots per sample were bleached for 500s using white light at room temperature before they were stored at room temperature for 5 hours and bleached again. A known radiation dose similar to a late MIS 12 age attribution (250 Gy) was then administered. These aliquots were treated as unknown and measured using the SAR protocol. All samples recovered their known doses to within 10% and the mean ratio of measured/given dose is 0.98 ± 0.03 (Fig. 7d).

5.2. OSL age results

The results of the quartz OSL dating are shown in Table 4 alongside the dose rate data and D_e estimates from between 11 and 37 aliquots per sample. When the OSL ages are compared to the marine isotope curve (Fig. 8) derived from the ODP677 site (Shackleton et al., 1990), a relatively high degree of consistency can be seen in the distribution of dates which range from 391 ± 40 to 494 ± 43 ka BP. Any variation between individual dates is encompassed by scatter between multiple time-equivalent samples and thus there is no evidence that the ages systematically vary between different parts of the stratigraphic succession. All of the sample ages also lie within errors of a single cold stage and the dates approximately form a normal distribution (Fig. 8 inset) with a mean and overall uncertainty of 435 ± 21 ka BP, equivalent to MIS 12. It should also be noted that the standard deviation on the age distribution (28 ka) is less than the typical errors associated with each individual date (~50 ka). This strongly suggests that the glacial sequence was deposited near-concurrently within the age uncertainties.

The dates from the Late Devensian glaciofluvial sediments have a mean of 39 ± 2 ka BP. These ages are however older than that of a Late Devensian age attribution (*c.* 22 ka BP). An earlier Late Pleistocene ice sheet maximum and deglaciation age of ~40 ka BP in this area has been suggested by Bowen et al. (2002). However, based on the radiocarbon dates which suggest that Glacial Lake Sparks was ice-dammed in the Wash at ca. 22 ka BP (West et al., 1999), incomplete sunlight resetting (partial bleaching) of the OSL signal is considered more likely with the difference between the expected and measured age equating to a residual dose of ~20 Gy.

6. Discussion

6.1. Additional sources of age uncertainty

Partial bleaching of the luminescence signal during sediment transport can represent a problem in fluvial and glaciofluvial environments, leading to an overestimation of the depositional age. Partial bleaching is particularly significant in younger samples where the proportion of residual charge is likely to be large in comparison to the burial dose, leading to considerable age overestimation. However, based on the residual dose found in the MIS 2 glaciofluvial sediments, a radiation dose left from incomplete resetting is likely to be insignificant relative to the large doses that the Middle Pleistocene samples would have received during burial. In order to further test this, we used the approach of Bailey (2003) who suggested that partial bleaching may be detected if D_e is assessed as a function of the illumination time (referred to as $D_e(t)$ plots). The OSL decay curve is made up of the fast, medium, and slow components, each of which decay at different rates during light exposure and thus have different bleachabilities. In a fully bleached sample, the fast and medium components are expected to be completely reset, resulting in a flat $D_e(t)$ plot. Rising $D_e(t)$ values may occur in partially bleached samples due to an increasing contribution from the medium component which is harder to bleach. Several of the samples show flat $D_e(t)$ plots (Fig. 9a) with a Z value (the ratio between the D_e calculated from the initial 0.3s of the OSL decay curve and the D_e calculated from the last integration period) being indistinguishable from unity. Because the relative rise of $D_e(t)$ plots due to partial bleaching is reduced following further irradiation (both components accumulate charge therefore the relative remnant signal contribution to both components is reduced), it is still possible that these samples were not completely bleached. However, the $D_e(t)$ plots demonstrate that any remnant signal is likely to be small in comparison to the accumulated dose during burial. In contrast, a number of samples show falling $D_e(t)$ trends (Fig. 9b) with an average decrease of 7% as the signal integration time was extended from 0.3s to 2.4s (Fig. 9c). Jain et al. (2003) suggest that a falling $D_e(t)$ trend results from a thermally unstable slow component contribution which produces age underestimation. Therefore, it is more likely that some of our samples slightly underestimate rather than overestimate the depositional age. Murray et al. (2007) presented a simple method to assess severity of this effect by averaging the decrease in $D_e(t)$ over all of the samples measured, displaying these results as a $D_e(t)$ plot, and extrapolating the decreasing $D_e(t)$ trend to zero (Fig. 9d). These results suggest that only a 2-4% age underestimation is likely when calculating D_e's from the initial 0.3 or 0.6s part of the OSL signal with the caveat that a slow component could still be present even when the $D_e(t)$ is extrapolated to zero. However, a 6% age underestimation on average is expected when using the first 1.2s of the OSL signal. This factor, in conjunction with the beta source re-calibration explains the difference in age estimates in earlier unpublished data which were scattered between MIS 10 and MIS 12 (Pawley, 2006).

The water content of the sediment has an attenuating effect on the dose rate and therefore introduces a component of age uncertainty (Aitken, 1985). In considering water contents it is noted that the samples taken from quarry sections were situated above the present day groundwater table and therefore are unlikely to have been in continuous saturation. However, because these samples were also covered by tens of metres of sediment, we consider that their water contents are unlikely to have been significantly lower than their present day values measured from quarry sections which have partially dried-out upon exposure and lowering of the groundwater table. The assumed water contents were therefore averaged from the present day values and the measured saturated values, and a 25% relative uncertainty was applied to encompass wet or dry periods. In the younger samples taken from trial pit excavations, the present day water content was considered to represent a good approximation due to the near-surface position of the samples. If the estimated moisture values are too high or low within geologically reasonable limits, the ages are likely to be over- or underestimated in the order of ~5%. An additional source uncertainty relating to the dosimetry of the sediment comes from the potential for the environmental dose rate to change over time due to the leaching or addition of radiogenic isotopes, principally occurring in the U^{238} decay chain (Olley et al., 1997). However, because only 15 ± 2% of the total dose rate is derived from the uranium radioactivity in these sediments, even severe disequilibrium would result in a relatively small error.

6.2. Discussion of chronological significance

Previous interpretations over the chronology of Middle Pleistocene glaciation in eastern England can broadly be divided into three stratigraphical schemes. These consist of: (1) a two-stage scheme with glaciation occurring during the Anglian and Wolstonian stages (Baden-Powell, 1948; West and Donner, 1956; Mitchell et al., 1973; Gibbard et al., 1992; Banham et al., 2001); (2) a single-stage scheme with extensive glaciation occurring during the Anglian Stage (MIS 12) (Perrin et al., 1979; Banham, 1988; Hart and Boulton, 1991; Ehlers and Gibbard, 1991; Lunkka, 1994); and (3) a multiple-stage scheme with glacial advances occurring in several Middle Pleistocene cold stages (Hamblin et al., 2000; 2005; Clark et al., 2004; Lee et al., 2004a). The last of these schemes (Table 1) is based upon recognition of several lithologically distinct till sheets in northeast Norfolk, separated by glacial retreat sediments and which are interpreted to reflect glacier advances during eccentricity-forced climate cooling. The tills associated with these advances are from oldest to youngest, locally known as the Happisburgh, Walcott, Bacton Green, and Weybourne Town tills (Hamblin et al., 2000, 2005; Lee et al., 2004b). The earliest of these glaciations is represented by the Happisburgh Formation which is correlated with MIS 16 (Lee et al., 2004a). This is not subject of this paper because deposits associated with this ice advance do not outcrop within the study area. The Walcott Till is correlated with the Anglian Lowestoft Formation (MIS 12) and the Bacton Green and Weybourne Town tills form the newly defined Sheringham Cliffs Formation, and are correlated with MIS 10 (Hamblin et al., 2000, 2005; Clark et al., 2004). In addition, a younger ice advance forming the Cromer Ridge push moraine and depositing thick outwash fan sediments of the Briton's Lane Formation has been correlated with MIS 6 (Hamblin et al., 2000, 2005)

