LOESS IN BRITAIN AND IRELAND: FORMATION, MODIFICATION AND ENVIRONMENTAL SIGNIFICANCE, A REVIEW IN MEMORY OF JOHN CATT (1937-2017).

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ABSTRACT

Loess was first identified in England as early as the mid-19th century, although these deposits were later mapped as 'brickearth' or 'head-brickearth' by the British Geological Survey. Much of this material was subsequently recognised and named as loess again by soil scientists, most notably by J.A. Catt. The early reports of loess were mostly located in southeast England, however, more recently loessic deposits have also been reported from the north of England, possibly in Scotland, and as far west as western Ireland. Catt also appreciated that these deposits are the western limits of a broad cover of loess stretching across Eurasia. Here, contrasting models for the possible origin, transport pathways and reworking of these deposits are presented. While some of these British deposits are primary in-situ loess, a range of processes has likely affected many of them, including periglaciation, Holocene climatic, and human impacts. Luminescence dating has confirmed British loess to be primarily of late Pleistocene age, however, examples of older loess are also reviewed. Deposits in southeast England are the thickest and best expressed today, and these have yielded significant insight into both the mechanism of the hydroconsolidation (collapse) of loess and landscape evolution in northwest Europe during the Last Glacial Period. The thin and regional nature of British and Irish loess may make it an excellent material for studying loess formation, with advantages over the thicker deposits of typical loess of central Europe, where the impact of smaller scale landscape processes may be less obvious.

Keywords: Loess, brickearth, Quaternary, provenance, distribution, chronology

1. INTRODUCTION

Deposits of windblown loess are widespread across Europe, where they attain thicknesses of many 10's of metres (Lehmkuhl et al., 2021). At the western fringes of this loess belt, deposits of loess are also found in southern and northern England, and also possibly in Scotland, Wales, and the west coast of Ireland (Figure 1). This loess rarely attains a thickness of more than 4 m, and is generally less than 1 m thick.

While a single definition of loess is not universally agreed upon, loess can broadly be considered as a silt dominated, terrestrial sediment that has been entrained, transported, and deposited by wind (Muhs, 2013). Behind this simple definition though, loess shows significant variation in terms of its thickness, grain size, colour, mineralogy, geochemical composition, geotechnical characteristics and morphology (Pye, 1995). ‘Classical’ loess *sensu strictu* comprises homogeneous, buff coloured, calcareous silts and clays, with no clear sedimentary structure and a lack of larger clasts. Loess in Britain seldom fulfils these strict criteria, and rather exhibits a range of features indicative of reworking or redeposition (Figure 2). Catt (1977) established that while loess *sensu strictu* occurs adjacent to the Thames estuary, thinner loess deposits (less than 1 m thick) are widespread elsewhere and often integrated with other soil or sedimentary material (Figure 1).

Loess was first identified in Europe in the nineteenth century and was recognised in Britain soon after. Prior to that, the term '*brickearth*' had been used in England, but this term included any sediment suitable for brick manufacturing. One significant aspect, particular to loess research in England, is that after the initial recognition of this material as loess, it was later mapped by the British Geological Survey (BGS) as brickearth or head brickearth. Currently BGS maps refer to these deposits as head silt, river silt, fluvio-aeolian silt or loess, and this changing and variable terminology has led to confusion. Furthermore, in some particular areas, loess-like silts have been given sedimentary and stratigraphic unit names, *e.g.,* Langley Silt in the middle Thames Valley (Gibbard, 1985). However, many brickearths and formalised silt deposits may not be entirely comprised of loess. Instead, these deposits may be in-part reworked by syn or post-depositional processes, and in some cases not related to aeolian silt deposition at all (*e.g.,* Rose et al., 1999). Here, the term loess is used where a deposit conforms to the general definition of an aeolian, silt dominated, terrestrial sediment (Muhs, 2013), and the term reworked loess is used where pre-existing loess has been reworked by other processes. Where the difference is not clear in published literature the terms used by the initial authors are restated.

Many early studies into the application of luminescence methods on sediments were conducted on loess from southern England (*e.g.,* Wintle, 1981) and these showed that much of this material is of Late Pleistocene age (Marine Oxygen Isotope Stage (MIS) 2 – 4; here referred to as the Late Glacial Period), with the majority being MIS 2 in age. Some older deposits of loess, up to MIS 12, have also been identified in parts of Britain, but with a very limited extent (*e.g*., Rose and Allen, 1977; Rousseau and Keen, 1989; Parks and Rendell, 1992; Murton et al., 2015). Loess in Britain is also sometimes spatially (and to some extent temporally) associated with coversand deposits (a periglacial aeolian deposit of medium to very fine-grained sand with little interstitial silt and clay); however, a review of research on coversands in Britain is beyond the scope of this manuscript and the reader is referred to Bateman (1998) and Baker et al. (2013). An extensive body of literature exists on British loess, including research from many sciences: sedimentology and stratigraphy, geomorphology, geology, pedology, archaeology, brick-making, engineering, and palaeoclimatology. Whilst this has led to an extensive understanding of some aspects of British loess, it has also meant that some findings have been overlooked between disciplines and in a wider context.

John A. Catt (1937–2017) is credited for recognizing the wider distribution of loess across the British Isles and for his work compiling maps of British loess. He contributed to unifying the discipline-biased definitions of loess through re-defining loess on the basis of its formational stages. However, the minutiae of his outputs have perhaps been underemphasized.

This paper first revisits the earlier research that underpins Catt’s work and continues with paradigms developed by Catt, and how these have shaped the appreciation of loess in Britain and Ireland. The origin and distribution of loess in Britain (including the Channel Islands) and Ireland is then considered from a process-based perspective, before considering geotechnical and past climate-chronostratigraphic aspects in more detail. Overall, the aims of this paper are to provide a review of the context and significance of modern loess research in Britain and Ireland. Specifically, the paper provides: (1) a review of early loess research; (2) an outline of the contribution of John Catt to British loess research; (3) a review of possible provenance-transportation-deposition-alteration models and; (4) a discussion of the age and palaeoenvironmental significance of loess in Britain and Ireland. Finally, suggestions for future research are outlined.

2. EARLY RESEARCH: THE BACKGROUND TO CATT'S WORK

The resemblance between continental European and English loess was first suggested by d'Archaic (1839) and expanded by Prestwich (1863). Prestwich pointed out the close connections between loess deposits and rivers, an idea which influenced some later workers (*e.g.,* White, 1917 and Everard, 1954) in associating the origin of what they called brickearth to river floodloams in Hampshire (see also Smalley et al., 2009). Brickearth is a (genetically) non-specific term applied to any deposit that can be used to make bricks. Smart et al. (1966) described brickearth as "*friable and sandy, but every gradation exists to a clayey loam*". Early reports of brickearth from many locations in Britain have since been identified as loessic material; however, the two terms are not synonymous and many deposits that were originally labelled as brickearth are not comprised of undisturbed wind-blown loess (*e.g.,* Rose et al., 1999).

The silty deposits found in parts of Kent and Essex (Figure 1) were ideal for the manufacture of bricks and a substantial brick making industry developed in these areas from at least the 17th century. The closing of the 19th century marks the extensive exploitation of the brickearth deposits across northwest Kent to build the London suburbs. One especially significant deposit of possible loessic brickearth was located at Crayford (Figure 3) and typifies the problems associated with interpretation of these now inaccessible or removed deposits. Kennard (1944) described two brickearth units separated by a marine band with a total thickness up to 15 m. The lower bed contains Palaeolithic artefacts (Chandler, 1914) as well as bones of *Mammuthus primigenius, Ceolodonta antiquitatis* and *Ovibos moschatus,* indicative of a cold steppe climate (Bull, 1942). Whitaker (1889) described the lower bed as having sandy laminations, and Kennard (1944) also described lenticular bands of sand and pebbles. The marine band is up to 1.5 m thick and contains such abundant fossils of *Cyrena* *fluminalis* (Mull), a large marine bivalve, that it became known as 'the Corbicula bed' after the genus. The upper brickearth bed was described by Leach (1905) as thinly bedded, more clay rich than the lower unit, but also with discontinuous pebble layers (one named the 'trail') and few fossils. Chandler (1914) commented that the 'trail' is composed of local materials derived from higher ground in the immediate vicinity, with pebbles, often oriented vertically, potentially explained by freeze-thaw processes. Overall, Kennard (1944) argued that the Crayford deposit was not loess as the lower bed showed evidence of deposition in a shallow stream and the upper bed was the result of *"sludging from higher ground during a period of greatly increased rainfall*". However, from these descriptions the possibility remains that some of this material was loess reworked under a periglacial environment.

During the early part of the 20th century, the British Geological Survey (under its various names) continued detailed geological mapping of the country. While the constraint of generally only recording deposits over 1 m thick will have meant that many thin loess deposits were not mapped, a number of the explanatory memoirs chart the changing understanding of the origins of what they did map as brickearth, as well as its distribution. Here, the terms used by these publications are retained as it is unclear whether some of these deposits are true loess.

In the New Forest area of Hampshire (Figure 1), White (1915) described brickearth less than 1 m thick that grades both laterally and vertically into Coombe rock (a periglacial sediment found in the dry valleys of the English chalk lands composed of chalk rock, flint fragments and silty chalk mud). A key observation was that it overlies various different strata, 'levelling up' the surface of underlying deposits (White, 1915); this characteristic of blanketing pre-existing terrain is a classic feature of loess. However, the variable nature of brickearth in north Kent was recognised by Dines et al. (1954) who separated the brickearth near Chatham (Figure 3) into two types: head-brickearth and river-brickearth; and also noted that some brickearths closely resemble the loess of Europe.

Holmes et al. (1981) identified three separate brickearth horizons, also in north Kent, and related these to river terraces, again highlighting the widely variable nature of the deposit. Worsley (1983) suggested that much of the brickearth present in the same area is of local derivation and of uncertain chronostratigraphic status, but that older layers may be wind-blown. However, a BGS report (McMillan and Powell, 1999, pg. 10) later stated that "*brickearth and its associated terms are now regarded as obsolete*"; they proposed the term 'fluvio-aeolian silt' for sediments of uncertain or aeolian/fluvial origin.

