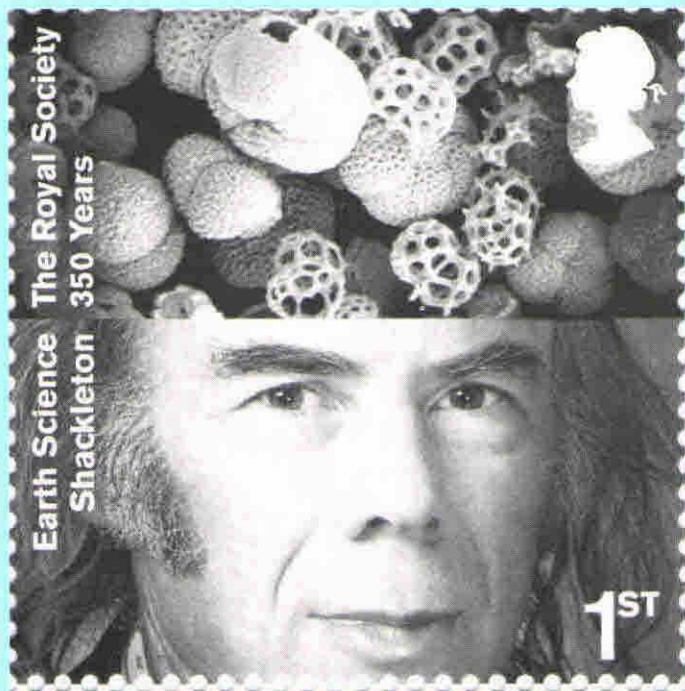

NUMBER 121

JUNE 2010

QON

Quaternary Newsletter



A publication of the
Quaternary Research Association

QUATERNARY NEWSLETTER

EDITOR:

Dr M.D. Bateman, Department of Geography, University of Sheffield,
Winter Street, Sheffield, S10 2TN.

(e-mail: M.D.Bateman@sheffield.ac.uk)

Instructions to authors

Quaternary Newsletter is issued in February, June and October. Articles, reviews, notices of forthcoming meetings, news of personal and joint research projects, etc. are invited and should be sent to the Editor. Closing dates for submission of copy (news, notices, reports etc.) for the relevant numbers are 1st January, 1st May and 1st September. These dates will be strictly adhered to in order to expedite publication. **Articles must be submitted at least 6 weeks before these dates in order to be reviewed and revised in time for the next issue of QN, otherwise they may appear in a subsequent issue.**

Suggested word limits are as follows: obituaries (2000 words); articles (3000 words); reports on meetings (2000 words); reports on QRA grants (500 words); reviews (1000 words); letters to the Editor (500 words); abstracts (500 words). Authors submitting work as Word documents that include figures must send separate copies of the figures in Jpeg format. Quaternary Research Fund and New Research Workers Award Scheme reports should limit themselves to describing the results and significance of the actual research funded by QRA grants. The suggested format for these reports is as follows: (1) background and rationale (including a summary of how the grant facilitated the research), (2) results, (3) significance, (4) acknowledgments (if applicable). The reports should not (1) detail the aims and objectives of affiliated and larger projects (e.g. PhD topics), (2) outline future research and (3) cite lengthy reference lists. No more than one figure per report is necessary. Recipients of awards who have written reports are encouraged to submit full-length articles on related or larger research projects.

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COVER PHOTOGRAPH

The Royal Mail stamp commemorating Professor Nick Shackleton's achievements in Earth Science. This was recently published as part of a set marking The Royal Society's 350th Anniversary.

OBITUARY

DEATH OF ROGER JACOBI

Roger Jacobi was a close friend. He died after a long illness on 9th December 2009. We had known each other since the early 1970s when Roger had left the Star Carr Mesolithic Dog skull on the continental express at Aachen and had been banned from the Natural history Museum's Osteology Room. Roger was allowed into Palaeontology by my then boss, Antony Sutcliffe to work on some French Cave material from the Lartet and Christie Collection which had been transferred from the British Museum and I was told to keep an eye on him. He was more than a little strange, but we got on together OK, and I was very impressed by his studious nature and his microscopic handwriting.



We didn't start publishing together until 1989, about three years into our joint excavations at Gough's Cave, Cheddar, Somerset. During that time we had got to know each other very well. We shared a deep commitment to our respective subjects. I was acutely aware of the fact that I was dealing with a man with the most extraordinary mind: an absolutely terrifying memory connected to the ultimate human recall mechanism. Knowing Roger was a bit like making friends with a world-class encyclopaedia.