The SAR OSL age estimate of 435 ± 21 ka BP for the glacial sequence is consistent with a previous attribution of Anglian stage glacial deposits to MIS 12 based on ESR dating (404^{+33}_{-42} ka BP) suggesting that Hoxnian temperate stage lake sediments overlying Lowestoft Formation till at Hoxne are of MIS 11 age (Grün and Schwarcz, 2000). It is furthermore in keeping with U-series dating of Hoxnian deposits to MIS 11 at Marks Tey (Rowe et al., 1999). At both of these sites, continuity in sedimentation is thought to be well demonstrated because the organic deposits rest in kettle holes or tunnel valleys cut into Anglian Lowestoft Till. The reliability of the Marks Tey U-series ages has since been questioned and based on a re-evaluation of the geochemical data, the Anglian/Elsterian has also been correlated with MIS 10 (Geyh and Müller, 2005). AAR geochronology also suggested that the Hoxne type site was correlated with MIS 9 (Bowen et al., 1989), although this was in contradiction with the revised ESR ages of Grün and Schwarcz (2000). However, amino-acid racemization (AAR) geochronology at additional sites such as Barnham (Preece and Penkman, 2006) as well as TL dating (471 ± 51 ka BP) and U-series ages (ca. 390-410 ka BP) at West Stow (Lewis, 1998; Preece et al., 2000) indicate that the Lowestoft Till is overlain by MIS 11 deposits at a number of localities and thus must pre-date MIS 11. ESR ages on tooth enamel at three locations in the West Runton Freshwater Bed also suggest that the overlying glacial sediments were deposited after

MIS 13 (Rink et al., 1996). However, this estimate was lacking in precision with ages ranging from 346 ± 55 (early-uptake model) to 464 ± 84 ka BP (linear-uptake model).

In west Norfolk at Tottenhill, the U-series dating of a peat unit within the Nar Valley Formation to MIS 9 has raised some questions regarding the MIS 12 attribution of glacial deposits attributed to the Anglian glaciation (Rowe et al., 1997; Hamblin et al., 2000, 2005; Clark et al., 2004). The Nar Valley Formation rests in a glacially modified valley filled with Woodlands Farm Till at its base, which is traditionally correlated to the Anglian Lowestoft Formation (Ventris, 1996). This is overlain by glaciolacustrine sediments that pass conformably upwards into the Nar Valley Clay (shallow marine transgressive deposit) and Nar Valley Freshwater beds (including the peat from which the U-series date was obtained). The pollen sequence of the Nar Valley Clay and Freshwater beds record the last part of a cold stage and the early part of a temperate stage, suggesting that continuous sedimentation occurred between the glaciogenic sediments and the overlying clays and peats (Ventris, 1996). Hence the underlying Woodlands Farm Till could date to MIS 10 (Scourse et al., 1999) and an alternative correlation with glacial deposits (the Oadby Till) in the English Midlands has been proposed (Hamblin et al., 2000, 2005; Clark et al., 2004). An MIS 10 age has also been suggested for the Oadby Till based on the correlation of the glacial deposits with the river terrace stratigraphy of the Upper Thames Catchment (Sumbler, 1995, 2001). On the other hand, the assumption that a continuity of sedimentation exists between the glacially-modified valley and its infill of glaciolacustrine and estuarine sediments may prove incorrect because these valleys are known to have complex histories (Cox, 1985), leaving potential for hiatuses to exist within their sedimentary sequences.

The alternative correlation of part or all of the glacial sequence with MIS 10 is also precluded by the results presented within this study because the majority of dates are fixed within an MIS 12 timescale irrespective of any plausible water content variations or radioactive disequilibrum. Consequently if the MIS 12 attribution of glacial sediments at several sites in north Norfolk is accepted, this presents a major problem for an MIS 10 age attribution of the Oadby Till in the English Midlands. This is because the Oadby Till is known to have been deposited from the northeast by ice flowing onshore into The Wash and carrying chalk from the bed of the North Sea basin (West and Donner, 1956; Rice 1968, 1981; Perrin et al., 1979; Rose, 1992). Thus, any ice sheet which extended into the English Midlands by flowing through The

Wash must also have covered west and north Norfolk. No evidence was found within this study that the sites dated to MIS 12 in north Norfolk have been subsequently overridden. If the ice flow trajectory of the Oadby Till was not through The Wash but rather from central Lincolnshire (Fish and Whiteman, 2001), ice would still be expected to have covered north Norfolk. Therefore, the lack of evidence for MIS 10 glaciation in north Norfolk suggests that the age of glacial deposits attributed to MIS 10 elsewhere requires further scrutiny.

The available OSL ages do not support the possibility that the tills and outwash sediments within the Cromer Ridge complex were deposited during MIS 6. This is because the dates from outwash overlying the glacial sequence at Sheringham and underlying the deposits of both the northwest and southwest flowing ice lobes at Glandford all indicate a substantially older age. Therefore it appears that any MIS 6 glaciation in the region must have had a similar or lesser extent to that of the LGM. Indirect evidence for glaciation in west Norfolk within the low-lying Fenland basin during MIS 6 is represented by glacial outwash sediments at Tottenhill (Gibbard et al., 1992). These outwash deposits overlie an interglacial peat within the Nar Valley Clay Formation which has been dated by U-series to 317 ± 14 ka BP, equivalent to MIS 9 (Rowe et al., 1997). They also underlie a possible MIS 5e palaeosol (Lewis and Rose, 1991). In this study however, we have found no evidence to suggest that ice sheets during MIS 6 advanced further south than this limit. The method of separating Middle Pleistocene glacial deposits into MIS 12, 10, and 6 glaciations based on morphostratigraphy and the interpretation that landforms such as the Cromer Ridge must date to a post-Anglian glaciation owing to their apparent morphological 'freshness' (Clark et al., 2004; Hamblin et al., 2005) is not supported by the dating results in this study.

7. Conclusions

- The age of 18 samples of glaciofluvial and glaciolacustrine outwash taken from six sites across north Norfolk was determined using OSL dating of coarse-grained quartz.
- The low radioactive isotope concentrations of sediments in this area enable the traditionally accepted age limit of luminescence dating to be extended into the Middle Pleistocene.

- The form of the dose response curves, pre-heat plateaux tests and dose recovery experiments also support that equivalent doses can be reliably measured in these samples throughout their lifetime.
- All of the luminescence ages presented here fall within the age range that is assigned to MIS 12 (Shackleton et al., 1990).
- An MIS 12 age for the glacigenic deposits of north Norfolk is at variance with the model proposed by Hamblin et al. (2000, 2005), but is in accord with previous age estimates from U-Series, ESR, and AAR dating of overlying organic deposits to the south of the study area which are correlated with MIS 11 (Bowen et al., 1986; Lewis, 1998; Grün and Schwarcz, 2000; Preece et al., 2000; Preece and Penkman, 2006).
- Widespread glaciation of the northern East Anglia region during MIS 10 is also not supported despite the U-series ages on overlying sediments (Rowe et al., 1997), and the relationship with the fluvial terrace stratigraphy of the English Midlands (Sumbler, 1995, 2001; Keen, 1999).
- The new age data raise serious questions over recent suggestions of an MIS 10 age for the Oadby Till of the English Midlands.
- The view that the Cromer Ridge was formed by an ice sheet advance equivalent to the MIS 6 glaciation of northwest Europe is not supported by the evidence presented in this study.