A major issue with interpreting these past studies is that much of the 'brickearth' material is now inaccessible or removed. As such, early suggestions of up to *c.* 16 m of brickearth, for example on the Hoo Peninsula (Figure 3) as relayed in Dines et al. (1954), cannot now be tested. One exception to this inaccessibility is the loess at Pegwell Bay, on the northeast Kent coast of the Isle of Thanet (Figure 3). These deposits facilitated increasing recognition of loess *sensu strictu* in southeast England, and continue to be very important in the study of loess in Britain generally. White (1928) described the deposit at Pegwell Bay as brickearth standing in a typical vertical face up to 4 m high with rough prismatic jointing. The upper 1-2 metres is reddish-brown with a very low calcium carbonate content, whilst the lower part is yellowish-brown and calcareous (Figure 2a). A band of flint pebbles up to 5 cm in diameter can sometimes be seen at the junction with the underlying Thanet Formation (Palaeocene), while small vertically oriented flint pebbles also occur up to 30 cm above the junction, which is an interesting parallel with Chandler's (1914) observations on the upper brickearth at Crayford. Pitcher et al. (1954) classified the deposit as a 'true' loess resting unconformably on Cretaceous and Paleogene rocks disturbed by freeze-thaw processes.

In the Thames estuary area, Burchell (1935) described the stratigraphy of a channel cut in chalk near Northfleet in northwest Kent (Figure 3), noting two layers within a "*brown clayey loam of sub-aerial origin*". The lower unit contained *Pupilla muscorum* fossils while the upper was "*decalcified and devoid of shells*", suggesting a close similarity to the stratigraphy at Pegwell Bay (Figure 2a). Other loess-like brickearths from outside the Thames Basin were also increasingly recognised as similar to loess, including in Hampshire and West Sussex (Palmer and Cooke, 1923; Martin, 1929; Kay, 1939; Hodgson et al., 1967; Perrin et al., 1974) (Figure 1). Warren (1942) noted loess in a brickyard, north of Brentwood in southwest Essex (Figure 3); describing it as a small local deposit *c.* 3 m thick, overlying a buried land surface. Farther north, on the Durham coast (Figure 1), Trechmann (1919) described a silt deposit that he claimed was identical with European loess in chemical, physical, and stratigraphical terms. In Derbyshire (Figure 1), Pigott (1962) studied the heavy mineral assemblage of the silt in the soil overlying the Carboniferous limestones and concluded that there was a loessic input to these soils. These studies revealed that loess is distributed much farther afield than just southeastern England, and demonstrate increasing recognition of loess deposits in Britain.

This recognition was cemented with the publication of two papers on loess in Britain in reports from the loess commission and sub-commission of the International Union for Quaternary Research (INQUA); Tilley (1964) and Dalrymple (1969). The production of an INQUA Loess Map of Europe was one of the major aims of the INQUA Loess Commission, and a version was eventually produced (Haase et al., 2007); however, no loess in Britain or Ireland is shown on that map. Fortunately, the new European loess map of Lehmkuhl et al. (2021) partially rectifies this and shows loess in southern Britain, particularly around Kent and Hampshire.

3. JOHN A. CATT'S CONTRIBUTION

John Alfred Catt was born in Kent in 1938 and studied geology at University of Hull, receiving his Doctorate on the glacial geology of east Yorkshire in 1964. He immediately took an appointment as Scientific Officer at the Rothamsted Experimental Station (now called Rothamsted Research) where he worked until 1999. During the 1960s and 1970s the concept of 'soil series' (detailed descriptions of individual soils based on particle size, parent materials and mineralogical characteristics) was evolving and Catt was ideally placed to identify loess as a component within soils in Britain. Catt utilised observations of particle size and mineralogy to great effect to distinguish the loessic component from other soil materials, noting the presence of loess material in previously undocumented areas, such as Norfolk (Catt et al., 1971). His published output includes nearly 200 peer-reviewed papers, many official reports and several books covering such topics as Quaternary and Cenozoic geology, soil development on chalk landscapes, as well as loess and palaeosol stratigraphy. Catt compiled maps of British loess for the INQUA loess map of Europe (Hasse et al., 2007), but for unknown reasons his contribution was not included. On retirement Catt was made Honorary Professor of geology at several institutions including Birkbeck College and University College London; he was also awarded the Distinguished Service Award from the Geological Society of London in 2015. He passed away in December 2017.

The 10th INQUA Congress was held in England in 1977 and Catt wrote the 'Loess and Coversands' chapter for the accompanying book (Catt, 1977). This set the scene for further investigation of British loess and was in some ways the culmination of Catt's early endeavours to place the study of British loess on a proper scientific footing (see also Catt 1978;1979a, b). Catt later promoted and discussed earlier work in defining loess on the basis of its formation stages, in particular with reference to works of Smalley (1966) and Smalley and Smalley (1983). These authors had introduced the idea of three actions ‘P-T-D’, representing the three basic operations (Provenance, Transportation, Deposition) that impact the nature of a sedimentary deposit. In this way, Catt brought together the confused definitions and subdivisions of loess among geotechnical, pedological, petrological, geomorphological, sedimentological, climatic, soil science, Quaternary and soil mapping workers (Catt, 1988).

Catt was also well aware of the benefits that the presence of loess gave to a soil, as loess contains abundant available macro and micronutrients, can be easily worked, and gives good drainage and aeration, while still offering adequate water supply to crops (Catt, 1978, 2001). He noted that in many areas with a thin soil cover, or where underlying rocks do not easily release nutrients, or which are susceptible to water logging, even a thin (< 1 m) loess cover can greatly enhance agricultural potential (Catt, 1978). He even went so far as to say that loess should be recognised as one of the country’s minor natural resources.

4. A PROCESS BASED APPROACH TO BRITISH AND IRISH LOESS

In this section the Provenance, Transportation, Deposition model (P-T-D) is applied to some locations within Britain and Ireland. However, the formation of loessic deposits in Britain is probably quite complex, and may involve and link together multiple different landscape processes and agents. It is emphasised that the assignments here are propositions that require testing and are aimed at stimulating research directed at understanding the origins of loess in Britain. This section also considers the importance of reworking of loess deposits in Britain, and the impact of bedrock type on loess distribution.

4.1 Provenance: the source of British and Irish loess.

Pye (1995) outlined various mechanisms that may produce silt-sized material: glacial grinding; frost weathering; release of existing silt-sized particles from parent rock; fluvial abrasion; aeolian abrasion; salt weathering; chemical weathering; clay pellet aggregation and biological processes. Pye (1995) further classified loess deposits into three groups: periglacial loess - for deposits that show a “*close spatial relationship with Quaternary continental glaciation*”, as described by Smalley (1966); peridesert loess- those on the margin of desert areas, as described by Smalley and Vita-Finzi (1968); and perimontane loess - for those deposits close to high mountains as described by Smalley and Smalley (1983). Li et al. (2020) reviewed loess deposits globally and also defined three types (the Taiyuan system):

CR - continental glacier provenance-river transport mode; MR - mountain provenance-river transport mode and MRD - mountain provenance-river transport-desert transition mode.

There has been considerable debate about the sources of loess in Britain (*e.g.,* Fall, 2003), which also has implications for understanding the possible production mechanisms for this loess. Many earlier studies advocated weathering of regional bedrock as the main source of loess deposits *(e.g.,* weathering of Cornubian granite for the Lizard Loess in Cornwall; Coombe et al., 1956). Later, two main contrasting models of more far-travelled dust have been proposed to describe the source of loess in southern Britain, both evoking glacial grinding as the silt production mechanism (Figure 4).

Lill and Smalley (1978) proposed bedrock grinding by the ice sheets of the Last Glacial British Irish Ice Sheet (BIIS) as the first production point (P1). A number of studies have supported this assertion, *e.g.,* Madgett and Catt (1978) and also Bateman and Catt (2007) confirmed that the mineralogy of loess in eastern England closely resembles that of the Last Glacial Skipsea Till. Particle size data (Bateman and Catt, 2007) further implied aeolian transport of this material from BIIS glaciofluvial outwash plains in the North Sea basin (Figure 1).

In Essex (Figure 1), Eden (1980) reported heavy mineral assemblages in the loessic cover that broadly match deposits elsewhere in England, Belgium and the Netherlands. He also proposed a source in the North Sea basin, but possibly fed rather by the Fennoscandian Ice Sheet (FIS), as evidence from the presence of abundant amphiboles, including the possible presence of arfvedsonite. In any case, under this scenario glaciofluvial drainage systems in the sub aerial North Sea basin would be the main T1 transport event (model 1 in Figure 4). In this model the loess in southern Britain would be classified as 'periglacial' by Pye (1995) and could fall into the CR classification under the Taiyuan system (Li et al., 2020).

An alternative, but speculative, model was proposed by Smalley et al. (2009) in which P1 lies in the Alps, under the Alpine Ice Sheet. T1 would then probably be along the Rhine corridor (model 2 in Figure 4), with silt transported north to form deposits in Belgium, the Netherlands and southeastern England. It is worth noting however, that while heavy mineral assemblage data has been used to support a BIIS (or FIS) origin for loess in Britain, no such evidence has been presented for the Rhine model. This model was proposed to emphasise the contribution that major rivers likely play in long distance silt transport, an idea which is supported by provenance data in many loess regions globally (Újvári et al., 2012; Nie et al., 2015; Fenn et al., 2022; Költringer et al., 2022). In the Rhine model the loess in southern Britain would be classified as 'perimontane' by Pye (1995) and would fall into the MR classification under the Taiyuan system (Li et al., 2020).

Although these two competing models are the dominant explanations of loess in Britain, the situation may be more complex than this. Several studies, *e.g.*, Catt (1979b); Derbyshire and Mellors (1988); and Fall (2003) have reported a general fining of loess material from east to west across southern Britain, a trend that is consistent with a single North Sea source fed by either the Rhine or the northern ice sheets. Fall (2003), however, also noted that there were local influences on this general trend; *e.g.*, loess in the Hampshire Basin (Figure 1) shows coarser components than loess to the east. He argued that these deviations from the overall E-W trend are due to local bedrock sources as well as the impact of additions of silt material to the English Channel system by rivers draining southern England.

Loess material has also been reported farther west in Devon (Harrod et al., 1973; Cattell, 1997) and Cornwall (Catt and Staines, 1982; Roberts, 1985; Scourse, 1991) (Figure 1). While the loess in Devon is generally thin, in Cornwall it reaches up to *c.* 2 m in thickness, with the thickest loess deposits found on the serpentinite and gabbro of Cornwall, particularly on the Lizard Peninsula (Ealey and James, 2011) (Figure 1 and 2b). The Lizard Loess stratotype was coined by Roberts (1985) and is at least partly geliflucted; however, the uppermost unit seems likely to be a non-calcareous aeolian loess (Ealey and James, 2011). Coombe et al. (1956) showed that the mineralogy of Lizard Loess was incompatible with an origin from the underlying serpentinite bedrock, and they evoked nearby Cornubian granites as the source. This idea was later partially supported by Catt and Staines (1982), who further suggested that the sudden increase in thickness of the Cornish loess, its larger modal grain size, and different heavy mineral assemblage indicated a new source, different to the one driving the main area of loess deposition in southeast England. Even farther to the west, Scourse (1991) proposed that the western BIIS was the source of loess deposits on the Scilly Isles (Figure 1). Loess on Jersey reaches up to 4–5 m in thickness (Keen et al., 1996) (Figure 1), but in terms of origin these deposits probably have more in common with loess in Normandy and Brittany than loess in southern Britain.

