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Development of a subglacial drainage system and its effect on glacitectonism within the polydeformed Middle Pleistocene (Anglian) glacigenic sequence of north Norfolk, Eastern England

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ABSTRACT

The efficiency of subglacial drainage is known to have a profound influence on subglacial deformation and glacier dynamics with, in particular, high meltwater contents and/or pressures aiding glacier motion. The complex sequence of Middle Pleistocene tills and glacial outwash sediments exposed along the north Norfolk coast (Eastern England) were deposited in the ice-marginal zone of the British Ice Sheet and contain widespread evidence for subglacial deformation during repeated phases of ice advance and retreat. During a phase of easterly directed ice advance, the glacial and pre-glacial sequences were pervasively deformed leading to the development of a thick unit of glacitectonic mélange. Although the role of pressurised meltwater has been recognised in facilitating deformation and mélange formation, this paper provides evidence for the subsequent development of a channelised subglacial drainage system beneath this part of the British Ice Sheet filled by a complex assemblage of sands, gravels and mass flow deposits. The channels are relatively undeformed when compared to the host mélange, forming elongate, lenticular to U-shaped, flat-topped bodies (up to 20–30 m thick) located within the upper part of this highly deformed unit. This relatively stable channelised system led to an increase in the efficiency of subglacial drainage from beneath the British Ice Sheet and the collapse of the subglacial shear zone, potentially slowing or even arresting the easterly directed advance of the ice sheet.

1. Introduction

Subglacial drainage systems have been shown to exert a strong influence upon the processes operating within the beds of glaciers, sediment mobility and ultimately ice sheet dynamics (Kamb, 1987; Stokes and Clark, 2001; Breemer et al., 2002; Lowe and Anderson, 2003; Bell et al., 2007). The pathways followed by pressurised subglacial meltwater have been described as taking the form of either: (i) thin sheets or films developed along the ice-bed interface (Weertman, 1972; Alley, 1989; Sharp et al., 1990; Hubbard and Sharp, 1993) potentially leading to the decoupling of the ice from its bed and rapid forward motion of the ice; (ii) intergranular flow, with meltwater flowing through pore spaces (Darcian flow) within subglacial sediments (Hubbard et al., 1995; Boulton et al., 1995) promoting soft-sediment deformation of the bed (deforming beds); (iii) distributed flow through a network of linked cavities (Sharp et al., 1989) or braided canals (Shoemaker, 1986; Clark and Walder, 1994; Benn and Evans, 2010) between the ice and underlying bed; or (iv) discrete, highly efficient systems of drainage channels or tunnel valleys feeding meltwater to the margin of the glacier or ice sheet (Wingfield, 1990; Ó Cofaigh, 1996; Praeg, 2003; Huuse and Lykke-Andersen, 2000; Longeran et al., 2006).

Studies of the subglacial hydrology of contemporary ice sheets (e.g. Greenland) indicate that there is a direct correlation between the volume of meltwater entering the bed of the glacier and a seasonal increase in the velocity of the overriding ice (e.g. Zwally et al., 2002; Joughin et al., 2008; Schoof, 2010). This link is complex, with work by Schoof (2010) demonstrating that the subglacial drainage system switches between different modes as it adapts to the variable input of surface water into the bed, with the variability in meltwater input, rather than total volume, forming the main driver for ice-sheet acceleration (also see Lüthi, 2010). The introduction of meltwater into an actively deforming bed can promote the development of either relatively faster flowing ice streams which aid in the regulation of the size and shape of ice sheets, or transient surge-type flow behaviour of glaciers (Kamb, 1987; Siegert and Bamber, 2000; Breemer et al., 2002; Lowe and Anderson, 2003; Tikku et al., 2004; Bell et al., 2007). In contrast, the development of relatively stable channelised drainage systems

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Table 1
Lower and lower Mid-Pleistocene stratigraphy of northern East Anglia with particular reference to units that crop-out within the Sheringham–Weybourne study area shown in bold.

Lithostratigraphy (subgroup/formation/member)	Sediment	Environment and process	Chronostratigraphy
Briton's Lane Formation			Mid-Pleistocene
Briton's Lane Sand and Gravel Member	Sands and gravels	Proglacial outwash	
Runton Sand and Gravel Member (RSG)	Sands and gravels	Proglacial outwash	
Sheringham Cliffs Formation			
Weybourne Town Till Member	Very chalky diamicton	Subglacial till	
Bacton Green Till Member (BGT)	Sandy diamicton	Subglacial till	
Ivy Farm Laminated Member	Stratified silts and clays	Glaciolacustrine	
Marl Bed	Stratified marl	Glaciolacustrine	
Lowestoft Formation			
Lowestoft Till Member	Chalky, clayey diamicton	Subglacial till	
Walcott Till Member	Silty, clayey diamicton	Subglacial till	
Happisburgh Formation			
Happisburgh Till Member (HT)	Sandy, grey diamicton	Subglacial till	
Wroxham Crag Formation (WCF)			Lower Mid-Pleistocene
Mundesley Member (MM)	Sands and gravels	Shallow marine	
Cromer Forest-bed Formation			
West Runton Freshwater Bed	Organic muds	Fluviatile, floodplain	
Wroxham Crag Formation			Lower Pleistocene
Mundesley Member	Gravels, sands and muds	Tidal, shallow marine	
White Chalk Subgroup	White, flinty chalk	Deep marine	Upper Cretaceous