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Fig. 1. (a) Location of study area and traditional interpretation of the extent of northwest European Pleistocene ice sheets (adapted from Ehlers and Gibbard, 1991; Ó Cofaigh and Evans, 2007). (b) Extent of multiple Pleistocene ice advances in eastern England as recognised in the recent stratigraphic model of Clark et al. (2004) and Hamblin et al. (2000, 2005). (c) Site locations for OSL sampling. The LGM ice limit is also shown (Straw, 1960; Brand et al., 2002; Andrews et al., 2002; Pawley et al., 2006).

Fig. 2. Simplified ice flow patterns in eastern England adopted from Rose (1992). (1) Early (Lowestoft) ice flow phase from central England; (2) Late (Lowestoft) ice flow phase across chalk on what is now the bed of the North Sea and into the Wash and Fenland basin; (3) Generalised ice movement direction from the north associated with the deposition of brown to grey coloured, sandy till facies in northeast Norfolk.

Fig. 3. (a) Structure and stratigraphy of glaciotectonised planar laminated sands, silts, and gravels underlain by chalk-rich diamicton at the Docking quarry section. Four OSL samples were taken from sand beds, including one sample from a glaciotectonised raft; (b) The stratigraphic succession at Risinghill Plantation and OSL sampling locations. Lithofacies coding scheme is modified from Eyles et al. (1983). Dmm - diamicton, massive; Gcm - gravel, massive; Gch - gravel, horizontally bedded; Gmm - matrix supported massive gravel; Sm - sand, massive; Sh - sand, horizontally bedded; Sr - sand, rippled; Ssc - sand, crudely laminated; Fl - fines, laminated; Fm - fines, massive; d - deformed.

Fig. 4. (a) Representative stratigraphic logs for the Glandford quarry sections, clast fabric measurements, shear plane orientations, and the position of OSL samples. The lower diamicton unit is shown by the grey fill; (b) General section diagram showing structural deformation of the lower part of the Glandford sequence.

Fig. 5. Sedimentary log and OSL sample positions from sands and gravels at the Briton's Lane quarry. Small inset log shows the glacial and pre-glacial stratigraphy of underlying sediments from the borehole described in Pawley et al. (2005).

Fig. 6. SAR growth curves for samples RH-06-153 and 150 showing the natural (N) measurement, four regenerative points (R), and the zero point (Z). The growth curves are fitted with a saturating exponential plus linear fit.

Fig. 7. (a) Pre-heat plateau performed on RH06-143 with the De measured from groups of 8 aliquots using SAR but with the PH1 temperature incrementally increased from 180 to 280 C°; (b) effect of pre-heat conditions on recycling ratios; (c) effect of pre-heat temperature on recuperation; (d) dose recovery tests on 7 samples with a dose of 250 Gy.

Fig. 8. Comparison of OSL ages with the marine isotope record derived from the ODP677 site with Marine Isotope Stages numbered (Shackleton et al., 1990). Inset shows the age distribution as a histogram with a class interval width of 20 ka.

Fig. 9. (a) $D_e(t)$ plot for sample RH06-141 from Briton's Lane quarry. (b) Falling $D_e(t)$ plot for sample RH06-145 from Docking indicative of a slow component contribution. (c) Average Z values (the ratio between the D_e calculated from the initial 0.3s of the OSL decay curve and the De calculated from the last integration period, 2.4s) of all Middle Pleistocene samples showing a slight tendency for decreasing $D_e(t)$ trends. (d) Average D_e values for all samples plotted as a function of illumination time and normalised against the initial 0.3s integration internal. The data is well approximated by a quadratic fit and suggests that a 2-4% decrease in D_e is expected if the average D_e from the 0.3 or 0.6s interval is extrapolated to zero.

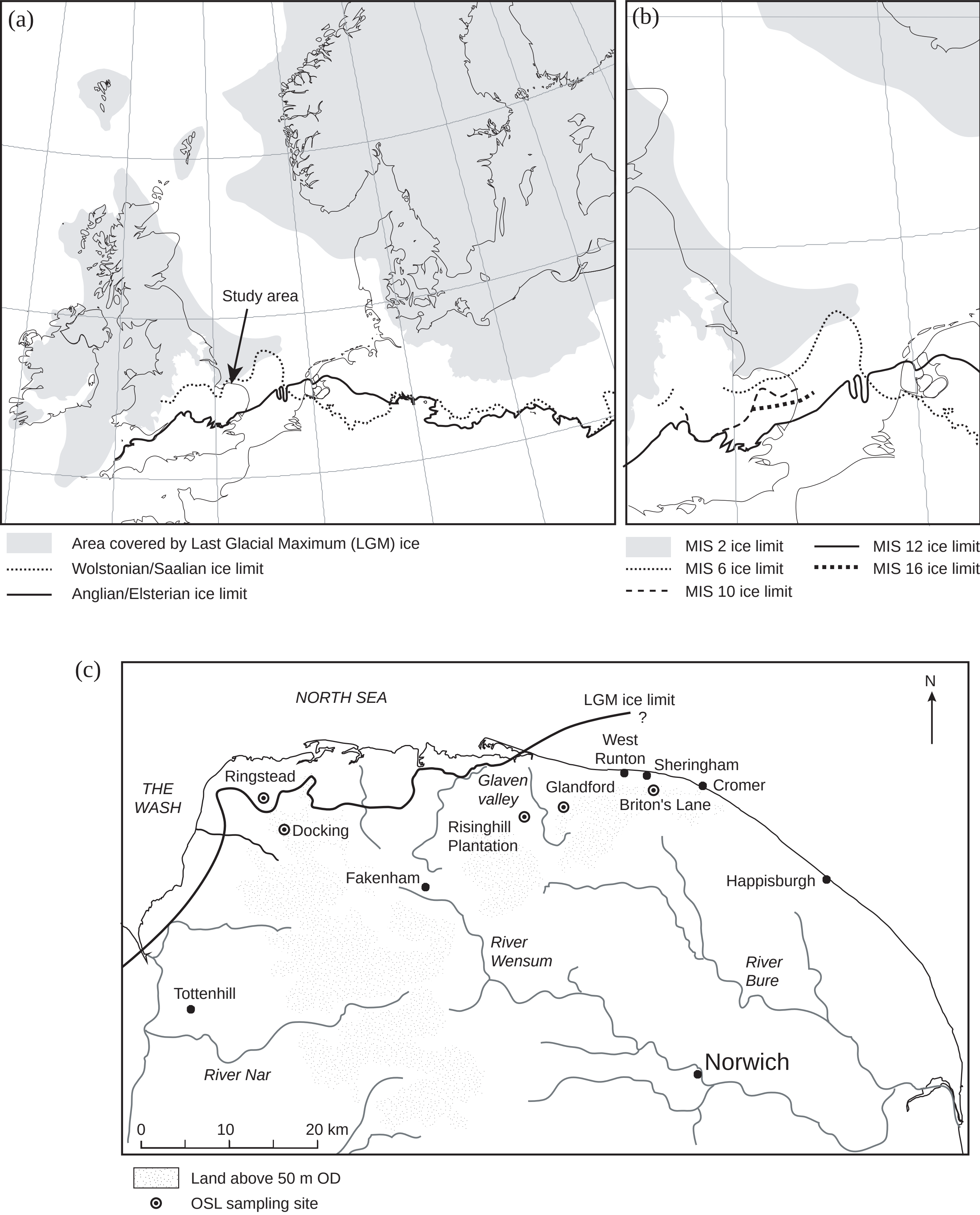

(a)
Study area
Area covered by Last Glacial Maximum (LGM) ice
Wolstonian/Saalian ice limit
Anglian/Elsterian ice limit
(b)
MIS 2 ice limit
MIS 6 ice limit
MIS 10 ice limit
MIS 12 ice limit
MIS 16 ice limit
(c)
NORTH SEA
LGM ice limit
?
N
THE WASH
Ringstead
Docking
Glaven valley
Glandford
West Runton
Sheringham
Cromer
Briton's Lane
Risinghill Plantation
Fakenham
Happisburgh
River Wensum
River Bure
Tottenhill
River Nar
Norwich
0
10
20 km
Land above 50 m OD
OSL sampling site

Fig. 1.