Overall, it is hard to reconcile the change in loess characteristics in mainland Cornwall with a Rhine or Eastern BIIS source, via the North Sea. Rather, a source from the western BIIS (Irish Sea Ice Stream) or from other local bedrock, seems far more plausible. On the Isles of Scilly, the link with the western BIIS is even more convincing, as there are clear mineralogical, geographical and stratigraphic associations with the Scilly Till and Tregarthen Gravel glaciofluvial outwash (Scourse, 1991). However, Fall (2003) argued against the idea of a western BIIS source for Cornwall, and proposed that renewal of sediment sources in the English Channel via local rivers may be more important.

In southeastern England too, local bedrock sources for loess have been evoked in numerous studies. Pitcher et al. (1954) interpreted the top of the Thanet Formation, below the loess at Pegwell Bay (Figure 1), as showing a "*pre-loess frost soil*" and stated that much of the silt that forms the loess here could have locally deflated from the Thanet Formation. They also stated that the heavy mineral suite of the loess bears a strong affinity to that of the Thanet Formation, although this somewhat contradicts findings from later heavy mineral work (Catt, 1985; Bateman and Catt, 2007). Burrin (1981) described silty alluvium in some rivers in Kent (Figure 3) and explained this as eroded from loess deposits, however, Gallois (1982) disputed this and argued it could be a product of bedrock weathering. Shephard-Thorn (1988) also suggested that the older brickearth on the Isle of Thanet may have been derived by degradation of outliers of Thanet Formation rocks. Catt et al. (1987) reinvestigated loess-like deposits overlying sands of the Thanet Formation at Borden in Kent (Figure 3) that had been previously described as loess by Tilley (1964) and concluded that the deposit was in fact a Holocene colluvial soil derived from the underlying rocks. Furthermore, Milodowski et al. (2015) argued for two different sources for the upper and lower loess units in the Thanet loess. They suggested that the lower loess unit shows similarities in clay, detrital carbonate and volcanic mineralogy and quartz micro-texture to the underlying Thanet Formation. In contrast, the upper loess unit shows a different mineralogy with more angular grains indicating derivation from distal glacial material.

Understanding of the origin of loess deposits in other parts of Britain is limited by the fact that so few studies have been conducted on them. In Wales, a thin (< 1 m) loess cover has been noted covering tills and glaciofluvial outwash in southwest Wales and the Gower Peninsula (Case, 1983) (Figure 1), as well as at coastal sections near Aberystwyth (Watson

and Watson, 1967) (Figure 1) and in North Wales (Lee and Vincent, 1981). Vincent and Lee (1981) suggested that silts found in a number of locations in northwest England are derived from the glacigenic sediments in Morecambe Bay (Figure 1), and may be genetically related to the deposits in North Wales (Lee and Vincent, 1981). On the Durham coast (Figure 1), the deposit originally described as loess by Trechmann (1919), was re-interpreted as a marine silt by Davies (2008) although it may also include reworked loess. There have been few reports of loess in Scotland; a 1 m thick possible aeolian silt in the Central Lowland region near Kinross (Figure 1) was reported by Galloway (1961) and Ballantyne (1984) noted silt-rich diamictons that may in part have loessic origin on the northwest Scottish mountains. However, whether these relate in any way to aeolian dust and loess formation is unclear, and further study is much needed. In any case, out of the two main source models proposed above, the most plausible source for the Welsh and northern British deposits would be the BIIS, either directly at the ice limits or via the sub aerial Irish Sea or North Sea shelves.
In Ireland, loess has also been reported in the karst region of the Burren in County Clare (Figure 1 and 2c). Moles et al. (1995) initially identified loess as a potential soil parent material in the Burren National Park, but following further study of the area they withdrew this conclusion, due to the presence of granite pebbles within the soils (Moles and Moles, 2002). Silt from a large doline (karst depression) in the Burren was described by Vincent (2004) who concluded the silt to be loess deflated from glaciofluvial sediments in Galway Bay.

In summary, the BIIS model remains the best supported by available evidence, and may account for much of the loess in Britain and Ireland. However, the Rhine model is plausible at least in southern Britain, and local variations do exist in loess mineralogy, thickness, and grain size that suggest some local contributions. This is well illustrated in the work of Fall (2003) who demonstrated that geochemical variations in loess occur geographically, particularly for zirconium (Zr), and that this hints at local source inputs, even if the bulk of the material has a single source in the North Sea. Overall, even if local bedrock sources only have a secondary influence on loess accumulation, the origin of loess in southern Britain remains to be fully agreed upon.

4.2 Transportation: dust transporting winds.

In this section the nature of winds that may have caused the initial aeolian transport of dust onto the land area of Britain are considered. Under the BIIS source scenario, T1 is glaciofluvial transport to the southern North Sea basin, and T2 would be easterly or northeasterly winds deflating these silts and resulting in dust deposition over many parts of Britain. Catt (1978) argued that the result was a more or less continuous cover of loess up to a few metres thick to the south of the last glacial ice margins.

Lill and Smalley (1978) suggested that the enlarged presence of European ice sheets during the Last Glacial Maximum (LGM) implies that ice sheet anticyclonic winds would have driven easterly airflow over Britain and lead to the observed distribution of loess in Britain. This seems plausible, especially given more recent modelling results indicating the likely greatly enhanced high pressure conditions over the Last Glacial ice sheets (Ludwig et al., 2016). It would also be compatible with extensive dust sources in the North Sea and to some extent the English Channel basins. However, the presence of this high pressure system would also have deflected Atlantic cyclones further south; the tracking of these storms along the English Channel during the LGM would have also caused easterly flow over southern Britain (Antoine et al., 2009; Pinto and Ludwig, 2020). Stevens et al. (2020) proposed that the surging of the Irish Sea Ice Stream during Heinrich event 2 would have further deflected these Atlantic depressions along the English Channel, enhancing this effect and causing increased loess accumulation. These Atlantic storms would have produced more gusty winds, which might aid sediment deflation.

A further dust transport mechanism could be katabatic winds flowing from ice sheet margins; Lefort et al. (2019) proposed that these more northerly winds would explain loess distribution along the southern English Channel, particularly in Brittany, but potentially also on Jersey. Interestingly, if the Irish Sea Ice Stream outwash was indeed the source for the thicker, coarser and mineralogically different loess of Cornwall (Catt and Staines, 1982; Scourse, 1991), this would also indicate a more northerly to north westerly dust transporting wind regime in the more westerly parts of Britain, potentially supporting this assertion for Brittany by Lefort et al. (2019). Indeed, Ealey and James (2011) suggested that the Cornish deposits have much in common with the loess of western France and the Channel Islands, also hinting at a similar origin. However, while northerly katabatic winds may help to explain the increase in loess thickness in the west of Britain proximal to the Irish Sea Ice Stream, it is harder to reconcile this hypothesis with east-west thinning of loess deposits in southern Britain generally. Furthermore, Smart and Findlay (2019) examined aeolian-derived sediments in the

Mendip area of Somerset, (Figure 1) and interpreted their results as indicating westerly dust transporting winds.

Overall, the precise nature of the winds responsible for the deposition of much of the loess in southern Britain is still unclear and the reasons for apparently changing wind directions farther west, and the extent of their influence, is also still debated. It is likely that katabatic, ice sheet anticyclonic, Atlantic storm, and westerly winds would all have had an impact on British loess deposition.

4.3 Deposition and reworking.

Pye (1987) outlined four reasons that may lead to deposition of suspended dust from the air: reduction in wind velocity; precipitation; 'capture' of particles by rough, moist or electrically charged surfaces; the particles becoming charged and forming aggregates. However, in Britain few researchers have detailed specific processes leading to loess deposition. Here, consideration is first given to two adjacent, contrasting areas in eastern Britain, the first showing widespread primary deposition and the second highlighting the role that rivers may play in reworking and redistributing loess, leading to thicker deposits in some regions.

4.3.1 Norfolk and Suffolk

Under the hypothesis of a North Sea basin source for southern British loess, significant deposits should occur on the east coast of England. Catt et al. (1971) and Corbett (1977) noted that large parts of northeast Norfolk (Figure 1) are covered by a thin, silty deposit which also contains variable amounts of sand and clay with occasional flints. Catt et al. (1971) used the term 'coverloam' to describe this deposit as they believed it to be composed predominantly of loess but altered by weathering and other soil forming processes. Furthermore, detailed geochemical study of soils in Norfolk and Suffolk by Scheib and Lee (2010), supported Catt's claim that loess is prevalent in the region. These soils contain elevated levels of zirconium (Zr) and hafnium (Hf), which are elevated in loessic soils (Taylor et al., 1983). These are likely to be D2 deposits (Figure 4), the original Last Glacial loess deposit on the present land surface.

Expanding on this, Scheib et al. (2014) also found a similar strong correlation between Zr and Hf concentrations and known areas of aeolian deposition over the whole of Europe. Interestingly, known loess deposits in east Kent, Sussex, Essex and Norfolk were clearly indicated, whilst other elevated Zr concentrations were shown in the Glencoe area of Scotland and in southwest Cork in Ireland (Figure 1), where loess deposits have not been previously reported.