I recall a morning when we were working together on the fossil mammal collections down at Taunton – a monstrous job. I had gone down to breakfast in our guesthouse and after about half an hour the owner was getting quite distressed by Roger's prolonged absence. I was sent upstairs to tell him his toast was cold and I found him glued to the television, watching the Teletubbies. With some protest he was encouraged to take his breakfast more seriously, but his continual cries of "La La" and "Po" very nearly had us thrown out on the streets.

Working with Roger was extremely entertaining. Although we had rarely decided what we were going to say in advance, we battled through each and every sentence like some kind of mortal combat, a tweak here requiring a major verb modification there. Generally speaking each of us gave as good as we got. At the end of a day long fight only a good bottle of wine could make the world seem habitable again.

Roger was a brilliant British prehistorian. His knowledge and understanding of the lithic technologies of our Mesolithic and Upper Palaeolithic record was unparalleled. He was also a master of the Middle Palaeolithic and he left many people standing on the Lower Palaeolithic as well. I taught him the rudiments of teeth and bones, and he quickly became very good on many mammalian species present in the British record. It was an absolute privilege to know and work with Roger, an experience which I will always remember and always treasure. In his later years we published numerous papers together, many of which attempted to define the British late Pleistocene record by virtue of its mammal fauna. Only time will tell if we got the record straight, but I have to say that the process has been electrifying.

I know I am only one of many people who are going to miss Roger a lot. He was taken from us in his prime, and he had so much brewing in his mind which he wanted to do. Roger's paper archive will go to the British Museum and – with time – this will be available to others, but please spare a thought for the work which will need to be done before that's possible!

I have no insight into where people go when they die - if anywhere at all, but Roger is a person who it will be difficult to shake off, and I'm not even sure many of us will try that hard. I always hoped he would be around for a very long time, and if I know Roger, he will.

Andy Currant
Natural History Museum
Cromwell Road
London SW7 5B

ARTICLES

IMPLICATIONS OF RECENT RESEARCH FOR THE TIMING AND EXTENT OF SAALIAN GLACIATION OF EASTERN AND CENTRAL ENGLAND

Rob Westaway

Received 14th March 2010 Reviewed and accepted 6th May 2010

Abstract

The aim of this study is to present a review and synthesis of evidence pertaining to post-Hoxnian, pre-Ipswichian glaciation of eastern and central England. In principle, such glaciation could have occurred during one or more of marine isotope stage (MIS) 10, 8 and 6. On the balance of probability, the evidence is shown to favour MIS 8, although MIS 10 cannot be excluded as the timing of this glaciation. However, additional work, including numerical dating and re-examination of the stratigraphy of key sites, will be required to test and substantiate any such hypothesis.

Introduction

The glacial limits in Britain during the Devensian Last Glacial Maximum (LGM; MIS 2) and during the Anglian (MIS 12) are well-established. However, the dimensions of any ice sheet(s) within Britain during other Middle Pleistocene cold stages remain controversial. Decades ago, the concept of a 'Wolstonian' (i.e., Saalian; post-Hoxnian, pre-Ipswichian) 'Gipping' glaciation was proposed (e.g., Baden-Powell, 1948; West and Donner, 1956); however, it was subsequently established that the glacial deposits in the 'Gipping' type area of SE Suffolk (Figure 1) could not be objectively distinguished from those of the Anglian (e.g., Bristow and Cox, 1973). Nonetheless, throughout the subsequent span of time, Allan Straw has repeatedly argued that a Saalian ice sheet reached central Lincolnshire and NW Norfolk (e.g., Straw, 1958, 1963, 1965, 1973, 1979, 1983, 2000, 2005), based on the lithology and disposition of the youngest glacial deposits in these localities. In his later publications (Straw, 2000, 2005) he has tended to favour MIS 8 rather than MIS 6 as the age of this glaciation, notably with regard to the pre-Devensian glacial deposits (Alabaster and Straw, 1976; Wymer and Straw, 1977) at Welton-le-Wold in north Lincolnshire (Figure 2), which Lewis (1999) had assigned to MIS 6. The 'New Glacial Stratigraphy' (NGS) of Britain has indeed postulated glaciations in MIS 16, 12, 10, 6 and 2 (e.g., Hamblin *et al.*, 2000, 2005; Clark *et al.*, 2004a); the MIS 6 glacial limit in this scheme is linked to sedimentary evidence at Tottenhill in west Norfolk