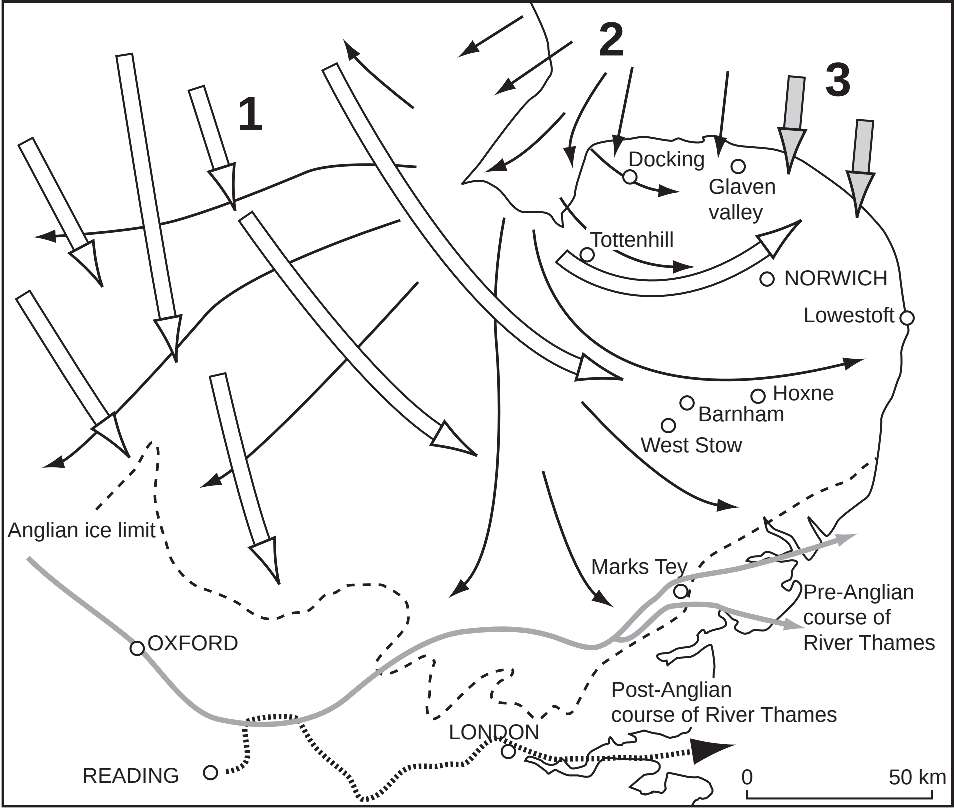

1
2
3
Docking
Glaven
valley
Tottenhill
NORWICH
Lowestoft
Hoxne
Barnham
West Stow
Anglian ice limit
Marks Tey
Pre-Anglian
course of
River Thames
OXFORD
Post-Anglian
course of River Thames
LONDON
READING
0
50 km

Fig. 2.