4.3.2 Thames Valley

Farther to the south, on the north side of the Thames estuary, Essex (Figure 3), contains some of the thickest loessic deposits in Britain; Gruhn et al. (1974) studied the Pleistocene chronology of southeast Essex and identified some ground material there as loess. Catt et al. (1987) noted that these deposits, which had previously been described as brickearth or head brickearth, were the thickest and most extensive loess deposits in Britain, although Eden (1980) had suggested that most of this material has been removed or is not accessible. Thick silt deposits are also found on the southern side of the estuary in Kent, and upriver along the Thames valley (Figure 3). Collectively these deposits are indeed some of the thickest in Britain. However, the genetic origin of some of the material remains unclear; in the middle Thames Valley, Gibbard (1985, 2020) acknowledged the likely multiple different origins of material labelled as brickearth and argued that use of the term ‘silt’ is preferable. Gibbard (1985) proposed that the name ‘Langley Silt Complex’ be applied to the main thickness of brickearth type silts thought to be in their original position in this area. These deposits appear to be extensive, and excavation of a site near Heathrow (Figure 3) revealed the existence of 4 m of Langley silts, suggested by Rose et al. (2000) to be, at least in part, wind-blown. This site is one of the most complete Last Glacial sedimentary sequences in Britain, and also shows a key similarity to the stratigraphy at Pegwell Bay (and Ospringe) in that while the lower 3 m of the Heathrow Langley silts are calcareous, the upper metre is non, or weakly calcareous. The cause of this alteration in Kent is the subject of debate (Clarke et al., 2007; Catt, 2008; Milodowski et al., 2015; Stevens et al., 2020), potentially relating to soil forming processes, dust deposition events, or periglacial reworking. However, given that this is an apparently widespread feature, potentially even occurring further south in the Channel Islands (Keen et al., 1996), it may have regional climatic significance.

The thick loessic deposits in the Thames Valley may be explained by the proximity of the region to North Sea basin dust sources. Another possible explanation may involve the influence of the Thames itself, in a situation comparable to other great loess rivers such as the Danube, Yellow, Mississippi and Volga rivers (Újvári et al., 2012; Nie et al., 2015; Muhs et al., 2018; Költringer et al., 2021; Fenn et al., 2022). However, in contrast to these rivers, there is no obvious mechanism for the production of large amounts of silt in the Thames basin. As such, any genetic association of the loess with the Thames requires that pre-existing loess material in the Thames catchment was reworked and transported by the Thames (T3 in Figure 4). Deposition of this material on the Thames floodplains would have been a good source of silt for deflation, transport and redeposition as thicker D3 loess deposits. This hypothesis would explain the unusual thickness of the Thames Valley loess, but requires further testing. Thus, the juxtaposition of a major source (North Sea basin) and concentrating agent (Thames valley) may have acted to produce the exceptional deposits in the region.

4.4 The role of bedrock

Comparison of bedrock geology and loess distribution maps of England shows an apparent association of loess with certain soluble rock types, for example Chalk (Figure 5), but also limestones and serpentinite. Both Pigott (1962) and Catt (1978) observed that limestone bedrock tends to favour the occurrence of loess in Britain, while Vincent (2004) noted the bedrock underlying the loess of the Burren, in Ireland, is also Carboniferous limestone. Catt (1988) further pointed out that the relationship of loess with limestone outcrops can be very striking; for example, in parts of north Yorkshire, where interbedded Jurassic sandstones and oolitic limestones form parallel outcrops on a relatively flat plateau surface, the limestones have a loess cover up to 1 m thick but the sandstones have a sandy podzol soil cover. Catt (1978) speculated that the presence of frost shattered carbonate material would become mixed with the loess material, enhancing secondary cementation by carbonates, preventing clay eluviation, and in turn making the deposits more resistant to erosion. This theory is supported by the lack of loess soils on outcrops of Permian Magnesian Limestone in northeast England, which is less soluble than other carbonate rocks so leading to less secondary cementation. In the following sections the impact of bedrock on the potential preservation of a loess cover is explored in a number of examples.

4.4.1 Chalk uplands

The upland areas of southeastern England: the Chilterns, Salisbury Plain, the North Wessex Downs and the North and South Downs (Figure 5) are largely composed of Cretaceous chalks and associated marls. These rocks contain varying abundances of very fine grain siliciclastic particles that may become concentrated in the overlying soils after chemical weathering of the carbonate. However, given the relatively proximal position of these chalk lands to the North Sea and Channel basins, loess or loess derivatives should also be common in these soils. A number of studies are outlined here which have attempted to differentiate wind-blown loess from weathering residuum in soils on Cretaceous chalk, these all suggest a close association between chalk and loess deposits (Figure 5).

Perrin (1956) and Perrin et al. (1974) demonstrated that at least some of the mineralogical component in soils on chalk heaths closely resembles that of European loess in terms of grain size and mineralogy. Avery et al. (1959) also examined three soils found on the chalk of the Chilterns (Charity, Batcombe and Winchester soil series) (Figure 5) and suggested that loess was present in all of them, mixed primarily with chalk and clay with flints as a 'solifluction' product or ‘Head’ material. Soil mapping by Cope (1976) also showed high levels of allochthonous silt in the soils of the chalk plateau, while grain size and mineralogical analyses conducted by Perrin et al. (1974) and Catt (1978, 1985) supported this idea. Catt (1978) additionally identified several soils (Hamble, Hook and the Park Gate soil series) that contain loessic material found on calcareous bedrock (*e.g.,* on the Isle of Thanet, East Kent, Figure 3). Similar soils containing loess are also found on the North Downs (Green and Fordham, 1973; Fordham and Green, 1973; Burnham and McRae, 1974). More recently, combined borehole sampling and geophysical analyses revealed the presence of loess material in a shallow (< 0.5 m) pit in the Stonehenge landscape on Salisbury Plain (Figure 1), filling in natural hollows and solution pipes (De Smedt et al., 2022).

Thus, it is probable that a thin loess, or loess derived cover, does exist on the chalk uplands of southeastern England. The presence of this loess cover on chalk is consistent with sources to the north and northeast in the North Sea basin, and are likely to be D2 deposits (Figure 4); however, this loess may only be a remnant of a previously greater cover. Favis-Mortlock et al. (1997) used computer modelling to demonstrate that part of this loess cover may have been eroded during the Holocene. They suggested an initial cover of 1.2 m of loess with a major period of soil erosion between 4,000 and 1,800 years ago. Indeed, at Kiln Combe in East Sussex (Figure 1), Bell (1983) described a sequence of colluvial soils in a chalk dry valley that shows a changing input of sediment type: 1) Bronze age soil includes loessic material; 2) soil of Romano-British age shows an input of Tertiary age material comprising stony clays and flint; 3) the Medieval soils include chalky colluvium. They interpreted these changes as due to the increasing effects of soil erosion through time, probably due to increasing farming impact. Several other archaeological excavations of soils in the dry valleys of the chalk also indicate a loessic contribution to the soil, *e.g.,* Catt and Staines

(1998) in Kent and Wilkinson et al. (2002) in East Sussex, although it is unclear how much of this was reworked and mixed into developing soils in situ.

4.4.2 Cornwall

Despite the lack of carbonate rocks in Cornwall (Figure 1), the distribution of loess there also shows a strong correlation with the bedrock type. Roberts (1985) and Catt and Staines (1982) argued there is an almost continuous mantle of loess over the serpentinite outcrop (*e.g.,* Figure 2b), but that it is generally absent from slate areas. Ealey and James (2011) noted that serpentinite is soluble, thus leaving little granular matter to form soil so that acidic loess can be more easily identified. In contrast, on other rock types loess may become incorporated into breakdown products. Ealey and James (2011) also noted that while loess is almost totally absent from slate bedrock regions, it is present on gabbro and granitic bedrock lithologies, albeit to a lesser degree than on serpentinite. This implies that there was a previous cover of loess over much of Cornwall, but that bedrock type controlled the degree to which this was preserved in situ. Indeed, Catt and Staines (1982) claimed the present distribution of loess in Cornwall is a result of some bedrock types being conducive to more intensive soil erosion than others. The impermeable nature of the slates in particular may lead to a process of saturation of any overlying loess leading to collapse and erosion.

4.4.3 Northern England

Loessic deposits in the northern half of England have been less frequently reported than in the south. However, two areas here with loess cover share a Carboniferous limestone bedrock, although they differ considerably in general appearance.

Much of the limestone plateau of Derbyshire (Figure 1) is covered by superficial ‘loam, chert-gravel or clay’ that Pigott (1962) argued is composed largely of loess with insoluble limestone residues. Pigott (1962) further claimed that the deeply weathered limestone surface is due to ‘interglacial’ weathering and that the absence of limestone pavements here is a consequence of the area lying outside the limits of the last glacial ice sheet. Farther north, the more obviously karstic areas around Morecambe Bay and across the Yorkshire Dales (Figure 1) were glaciated during the Last Glacial Period but loessic deposits have also been found here (Bullock, 1971; Vincent and Lee, 1981). Optically Stimulated Luminescence (OSL) dating of the loess around Morecambe Bay initially yielded primarily Holocene ages for these deposits, implying colluvial reworking of pre-existing loess deposits (Wilson et al., 2008), comparable to similar processes reported in the Weald and the Thames Valley.

4.4.4 The Weald of Kent and Sussex

Given the widespread presence of loess on chalk in southeast England, the eroded anticline that forms the Weald, between the North and South Downs (Figure 3), should have provided an ideal trap for any wind-blown silt (Catt 1978; Burrin 1981; Jefferson et al., 2003). However, as Catt (1978) pointed out there are few significant loess deposits within the Weald. This presents a conundrum, but again bedrock control on loess preservation may play a critical role. Saturation of loess deposits is more likely to occur on impermeable bedrock. In turn, this may cause collapse due to hydroconsolidation (sudden collapse due to wetting and loading), accelerating reworking of loess, as with the slates in Cornwall (Catt and Staines, 1982). Given that impermeable clay rich bedrock underlies significant areas of the Weald, this process may also explain the absence of loess there. The impermeable bedrock in turn may also have caused the tight drainage network on the Weald, further enhancing loess erosion. Indeed, Burrin (1981) and Burrin and Jones (1991) interpreted the homogenous, predominantly silt-sized material they found in the alluvium of the rivers Ouse and Cuckmere (Figure 3) as derived from loess; remnants of a formerly extensive but now eroded loess cover. A similar situation is described by Jefferson et al. (2003) for the River Arun (Figure 3), while Boardman (2003) reports that similar processes are still occurring on the South Downs up to the present day.

Under this scenario, the current distribution of loess and other silts across the Weald can be interpreted by a sequence of 'T' and 'D' events (Figure 4), where after initial loess fall (D2) a reworking event occurs (T3). This is a similar chain of processes to that evoked to explain the large thickness of the Thames Valley deposits, and indeed many loess deposits in southeastern England may be D4 deposits, after another phase of aeolian deflation and deposition (model 2 in Figure 4). Potentially, the Pegwell Bay deposits fall into this group, if the River Stour provided the mechanism for T3 movement. A variation on this model has also been proposed by Assadi-Langroudi (2019), who argued that some Wealden loess deposits are D5 in nature. It is possible that many different models of loess transport and reworking are applicable in different locations in southern Britain, which may account for the complex and diverse nature of the silty sediments in the region.