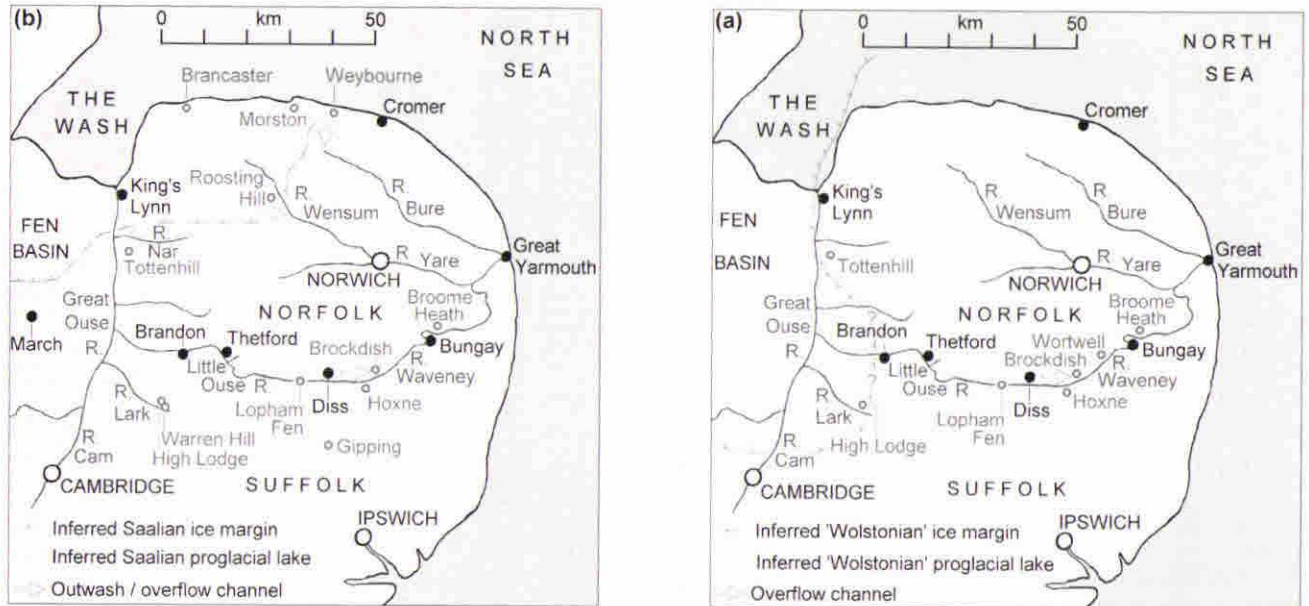


Figure 1. Summary sketch maps indicating relations between localities discussed and sites indicative of a post MIS12 and pre MIS5 glaciation. (a) Summary of the hypothesis of West (2009) except in the Brandon area where the interpretation (shown dotted line) is from Gibbard *et al.* (2009). (b) An alternative interpretation of the ice-margin geometry, suggested here. The ice margin is placed north of the Nar valley as sediments there, dated to the Hoxnian (e.g., Scourse *et al.*, 1999), show no evidence of subglacial deformation. An ice sheet covering the part of NW Norfolk, thus depicted, can be no younger than MIS 8, as the Morston raised beach (now dated to MIS 7; Hoare *et al.*, 2009) also shows no evidence of subglacial deformation. The inferred ice sheet abuts relatively high ground in western Norfolk directing outwash from the Tottenhill area southward, in accordance with the available evidence (e.g., Gibbard *et al.*, 1992, 2008).