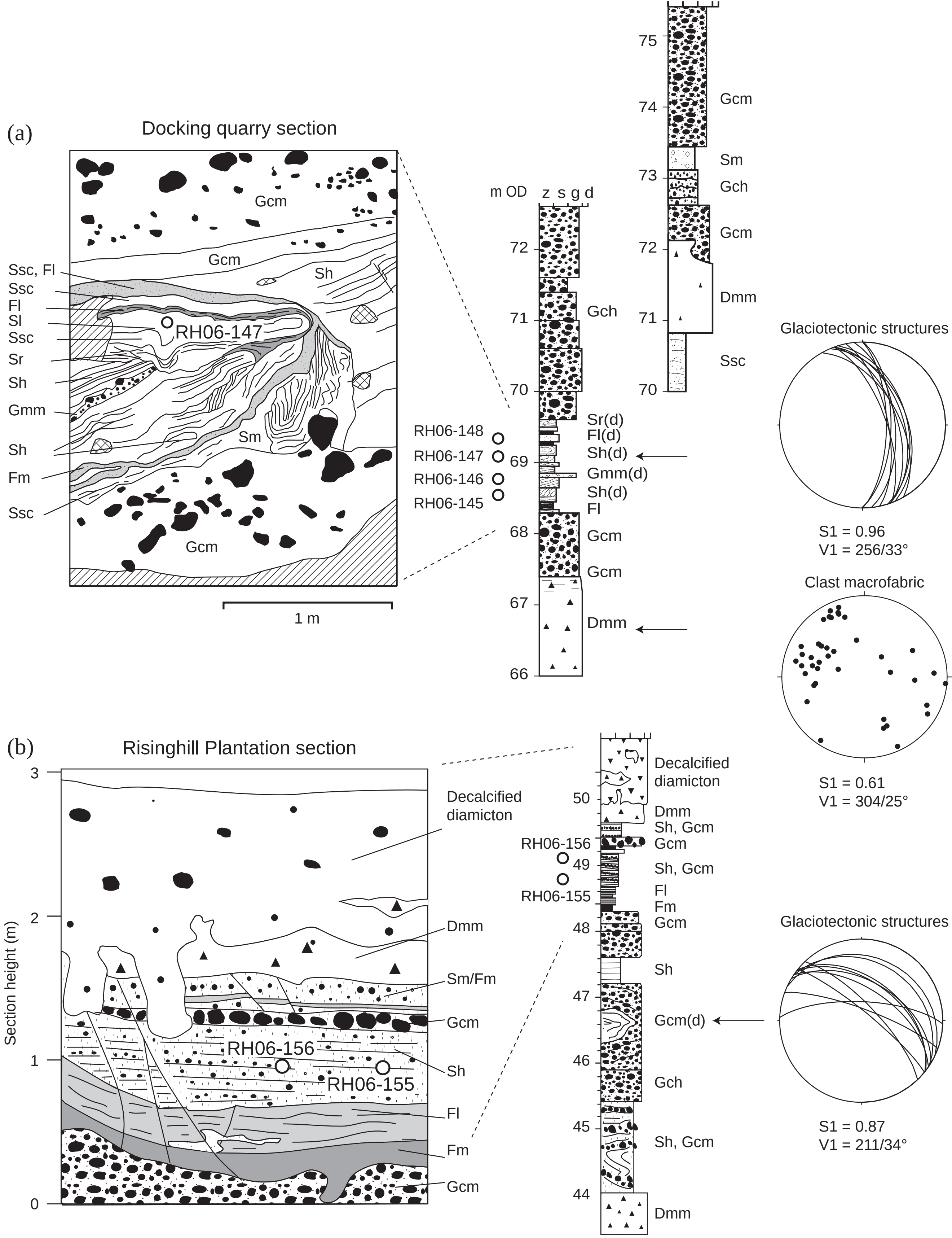
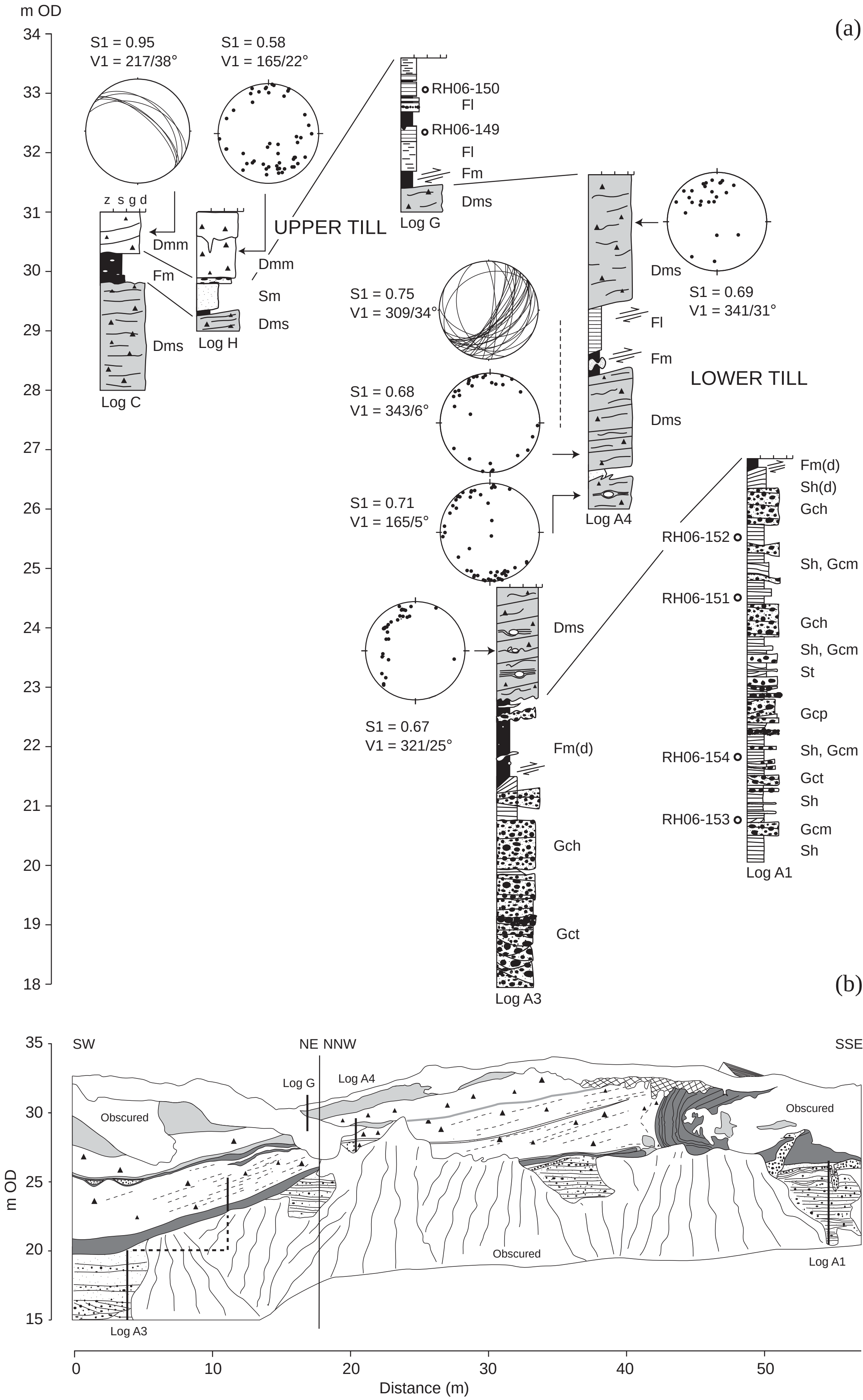

(a)
Docking quarry section
Gcm
Gcm
Sh
Ssc, Fl
Ssc
Fl
Sl
Ssc
Sr
Sh
Gmm
Sh
Fm
Ssc
RH06-147
Sm
Gcm
1 m
m OD
z s g d
72
71
70
69
68
67
66
Gch
Sr(d)
Fl(d)
Sh(d)
Gmm(d)
Sh(d)
Fl
Gcm
Gcm
Dmm
RH06-148
RH06-147
RH06-146
RH06-145
75
74
73
72
71
70
Gcm
Sm
Gch
Gcm
Dmm
Ssc
Glaciotectonic structures
S1 = 0.96
V1 = 256/33°
Clast macrofabric
S1 = 0.61
V1 = 304/25°
(b)
Risinghill Plantation section
Section height (m)
3
2
1
0
Decalcified diamicton
Dmm
Sm/Fm
Gcm
Sh
Fl
Fm
Gcm
RH06-156
RH06-155
50
49
48
47
46
45
44
Decalcified diamicton
Dmm
Sh, Gcm
Gcm
RH06-156
Sh, Gcm
RH06-155
Fl
Fm
Gcm
Sh
Gcm(d)
Gch
Sh, Gcm
Dmm
Glaciotectonic structures
S1 = 0.87
V1 = 211/34°

Fig. 3.



(a)
m OD
S1 = 0.95
V1 = 217/38°
S1 = 0.58
V1 = 165/22°
z s g d
Dmm
Fm
Dms
Log C
Dmm
Sm
Dms
Log H
UPPER TILL
RH06-150
Fl
RH06-149
Fl
Fm
Dms
Log G
Dms
Fl
Fm
S1 = 0.69
V1 = 341/31°
LOWER TILL
S1 = 0.75
V1 = 309/34°
S1 = 0.68
V1 = 343/6°
Dms
S1 = 0.71
V1 = 165/5°
Log A4
Fm(d)
Sh(d)
Gch
RH06-152
Sh, Gcm
RH06-151
Gch
Sh, Gcm
St
Gcp
RH06-154
Sh, Gcm
Gct
Sh
RH06-153
Gcm
Sh
Log A1
Dms
S1 = 0.67
V1 = 321/25°
Fm(d)
Gch
Gct
Log A3
(b)
SW
NE NNW
SSE
Log G
Log A4
Obscured
Obscured
Obscured
Log A1
Log A3
m OD
Distance (m)

Fig. 4.