However, Gallois (1982) disputed that the silty alluvial deposits of the Weald reported in Burrin (1981) were derived from loess, and argued rather that they could have been a product of bedrock weathering. In addition, Stevens et al. (2020) suggested that the timing of deposition of loess at Pegwell Bay implies a more direct coupling to ice sheet dynamics (*i.e.,* that Pegwell Bay loess deposition is a D2 event in a P1-T1-D1-T2-D2 sequence; model 2 in Figure 4), and so more research is needed to test the complex series of events that lead to the current loess coverage of southeast England.

4.5 In situ modification: the role of engineering studies in understanding the nature of loess deposits

The relationship between loess deposits and bedrock type promoted the original theory of 'loessification' - the idea that loess was formed through in-situ alteration of bedrock (Smalley et al., 2010; Sprafke and Obreht 2016). Catt did not agree with this theory, rather he emphasised how bedrock properties affected the preservation of aeolian deposited loess, and he explained clearly that diagenesis and pedological processes had a role in the formation of loess deposits (Catt, 1978; Antoine, 2003). He applied the P-T-D system and pointed to the addition of another factor - a change factor: C (Figure 4), so that the event-based system becomes the P-T-D-C system. He proposed that post-depositional changes due to periglacial and pedological processes should be acknowledged as a step in the development of these deposits echoing earlier claims of Pecsi (1990) that loess is more than 'just' an air-fall deposit.

Post-depositional modification of British loess has received much interest and some of that work is reviewed here. Emphasis has been predominantly on loess in southeastern England and mainly within the context of assessments over the geotechnical aspects of loess in the build environment with some of the most detailed studies of the composition and physical structure of British loess due to engineering concerns related to the development of major infrastructural projects. The results have led to a greater understanding of the microscopic structure of loess in southeastern England in terms of its deposition and early diagenesis, as well as post-depositional events and their implications for engineering properties.

The typically porous texture, well-sorted, and cemented structure of loess yields reasonably high strength at its natural moisture content, albeit with a susceptibility for hydroconsolidation - sudden volumetric collapse upon wetting under load (Assadi-Langroudi et al., 2018). The porous texture is formed predominantly of quartz grains held in place by a post-depositionally formed skeletal framework of clays, oxides and carbonates. Larger grains are often bridged with domains of finer grains that gain strength from interlocking and suction. However, once bonds are disturbed through wetting, the porous texture rapidly densifies. In America, Europe and Asia, this hydroconsolidation of loess is known to cause serious geotechnical problems and hazards (Turnbull, 1968; Rogers et al., 1994; Derbyshire, 2001). However, except for a few isolated cases (*e.g.,* Cattell, 1997; 2000), little has been published on damage caused by collapse of loess in Britain. This is probably due to the typically thin and shallow nature of British loess where a foundation embedment depth of 1.5-2 m is often enough to bypass the surficial loessic sequence.

Catt (1977) suggested that much of the loess across Britain has been reworked; one notable example of reworked English loess being the gull-fills at Allington, near Maidstone in Kent (Figure 3). The loess here was described by Bell et al. (2003) as a 0.5-1.0 m thick loam or silt soil that is essentially gelifluction material deposited on frozen ground (Catt, 1977). Bell et al. (2003) attributed the very low 0.5% carbonate content, low clay content and plasticity index of the Allington loess to the gradual disappearance of within sediment ice and the leaching of minerals by meltwater in the gulls. Notably, these post-depositional events appear to have had little impact on the naturally porous texture of loess in Allington. Bell et al. (2003) recorded elevated levels of collapsibility potential, but these are restricted to low levels of surcharge *i.e.,* lower than 200 kPa. Indeed, despite the fact that much English loess may be reworked, from an engineering perspective its collapsibility potential is often undiminished; in fact, reworked loess can exhibit as high collapsibility as non-reworked loess, only under lower surcharge levels. This is manifested in Mellors (1977) work, showing that many of the collapsible loessic samples obtained across England are gelifluncted. For Kentish loess, in particular, Mellors (1977) showed that reworking has failed to change the collapsible structure and Derbyshire et al. (1988) arrived at similar conclusions for loess at Pegwell Bay.

The loess in Ospringe in Kent (Figure 3) was subjected to a comprehensive programme of research, yielding a thorough understanding of collapse mechanisms and properties of Kentish loess (Zourmpakis et al., 2006; Northmore et al., 2008; Smalley and Markovic, 2013). Milodowski et al. (2015) concluded this decade long research and emphasised the range of bonding materials that define the inter-particle relations and which in turn control collapse potential. In their model, secondary clay and calcite bridges connect the silt grains and have a pivotal role in the collapsibility of loess. These bridges preserve the open structure of primary loess, but modification of these bonds upon loading in a wet state can lead to the sudden collapse of the open structure.

Milodowski et al. (2015) suggested that collapsibility of loess is marginal in the absence of inter-particle clay-calcite bonding units. Thus, the relatively lower porosity of the non/weakly calcareous upper loess in Pegwell Bay and Ospringe is indicative of their reworking and collapse; this reworking may be related to gelifluction processes (Milodowski et al., 2015), or to active layer processes (Stevens et al., 2020). An interesting aspect of Milodowski and colleagues' findings is the contradiction with previous suggestions that reworking has failed to change the collapsible structure of British loess (Mellors, 1977; Derbyshire et al., 1988). This difference in views may reflect different types or levels of reworking, or indeed the variable nature of British loess. However, any retained porous structure continues to pose a risk of wetted collapsibility.

Clay is the primary source of bonding for the particles in English loess and a possible source for clay in some chalk areas is Clay-with-flints; a weathering product of chalk described by Gallois (2009). West and Mills (2017) noted that the clay mineral composition of a brickearth near Southampton (Figure 1) is similar to that of Cretaceous Chalk. However, given the diverse potential sources of clay and the diverse ways it can combine with silt, loess may contain varied contents and minerals of clay. Northmore et al. (1996) reported clay content varying from 4% to 42% across south Essex and suggested the source to be adjacent cryoturbated clay formations. From a geotechnical perspective, maximum collapsibility occurs in loess containing a 11–24 wt.% clay (Lawton et al., 1989) with greater clay contents generally providing greater levels of strength. Across east and southeast England, undrained and drained cohesion of loess – indicative of short- and long-term strength – varies between 10 to 220 kPa and 10 to 70 kPa, respectively (Northmore et al., 1996). This rather broad range of strength is a manifestation of the high variability of clay content and makes the English loess as difficult a soil as the Langley Silt (indeed some Langley Silt maybe loessic) in terms of high spatial and temporal variability.

The secondary source of bonding between loess particles is calcium carbonate. Generally, calcium carbonate constitutes less than 10% of English loess, although actual levels are highly variable across the country and even within individual sections. Northmore et al. (1996) reported values ranging from 16.5% to 0.16% in south Essex (Figure 1), occurring as grains, nodules and tube fillings. Bell et al. (2003) reported that carbonate forms on average 10.4% and 11.7% of loess in south Essex and Kent respectively. However, as previously described several loess sequences in southeast England show a divide between an upper less calcareous layer and a lower more calcareous layer, *e.g.,* at Ospringe in Kent, Milodowski et al. (2015) reported less than 1% calcium carbonate in the upper sequence and 8-9% within the lower sequence, although the reasons for this are uncertain. In contrast, loess in southwest England, northwest England and Wales is commonly reported as 'decalcified' *e.g.*, Lee and Vincent (1981); Vincent and Lee (1981); Keen et al., (1996); Ealey and James (2011). Overall, studies of English loess from an engineering perspective have established better understanding of depositional and post-depositional reworking events, with implications for loess mineralogy and the formation of collapsible and non-collapsible fabrics due to climatic and environmental changes. In so doing, the engineering insights have crosscut multiple disciplines and are worth revisiting.

5. THE AGE OF BRITISH LOESS.

5.1 Last Glacial Period loess

Catt (1977) suggested that an upper Last Glacial Period (MIS 2) age for the loess deposits of southern Britain could be inferred by comparison with adjacent parts of continental Europe. There, the prevailing view was that the only widely distributed, undisturbed loess in continental northwestern Europe was upper Last Glacial Period (Late Weichselian/Upper Pleniglacial) in age, although it is worth noting that very few independent numerical ages existed for these deposits at that time either. Catt (1977) also noted that the frequent incorporation of loess into periglacial soil and gelifluction deposits probably indicated deposition of loess during peak glacial conditions; however, this gelifluted loessic material could also have been derived from pre-existing loess deposits. More recent evidence for the age of British loess is reviewed here.

Organic remains in British loess deposits are generally rare, meaning that radiocarbon dating of loess in Britain has so far had limited application. Despite this, terrestrial molluscan fauna found at a few loess sites in Kent and Jersey (Figure 1) allow tentative age assignment of loess to the middle and upper Last Glacial Period (Kerney, 1971; Rousseau and Keen, 1989; Preece, 1990). More recently, luminescence dating has proved an important method for assigning ages to loess deposits (Wintle, 1990). The first thermoluminescence (TL) dating of any loess globally was carried out by Wintle (1981) on deposits across southern England, from Kent to the Isles of Scilly. This study was key in pioneering TL approaches to loess deposits generally, and opened up the great potential of sediment dating by luminescence methods. The ages presented by Wintle (1981) ranged from 14.5 to 18.8 ka, reinforcing Catt's hypothesis that these were upper Last Glacial Period deposits. Later work also using TL methods corroborated these inferences, with loess from southeast England showing a TL age cluster of 10 to 25 ka (Parks and Rendell, 1992), and loessic 'brickearths' in the London area giving ages of < 19 ka (Gibbard et al., 1987). However, TL dating of surface and buried soils in loess at Pegwell Bay (Figure 3) yielded ages consistent with recent and early Holocene soil formation (Wintle and Catt, 1985), and OSL dating of loess in northwest England (Wilson et al., 2008) also suggests reworking in the Holocene.

In Kent, the Pegwell Bay and Ospringe sequences have been the subject of more recent luminescence studies. Clarke et al. (2007) used post-IR OSL dating to argue that the upper and lower units of these sequences were deposited in two separate phases in the upper Last Glacial Period, separated by a hiatus. However, Catt (2008) argued that based on the limited chronological data presented in Clarke et al. (2007) there was no evidence of multiple separate loess depositional phases coinciding with the different loess units. Stevens et al. (2020) recently applied the first high sampling resolution OSL dating to British loess, covering the entire sequence at Pegwell Bay for the first time. They showed a remarkably short episode of loess deposition, starting not before 25 ka and possibly occurring in two main phases centred on 25-23.5 ka and 20-19 ka. They argued that only with coalescence of Fennoscandian and British Irish ice sheets at the LGM are the atmospheric and sub-aerial North Sea drainage conditions set up to deliver sufficient sediment to southeastern England to form loess. Furthermore, they argued that two phases of BIIS North Sea ice lobe advance and retreat (and associated glacial lake drainage) control the possible two pulses of enhanced loess accumulation at Pegwell Bay. Further studies are needed to test this and determine whether this is a widespread feature of loess in Britain.