Modified from Lee et al. (2004) and Pawley et al. (2004).

beneath glaciers and ice sheets, associated with a steady supply of meltwater, may lead to the draining of the bed and deceleration of the overriding ice (Hubbard et al., 1995; Boulton et al., 2007a,b; Magnússon et al., 2010). In a Pleistocene context, there are several case studies that examine the range and distribution of preserved subglacial meltwater features (e.g. Piotrowski et al., 1999, 2006; Piotrowski, 2006). However, it has proved difficult to relate these directly to processes operating within the subglacial bed, and in-turn, their controls on ice sheet behaviour.

This paper presents evidence from the coastal cliff sections in north Norfolk, Eastern England for the development of a subglacial drainage system beneath the eastern margins of the Middle Pleistocene (Anglian) British Ice Sheet (BIS). This system comprised a series of relatively undeformed, sand and gravel bodies comprising several stacked channels, linked by smaller channels which were eroded into the polydeformed sequence of ice-marginal tills, waterlain diamictons and outwash sediments. This sequence contains widespread evidence (at various scales) for subglacial deformation (Dhonau and Dhonau, 1963; Banham, 1975, 1988; Hart, 1987; Hart and Boulton, 1991; Hart and Roberts, 1994; Phillips et al., 2008), deformable beds (Lee, 2001; Roberts and Hart, 2005; Hart, 2007) and the formation of a thick unit (up to 20–30 m thick) of glacitectonic mélange associated with large-scale subglacial shear zone beneath the Anglian BIS (Lee and Phillips, 2008; Phillips et al., 2008). The influence of the development of the subglacial drainage system on these subglacial deforming-bed processes is examined, in particular its effect on the style of deformation within the subglacial shear zone and ultimately the advance of the ice sheet across north Norfolk.

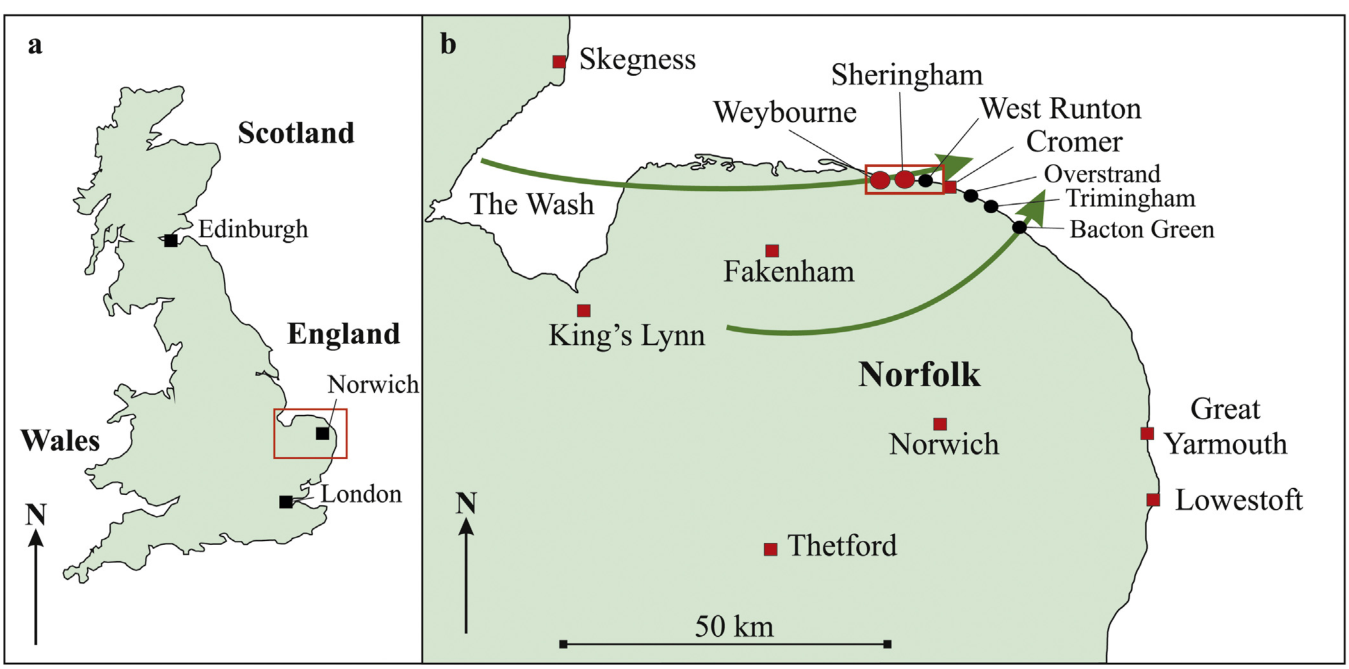

Fig. 1. Map showing the location of the Sheringham to Weybourne coastal section, north Norfolk, Eastern England. Green arrows denote main ice-flow direction during westerly directed ice advance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)