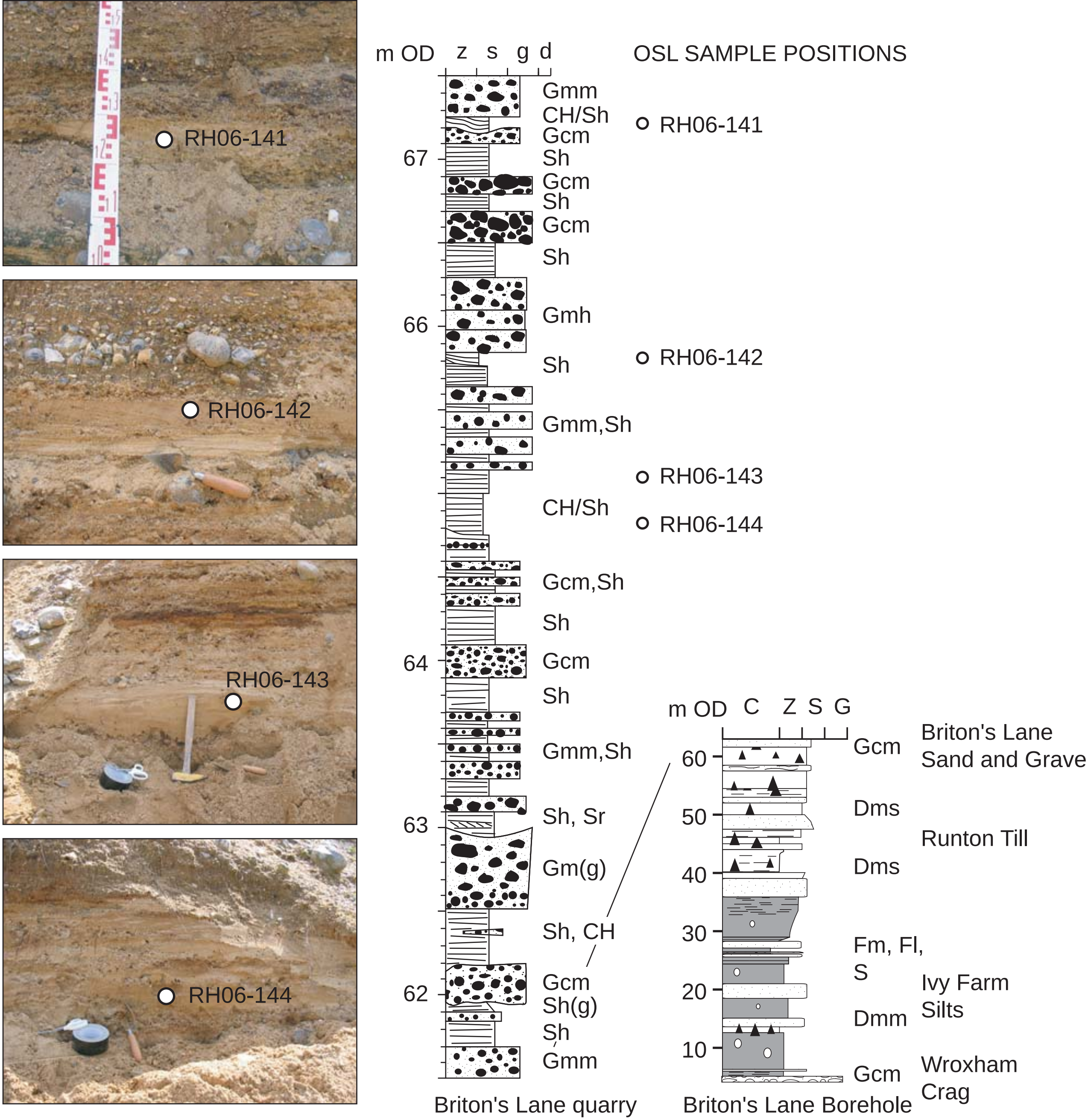

RH06-141
RH06-142
RH06-143
RH06-144
m OD
z s g d
OSL SAMPLE POSITIONS
Gmm
CH/Sh
Gcm
Sh
Gcm
Sh
Gcm
Sh
Gmh
Sh
Gmm,Sh
CH/Sh
Gcm,Sh
Sh
Gcm
Sh
Gmm,Sh
Sh, Sr
Gm(g)
Sh, CH
Gcm
Sh(g)
Sh
Gmm
67
66
64
63
62
RH06-141
RH06-142
RH06-143
RH06-144
m OD
C Z S G
60
50
40
30
20
10
Gcm
Dms
Dms
Fm, Fl, S
Dmm
Gcm
Briton's Lane Sand and Gravel
Runton Till
Ivy Farm Silts
Wroxham Crag
Briton's Lane quarry
Briton's Lane Borehole

Fig. 5.

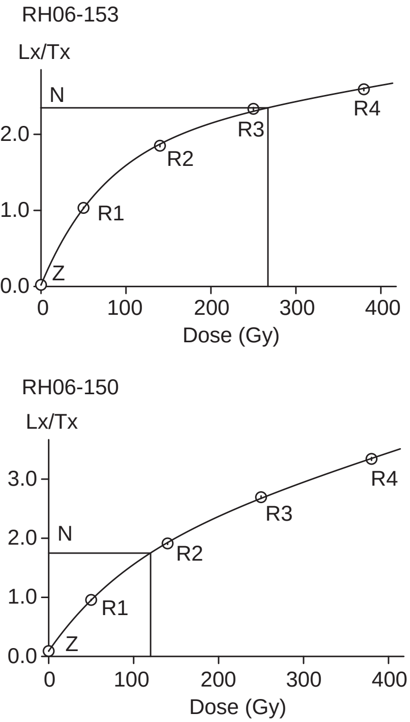
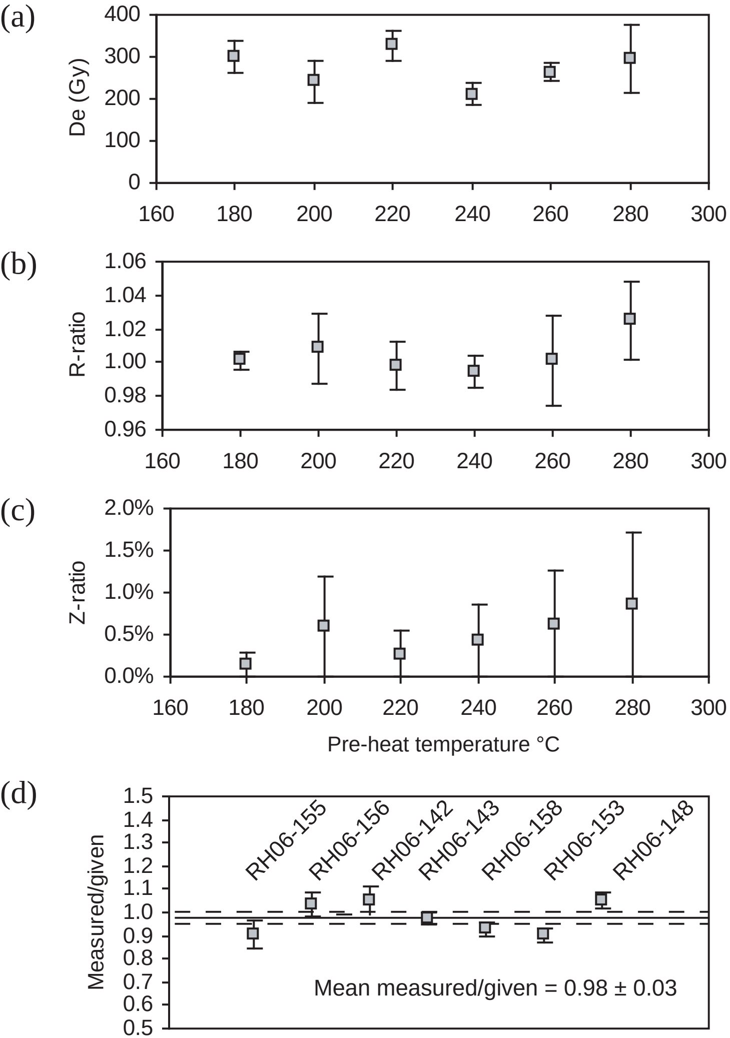
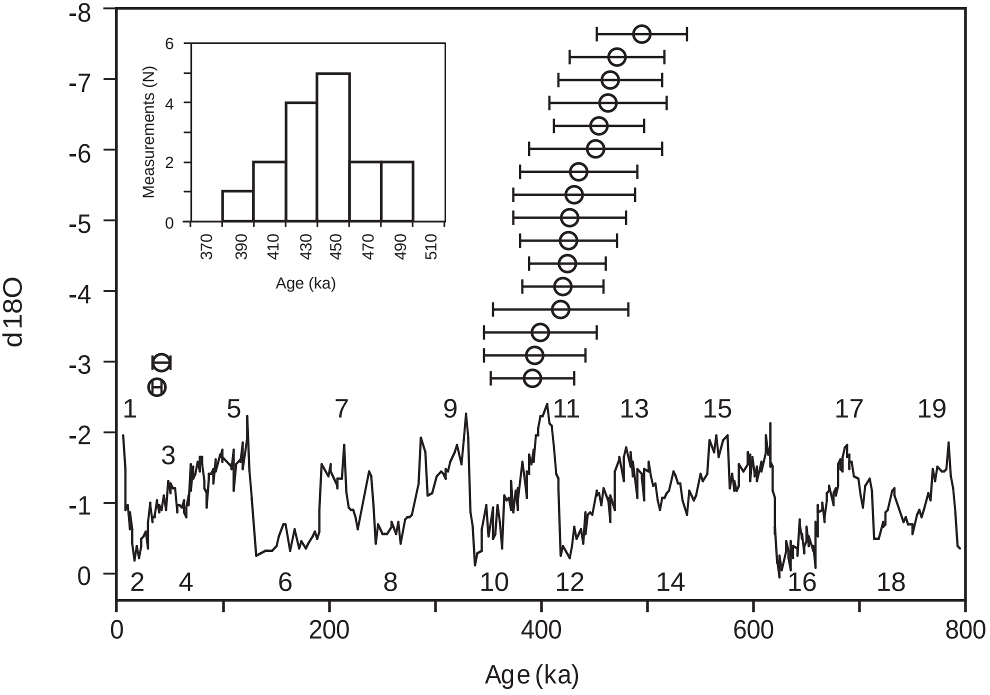