Loess deposition also occurred in northern England prior to maximum ice advance during the Last Glacial Period. In northeast England, Bateman et al. (2008) used OSL to date loess exposed under a Last Glacial Period till to 23.3±1.5 ka, suggesting loess accumulation prior to Last Glacial Period ice advance in the region. A further extensive programme of OSL dating of loess in northwest England has also been reported by Telfer et al. (2009) detailing several samples of possibly primary loess dating to *c.* 27 ka, with others dating to 19 – 16 ka, recovered from karstic features on the limestone uplands. They suggested that the *c.* 27 ka loess is a remnant of a pre ice advance loess protected due to its location in a doline, and therefore constrains the maximum age of the onset of Last Glacial Period ice coverage in the region. Parks and Rendell (1992) also TL dated a number of sites in southeast England to the early to middle Last Glacial Period (MIS 4 – 3).

5.2 Older loess deposits

Pre Last Glacial Period loess is rarely found in Britain. Rose and Allen (1977) described a 1.2 m thick calcareous loess underlying Anglian (MIS 12) till found at Barham in Suffolk (Figure 1). This loess shows a different mineralogy than younger loess deposits with, for example, more zircon and rutile but less hornblende, as well as a finer grain size. Rose and Allen (1977) argued that this older loess marks the onset of ice advance during MIS 12. Farther south, Parks and Rendell (1992) used TL dating to reveal pre Last Glacial Period age loess (to 200 ka) at a number of sites around Sussex and Hampshire (Figure 1), *e.g.*, Lepe Point, Boxgrove and Sussex Pad. On Jersey (Figure 1), loess is seen to underlie raised beach deposits of the last interglacial at Portelet and Belcroute, presumably implying a penultimate glacial age for these deposits (Keen et al., 1996). Juby (2011) summarised bio-stratigraphic, amino acid racemisation and artefact evidence from Crayford (Figure 3) to offer an MIS 7 age for the fauna found in the lower brickearth, implying that older loess deposits were being reworked and deposited at this time. An MIS 6 age was suggested for the upper brickearth based on the limited faunal remains it contains.

Pre Last Glacial Period loess is also found on southern English chalk. Based on mineralogical similarities with other dated loess deposits elsewhere, *e.g.*, at Barham, Avery et al. (1982) suggested that the doline infills on the Chiltern hills (Figure 1) include aeolian components of both MIS 12 and MIS 6 age; these locations are also known for recovery of Palaeolithic artefacts (Sampson 1978). Murton et al. (2015) described a variety of Quaternary sediments, including loess, that infill a number of river channels at Marsworth in Buckinghamshire (Figure 3), also on the Chilterns chalk. The deposits at this site span two temperate periods and an intervening periglacial period (probably MIS 6). No undisturbed loess sequence has been found here, but loess has been incorporated into silty and clayey loams as a result of mass movement and hill wash. Finally, loess found overlying chalk in a shallow pit at Stonehenge on Salisbury Plain has recently yielded three OSL ages spanning 240 to 150 ka (MIS 8 and 6) (De Smedt et al., 2022).

6. PALAEOENVIRONMENTAL STUDIES

Studies of variations in past climate proxies by age and depth are common in regions with thicker loess deposits (*e.g.,* China and central Europe). However, given the short duration of known loess deposition in Britain, the relatively modest thicknesses of these loess deposits, and the likely extensive post-depositional reworking, it is unsurprising that such studies are rare in British loess. Here, some of the palaeoenvironmental work conduced on loess in Britain is reviewed, grouped broadly by the main techniques and approaches applied. Terrestrial gastropods and assemblages of gastropod fauna, although quite rare in British loess, have occasionally been used to infer conditions during phases of loess deposition. A number of loess sites in the Channel Islands (Figure 1), notably at Portelet and La Motte (Green Island) on Jersey, yield a sparse molluscan fauna that indicate very cold, dry climate conditions during late middle and upper Last Glacial times (Keen, 1982; Rousseau and Keen, 1989). Sparse, cold climate molluscan fauna have also been found in loess at Reculver, east Kent (Preece, 1990) and the now lost loess section at Halling, west Kent (Kerney, 1971) (Figure 3). The Halling fauna suggest open, cold, dry conditions under a periglacial environment, supporting the extension of cold permafrost conditions into southern England, although changes in the fauna also hint at small climatic fluctuations.

Stratigraphic, geomorphic and sedimentary facies associations have also been used to understand shifts in climate and environment from British loess. For example, loess in Jersey and Cornwall (Figure 1) is often associated with other sedimentary units such as raised beaches and gelifluction deposits (Figure 2f), indicating a sequence of cold climate periglacial processes alternating with warmer periods of higher sea levels (Keen et al., 1996; Roberts, 1985; Scourse, 1991; Bates et al., 2003). Some loess units on Jersey show evidence of '*limon à doublet'* facies (Keen et al., 1996), consisting of thinly banded alternating sandy and silt loess couplets (Figure 2d), potentially indicative of freeze-thaw cycles of seasonal snow melt inducing low-energy overland flow (Derbyshire et al., 1988). Banded loess similar to '*limon à doublet'* has also been seen by the authors in some loess of the Lizard peninsula in Cornwall (Figure 1 and 2e), although it's formation and chronostratigraphic relationship to '*limon à doublet'* facies in Jersey (and northwest France) is unclear. Ealey and James (2008) also described other periglacial features at some sections in loess of the Lizard peninsula. This Lizard Loess unit therefore also shows evidence of periglacial active layer processes in a permafrost environment, extending the known range of permafrost conditions far into the southwest of Britain during the Last Glacial Period.

Periglacial stratigraphic features are also seen in British loess lying farther east. Kerney (1965) showed that the loess of Thanet, east Kent (including Pegwell Bay) is part of a sequence of sediments revealing the evolution of climate from the Last Glacial into the Holocene. Initial periglaciation is shown in heavily cryoturbated chalk, followed by later deposition of loess at the peak of the Last Glacial Period. Overlying this is a sequence of palaeosol, chalk detritus, another buried soil, and more detritus and slope wash, representing swings in climate at the end of the last glacial phase. Bates et al. (2003) noted the strong mixture of loess particles and discrete loess beds in 'head' deposits in parts of northern France and state that while most head deposits in southwest England are 'structureless' there is the potential for aeolian particles to be found in such deposits. These studies demonstrate how loess deposits are often found in association with a range of periglacial sediments and features, such as involutions or frost shattered bed rock, ice segregation and soft sediment deformation, and gelifluction deposits.

Evidence for climate amelioration is also seen in loess stratigraphy, Wintle and Catt (1985) demonstrated the existence of an early Holocene buried soil in the loess at Pegwell Bay. Furthermore, Stevens et al. (2020) suggested that the upper soil at Pegwell Bay may represent a Holocene soil overprinting a soil formed during a brief episode of climate warming during the Late Glacial interstadial.

A multiproxy study was conducted on c. 4 m of Langley Silt Complex (at least partly loess) in the Heathrow area (Figure 3) of Greater London (Rose et al., 2000) using particle size, $CaCO_3$ %, organic carbon content, and micromorphological analyses. Although the timing is tentative as no independent ages are available, they argued that aeolian deposition of silts occurred during multiple cold phases of the late Quaternary, while during a warmer, wetter middle Last Glacial, wind and surface wash deposited a laminated silt and sand with evidence of seasonal desiccation. After late Last Glacial loess accumulation, a soil developed during the Late Glacial interstadial, followed by renewed cooling during the Younger Dryas. Of particular interest for future work would be whether these Langley silts contained a longer aeolian record than appears to be preserved in east Kent, and if so, why that difference occurs.

More recently, Stevens et al. (2020) investigated the use of geochemical, particle size and mineral magnetic analyses in generating climate reconstructions at Pegwell Bay in east Kent. Geochemical data were strongly affected by post-depositional modification ascribed to active layer processes under a permafrost regime. Particle size data may be linked to wind strength, but the proximity to dust source areas and the availability of different grain sizes in source areas likely complicates interpretations. However, Stevens et al. (2020) showed that temperature dependent magnetic susceptibility could be used to identify the presence of secondary maghemite, which they argued may be formed during short-term (*i.e.,* centennial scale) weathering events under brief periods of warmer climate during the Last Glacial. This possibility requires further testing, but supports the assertions of short term climate events made by Kerney (1971) at Halling based on gastropod assemblages.

Independent dating studies of loess units also provide useful information on past environment. For example, Scourse (1991) argued that the Old Man Sandloess on Scilly (Figure 2f) is formed from outwash of the maximum extent of the Last Glacial Irish Sea Ice Stream, therefore directly marking the timing and limit of the ice stream advance. Stevens et al. (2020) also claimed that loess at Pegwell Bay is formed due to advance retreat cycles and drainage of the North Sea Lobe of the British-Irish Ice Sheet. These studies suggest that phases of dust accumulation, and by extension dust activity in the atmosphere, are driven by the dynamics of different components of ice sheets during the Last Glacial.

Evidence of more recent environmental changes recorded in loessic deposits has also been revealed by luminescence dating. Wilson et al. (2008) and Vincent et al. (2011) showed that reworking of Last Glacial loess from northwest England occurred during the early Holocene. Vincent et al. (2011) suggested that this colluviation was linked to wetter and cooler conditions associated with climatic deterioration reported for the North Atlantic region between 8.5 to 8.0 ka (Griffiths and Robinson, 2018). In this way, reworking of loess may be linked to specific, abrupt Holocene climatic events. Indeed, investigating the temporal relationship between loess deposition and episodes of reworking more widely may provide hints over the changing climatic and environmental controls and interactions of these two processes.

7. DISCUSSION AND FUTURE PROSPECTS

There is now widespread recognition across many disciplines for the presence of Late Glacial loess across many regions of Britain and Ireland. Deposited as a thin superficial layer, mostly, but not exclusively during the Late Pleistocene, much of this loess is likely to have been subject to periglacial processes that caused reworking and mixing with other superficial periglacial deposits (Figure 2g). This means British loess has become quite varied in appearance and texture (Figure 2); the P-T-D-C model provides a mechanism through which to consider this variability. Reworking due to episodic climate change during the Holocene such as the 8.2 ka event, as well as human activity, may also have been a factor. In southeast England extensive brickmaking has contributed to the loss of this once greater loessic cover. John Catt's conjecture was that this complex history may demand more detailed analyses and require further scientific investigation and consideration than is the case with many other classical loess deposits. Some specific ideas for further study are given here.

A first step in understanding loess deposits is constraining the origin and mode of production of the silts comprising loess. However, starkly contrasting views still exist in the literature over the likely sources of silt for loess across Britain and Ireland. Further provenance studies are needed to provide diagnostic data on loess source, and whether the loess in different parts of Britain and Ireland share the same source areas, or whether they vary geographically. Secondly, better definition of the true distribution of loess across Britain and Ireland is still required. John Catt made major inroads in this area, but improvements could be achieved using more extensive Hf and Zr soil geochemistry surveys, which could be combined with a study of the relationship between loess and various bedrock lithologies. Thirdly, the nature of the controls (deposition, reworking, preservation) on the distribution of this loess remains an outstanding and fundamental question. Better constraint of the specific areas where loess and loess derivatives are preserved is required to address this; this is perhaps particularly the case for northern Britain, Wales and Ireland. Fourthly, the controls on loess stratigraphy generally are sometimes poorly constrained. This is particularly the case with the sharp division between calcareous and non/very weakly calcareous loess in deposits in east Kent, Jersey and possibly also the Thames Valley. More specifically, key stratigraphic features like possible periglacial fragipans preserved in Lizard Loess and '*limon à doublet*' on Jersey require more targeted investigations to understand the driving forces behind their formation. A potential future related goal could be the development of a southern English loess stratigraphic scheme, as already exists for deposits in adjacent continental northwestern Europe (*e.g.*, Brittany; Monnier et al., 1997). Finally, while increasing numbers of studies are utilising independent dating (especially luminescence: Clarke et al., 2007; Bateman et al., 2008; Wilson et al., 2008; Telfer et al., 2009; Vincent et al., 2011; Stevens et al., 2020) to understand the timing of deposition of loess in Britain, the number of reported ages remains few and most studies have not utilised the high sampling resolution dating required to understand the precise timing and nature of loess deposition. This inhibits understanding of the controls on loess accumulation in Britain as well as the development of standardized chronostratigraphic schemes, and ought to be a strong focus for future work.

Fortunately, the scene is set for such an enquiry. Advances in mapping have now placed British loess firmly into the international literature (Lehmkuhl et al., 2021) such that at least the deposits in southeastern England are now considered a component of a Eurasian loess belt. This implicitly recognises that these deposits reflect wide-scale silt production and dust transport processes, connected and related to loess in adjacent NW continental Europe, rather than simply isolated deposits reflecting local processes in England, unrelated to wider dust transport. Furthermore, advances in provenance and dating techniques yield much more specific information on age and source of loess deposits, which ultimately should shed light on the specific origin and formation mechanisms of loess in Britain and Ireland.

8. CONCLUSIONS

Loess was widely deposited in many parts of Britain, and probably Ireland, during periglacial conditions associated with the Last Glacial Period, especially during MIS 2. However, much of this loess has been reworked by contemporaneous or Holocene surface processes, or by more recent human activity. Loess from previous glacial periods is also preserved in more localised deposits, for example in doline fills.

The Last Glacial Period loess deposits are thickest in southeast England and the Channel Islands, and are comprised of silt particles that probably originated from glacial outwash deposits in the exposed North Sea and Channel basins. These outwash sediments likely had an initial northern European or Alpine origin, although the relative importance of these initial sediment source areas remains debated. There were also probably additional inputs from local bedrock sources, but the extent of this remains unclear for many deposits. Loess deposits in parts of western and northern England, the Scilly Isles and Wales are more likely associated with glacial outwash deposits from the Irish Sea Ice Stream. While loess on the west coast of Ireland is probably associated with offshore glacial outwash deposits there. The generally east to west fining and thinning of loess deposits in southern England suggests easterly winds dominated dust transport, possibly related to enhanced ice sheet high pressure during the Last Glacial Period. However, there is debate about prevailing dust transporting wind directions in other parts of Britain and the Channel Islands, with possible influences from westerly and ice sheet katabatic winds have also been implicated in dust transport. The source and transport of British and Irish loess represents a key strand of future research, as it has implications for understanding atmospheric, ice sheet and landscape processes of Quaternary northwestern Europe.

The generally thin nature of the British-Irish loess deposits has meant they are highly prone to reworking and modification, first through periglacial processes such as gelifluction, and later by pedological processes. However, soluble bedrock types, such as chalk, appear to show a preferential retention of loess deposits. The reasons for this retention are uncertain but are potentially due to specific drainage conditions or chemical interactions involving calcium carbonate. Human activity during the Holocene may also have led to extensive reworking of loess in some areas of Britain. Significant quantities of English loess have also been removed by later human influences such as brick making and agriculture, and the expansion of the built environment over southeastern England has rendered some the thicker loess deposits here inaccessible. Despite this, a number of important loess sites in Britain remain accessible, and have been the subject of renewed focus in recent years. Furthermore, the generally thinner and often reworked loesses outside of southeast England show considerable potential for investigating landscape change and human influences over the British Isles, since the Last Glacial Period.

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FIGURES

1. General map of Britain and Ireland showing named locations, also showing loess distribution in England and Wales as mapped by John Catt (1977).
2. Photos of British and Irish loess sequences showing the variability within the deposits.
3. Map showing some key loess locations and rivers in southeast England.
4. Conceptual flowchart of two potential sequences of events leading to the formation of loess deposits in southeast England.
5. Map showing the correlation of the chalk outcrop in southeast England and soils with a high loessic content.

FIGURES

Figure 1. General map of Britain and Ireland, showing loess distribution in England and Wales mapped by John Catt reproduced with permission from British Quaternary Studies, 1978. Copyright with Oxford University Press reproduced with permission of Oxford Publishing Ltd through PLSclear, reference number 34147. Also shown are specific locations and counties mentioned in the text, the area within the red rectangle is enlarged in Figure 3.

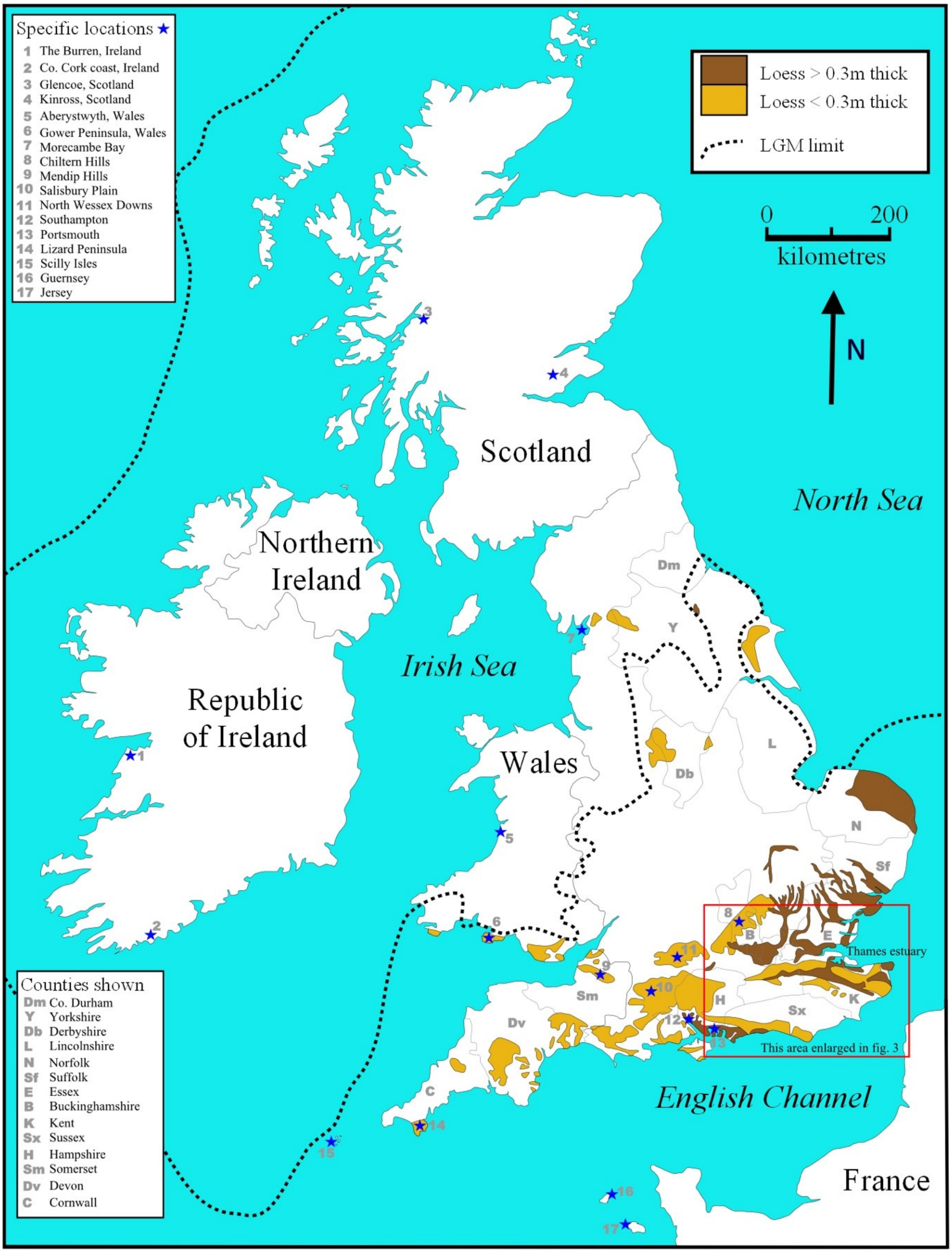


Figure 2. Photos of British and Irish loess sequences showing the variability within the deposits. a) Stratigraphy at the former hoverport site at Pegwell Bay; b) exposed loess at Chynhalls Point, Lizard Peninsula, Cornwall. Note that the loess covers Devonian serpentinite; c) possible loess on the Burren of western Ireland, pit dug at Glen of Clab; d) surface weathering of the section at Belcroute, Jersey, revealing sand and clay-silt banded loess (‘*limon à doublet’* facies); e) banded loess exposed at Lowland Point, Lizard peninsula, Cornwall; f) Old Man Sandloess capped by the Porthloo Breccia at Gimble Porth on Tresco, Isles of Scilly, the latter assumed to be a solifluction deposit (Scourse, 1991); g) loess mixed with (likely) geliflucted flint clasts exposed at low sea cliffs at Selsey, West Sussex. All photos by T. Stevens except c) by C. Bunce.