RH06-153
Lx/Tx
N
R4
R3
R2
R1
Z
2.0
1.0
0.0
0
100
200
300
400
Dose (Gy)
RH06-150
Lx/Tx
3.0
2.0
1.0
0.0
N
R4
R3
R2
R1
Z
0
100
200
300
400
Dose (Gy)

Fig. 6.



(a)
De (Gy)
400
300
200
100
0
160
180
200
220
240
260
280
300
(b)
R-ratio
1.06
1.04
1.02
1.00
0.98
0.96
160
180
200
220
240
260
280
300
(c)
Z-ratio
2.0%
1.5%
1.0%
0.5%
0.0%
160
180
200
220
240
260
280
300
Pre-heat temperature °C
(d)
Measured/given
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
RH06-155
RH06-156
RH06-142
RH06-143
RH06-158
RH06-153
RH06-148
Mean measured/given = 0.98 ± 0.03

Fig. 7.



d18O
Age (ka)
Measurements (N)
Age (ka)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19

Fig. 8.

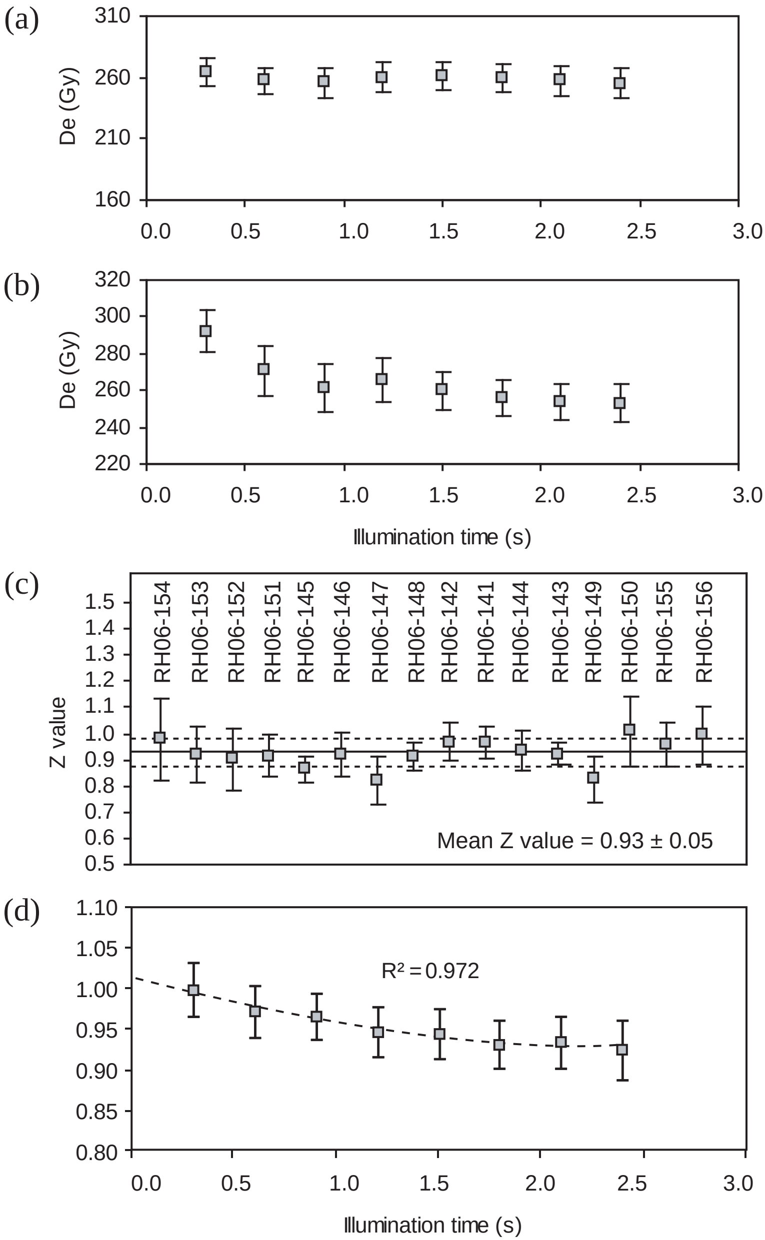

(a)
De (Gy)
310
260
210
160
0.0
0.5
1.0
1.5
2.0
2.5
3.0
(b)
De (Gy)
320
300
280
260
240
220
Illumination time (s)
(c)
Z value
RH06-154
RH06-153
RH06-152
RH06-151
RH06-145
RH06-146
RH06-147
RH06-148
RH06-142
RH06-141
RH06-144
RH06-143
RH06-149
RH06-150
RH06-155
RH06-156
Mean Z value = 0.93 ± 0.05
(d)
R² = 0.972
1.10
1.05
1.00
0.95
0.90
0.85
0.80
Illumination time (s)

Fig. 9.