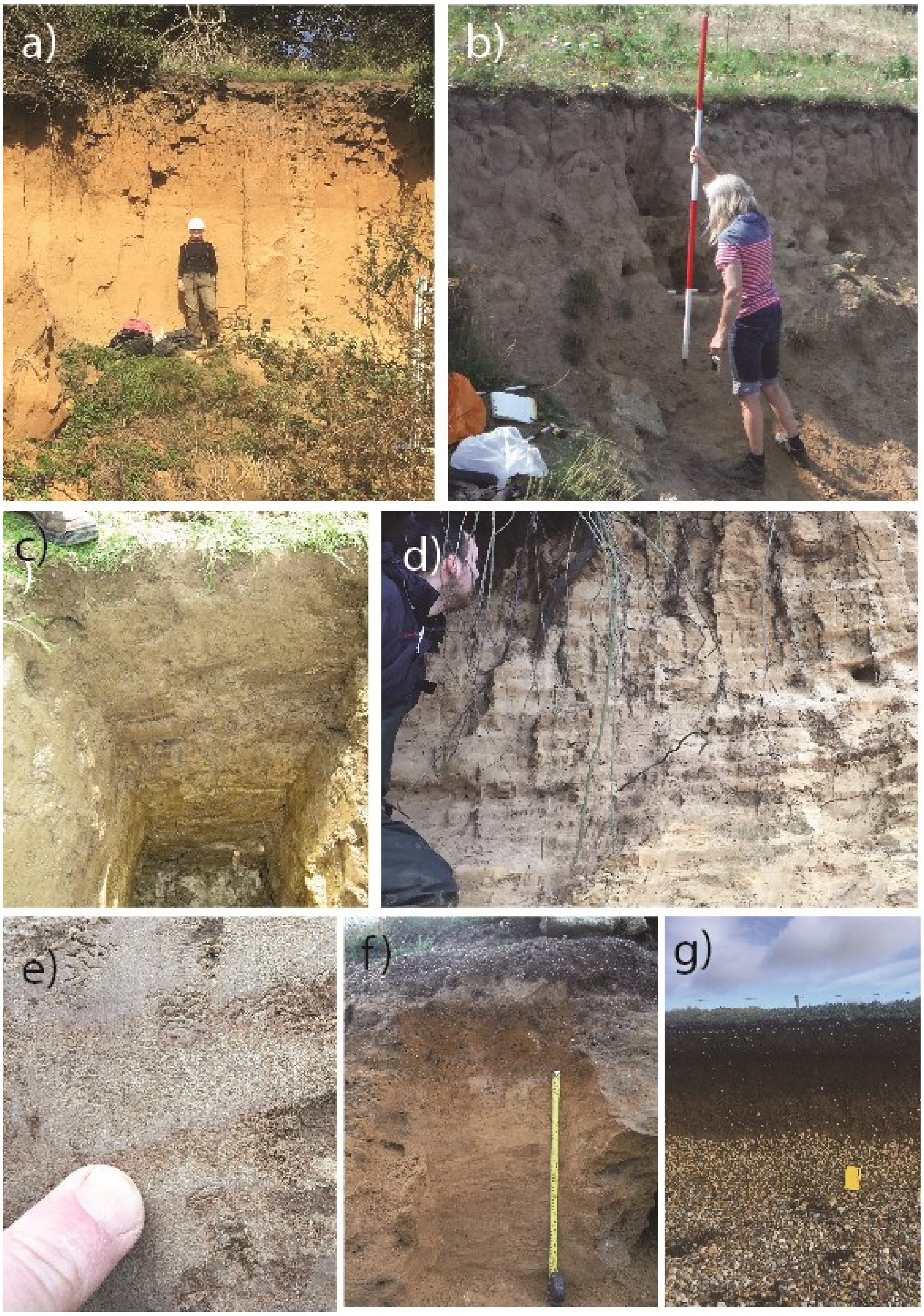
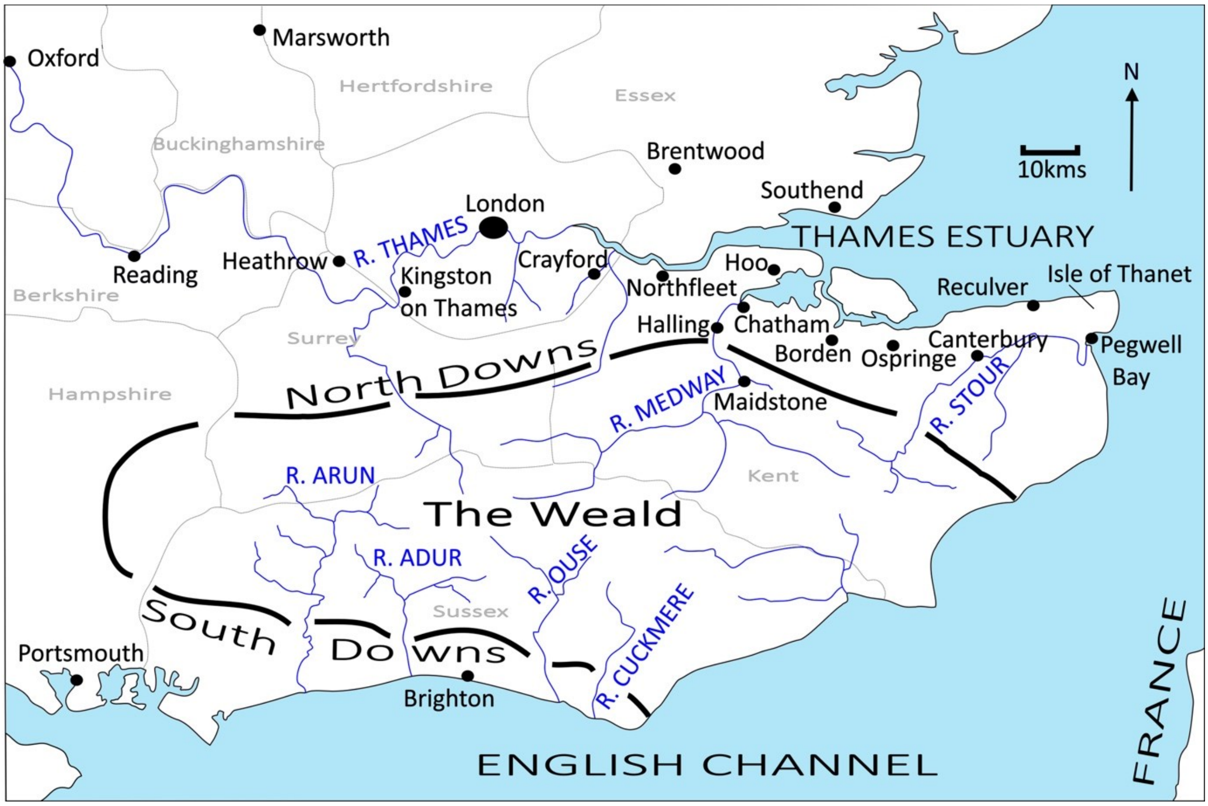


Figure 3. Map showing some key loess locations and rivers in southeast England. Map drawn by C. Bunce.



1593 Figure 4. Conceptual flowchart of two potential sequences of events leading to the formation of loess deposits in southeast England, following the deterministic P-T-D-C approach to loess deposit formation (see Smalley 1966, Catt 1988, Assadi-Langroudi 2019). BIIS = British-Irish Ice Sheet. FIS = Fennoscandian Ice Sheet.

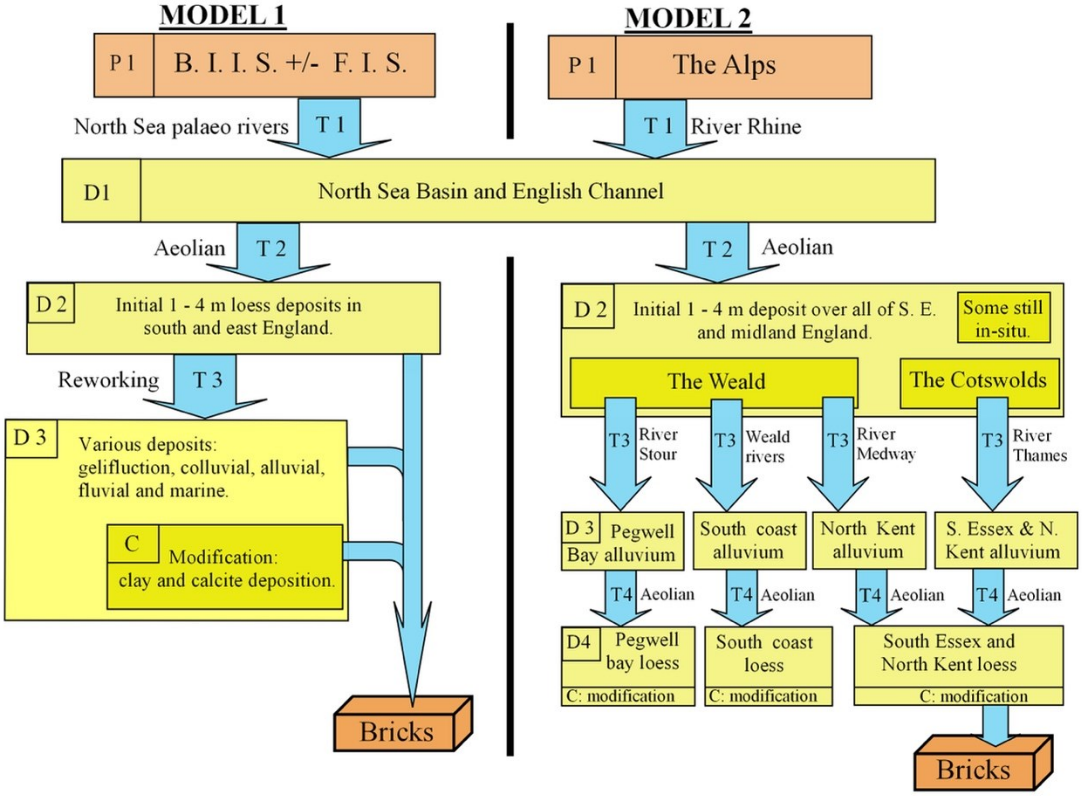


Figure 5. Map showing the correlation of the chalk outcrop in southeast England (based on mapping by British Geological Survey) and soils with a high loessic content (based on Catt, 1977, copyright with Oxford University Press reproduced with permission of Oxford Publishing Ltd through PLSclear, reference number 34147).