Site	Facies*	Environment and process	Stratigraphy	Bowen (1999)	Hamblin et al. (2005)
Docking	Gcm, Gch, Sh, Fl, Fm	**Glaciotectonised proglacial outwash**		Lowestoft Fm (MIS 12)	Sheringham Cliffs Fm (MIS 10)
	Dmm, Dms	Subglacial till	Weybourne Town Till Member		
Risinghill Plantation	Gcm, Gch, Sh, Fl, Dmm	**Glaciotectonised proglacial outwash**		Lowestoft Fm (MIS 12)	Sheringham Cliffs Fm (MIS 10)
	Dmm	Subglacial till	Weybourne Town Till Member		
Glandford	Dmm	Subglacial till	Weybourne Town Till Member	Lowestoft Fm (MIS 12)	Sheringham Cliffs Fm (MIS 10)
	Fl, Fm	**Glaciolacustrine lake bottom sediments**	Bacton Green Till Member	North Sea Drift Fm (MIS 12)	
	Dms	Subglacial till			
	Gcm, Gch, Sh, Sp, Gp	**Proglacial outwash**			
Briton's Lane	Gcm, Gmm, Sh	**Proglacial outwash fan**	Briton's Lane Sand and Gravel Member	North Sea Drift Fm (MIS 12)	Briton's Lane Fm (MIS 6)
	Dms	Subglacial till	Bacton Green Till Member		Sheringham Cliffs Fm (MIS 10)
	Fm, Fl, Dmm	Glaciolacustrine muds and rain-out facies	Trimingham Clays		
	G	Shallow marine	Mundesley Member		Wroxham Crag Fm (>MIS 13)
Ringstead	Sr, Sh, Gmm	**Lake margin sediments**	Ringstead Sand and Gravel Member		Holderness Fm (MIS 2)

Table 1. Stratigraphic summary of the study region and the chronostratigraphic scheme used by differing authors. Units that were sampled for OSL dating are highlighted in bold. * Lithofacies codes adoped from Miall (1978) and Eyles et al. (1983).

Step	Treatment	Observed*
Natural and regenerative measurements		
1.	Regenerative dose *Rx*[a]	
2.	Pre-heat (PH1) (260°C, 10 seconds)	
3.	OSL (130°C, blue LED's, 90% power, 50 seconds)	*Lx*
3.	Test dose (10 or 50 Gy's)	
4.	Cut-heat (PH2) (220°C)	
5.	OSL (130°C, blue LED's, 90% power, 50 seconds)	*Tx*
Recuperation and recycling ratio		
6.	Repeat point with 0 Gy dose	Z ratio
7.	Repeat R_1 or R_5 regeneration dose	R ratio
IR-OSL ratio		
8.	Repeat R_1 regeneration dose	
9.	Pre-heat (260°C, 10 seconds)	
10.	IR OSL (50°C, 50 seconds, IR diodes)	
11.	OSL (130°C, blue LED's, 90% power, 50 seconds)	*Lx* (on the IR OSL ratio)
12.	Test dose (10 or 50 Gy's)	
13.	Cut-heat (220°C)	
14.	OSL (130°C, blue LED's, 90% power, 50 seconds)	*Tx* (on the IR OSL ratio)

[a] in the first measurement cycle, no dose is given because the natural dose is being measured.
* the *Lx* and *Tx* values were derived from the first 0.3 or 0.6 seconds of the OSL signal minus a background level taken from the last 40-50 seconds of the measurement.

Table 2. Details of the SAR protocol used in the study. Steps 1-5 show the procedure used in the natural and regenerative measurement cycles. Four or five regenerative doses were used to bracket the D_e. Once these are complete, extra SAR points are measured to determine the recuperation ratio (Z-ratio), recycling ratio (R-ratio), and IR OSL ratio (Duller, 2003).

Sample	Grain size (um)	K (%)	U (ppm)	Th (ppm)	Total dose (Gy/ka)	%
RH06-143	180-250	0.00	0.32	0.14	0.022 ± 0.005	3.5
RH06-145	180-250	0.00	0.25	0.12	0.019 ± 0.004	3.1
RH06-148	180-250	0.01	0.20	0.09	0.015 ± 0.003	2.0
RH06-153	180-250	0.00	0.20	0.14	0.020 ± 0.005	3.2

Table 3. Concentrations of K, U, and Th determined in etched quartz samples, determined by NAA. The percentage contribution of the total internal quartz dose against the external dose is also shown.

Sample	Site	Grain size (um)	N	Burial depth (m)	K (%)	U (ppm)	Th (ppm)	Water (%)	Total dose rate (Gy/ka)	D_e (Gy)	Age (Ka)
RH06-141	Briton's Lane	180-250	34	23.0 ± 1.0	0.41	0.50	1.30	14	0.53 ± 0.04	264 ± 11	494 ± 42
RH06-142	Briton's Lane	180-250	28	25.0 ± 1.0	0.53	0.53	1.53	18	0.59 ± 0.05	278 ± 14	470 ± 44
RH06-143	Briton's Lane	180-250	37	30.0 ± 1.0	0.61	0.53	1.77	17	0.65 ± 0.05	274 ± 9	424 ± 36
RH06-144	Briton's Lane	180-250	25	26.0 ± 1.0	0.45	0.59	1.87	16	0.56 ± 0.04	254 ± 13	453 ± 42
RH06-145	Docking	180-250	12	5.0 ± 1.0	0.34	0.44	2.49	17	0.63 ± 0.05	292 ± 12	465 ± 49
RH06-146	Docking	180-250	16	5.0 ± 1.0	0.45	0.63	4.02	18	0.81 ± 0.07	342 ± 23	425 ± 46
RH06-147	Docking	125-180	17	5.0 ± 1.0	0.38	0.54	2.40	20	0.64 ± 0.06	253 ± 20	393 ± 47
RH06-148	Docking	180-250	16	5.0 ± 1.0	0.53	1.01	4.66	17	0.77 ± 0.06	324 ± 12	419 ± 38
RH06-149	Glandford	180-250	28	3.6 ± 1.0	0.34	0.34	0.58	17	0.49 ± 0.06	223 ± 16	450 ± 63
RH06-150	Glandford	180-250	22	2.9 ± 1.0	0.35	0.36	0.78	17	0.53 ± 0.07	222 ± 18	417 ± 64
RH06-151	Glandford	125-180	16	8.5 ± 1.0	0.41	0.46	1.23	17	0.55 ± 0.04	216 ± 13	391 ± 39
RH06-152	Glandford	125-180	19	8.0 ± 1.0	0.46	0.52	1.36	16	0.63 ± 0.05	267 ± 26	426 ± 53
RH06-153	Glandford	125-180	17	10.0 ± 1.0	0.48	0.53	1.90	19	0.64 ± 0.05	298 ± 27	462 ± 56
RH06-154	Glandford	125-180	11	9.0 ± 1.0	0.66	0.61	1.81	23	0.73 ± 0.06	316 ± 33	430 ± 58
RH06-155	Risinghill	180-250	23	3.0 ± 1.0	0.34	0.41	1.13	11	0.58 ± 0.07	262 ± 15	434 ± 55
RH06-156	Risinghill	180-250	21	3.0 ± 1.0	0.35	0.56	1.64	10	0.57 ± 0.07	236 ± 14	398 ± 53
RH06-157	Ringstead	180-250	18	2.2 ± 0.5	1.19	1.56	6.00	11	1.73 ± 0.12	64 ± 5	37 ± 4
RH06-158	Ringstead	180-250	11	1.6 ± 0.5	0.71	0.77	2.51	6	1.06 ± 0.09	43 ± 8	40 ± 8

Table 4. Summary of sample details (altitude, burial depth, assumed water content), number of aliquots measured (N), radioisotope concentrations, equivalent doses (D_e), and sample ages. Radioisotope concentrations are given from ICP-MS measurements apart from samples RH06-155 and 156 which are determined from γ-spectrometry because the pebbly texture of these samples made it impossible to obtain a representative sub-sample. Gamma dose rates are based upon γ-spectrometry in all samples apart from RH06-145 where only ICP-MS measurements were made. An internal quartz dose rate of 0.02 ± 0.01 Gy/ka is also included based on the average of four etched quartz samples (measured by NAA).