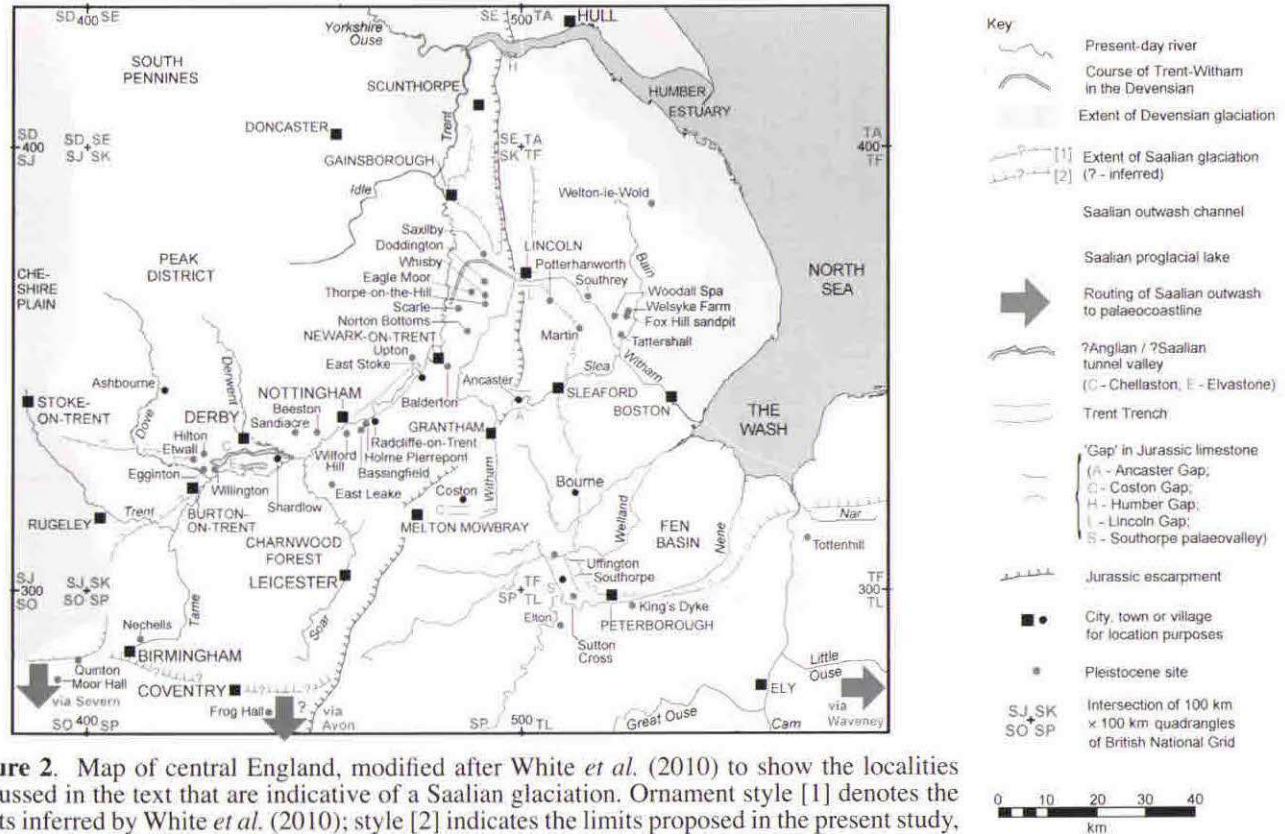


Figure 2. Map of central England, modified after White *et al.* (2010) to show the localities discussed in the text that are indicative of a Saalian glaciation. Ornament style [1] denotes the limits inferred by White *et al.* (2010); style [2] indicates the limits proposed in the present study, where they differ from [1]. Note limits may not have been glaciated simultaneously.

(Figure 1), interpreted as an outwash delta in a proglacial lake (Gibbard *et al.*, 1991, 1992). In contrast, Langford (2004) and Langford and Briant (2004) proposed that an ice sheet reached as far south as the Peterborough area (Figure 2) in MIS8, based on the dispositions of outwash deposits and glacial deposits (e.g., at Uffington and Southorpe; Figure 2) in relation to younger fluvial terrace staircases. Within the Nene valley at nearby Elton they, also, recognised deposits of a Saalian proglacial lake. Boreham *et al.* (2010) have also argued that the evidence from this region supports glaciation during MIS8. Taking this evidence into account, White *et al.* (2010) proposed the geometry of the ice sheet during the MIS 8 glacial maximum, in the area between Peterborough and Lincoln, depicted in Figure 2. In the meantime, Gibbard *et al.* (2009) have refined the interpreted geometry of the ice sheet which they regard as having existed during MIS6 (which they envisage as having reached almost as far south as Cambridge; Figure 1a) and the associated outwash channel system, the latter based on the summary of evidence by West (2007). As reviewed in this journal (Lewis, 2009), a thorough presentation of the evidence pertaining to this other Saalian outwash channel system, linking the modern catchments of the rivers Little Ouse and Waveney (Figure 1a), is now published (West, 2009). However, unlike Gibbard *et al.* (2009), this latter account is unspecific as to when this system was active, but nonetheless presents evidence that bears upon this issue (see below).

Published criticism of the NGS has largely concerned the MIS 16 aspect, which is now generally regarded as disproven through counter-arguments based on biostratigraphy (e.g., Preece and Parfitt, 2008; Preece *et al.*, 2009), improvements in dating (Preece *et al.*, 2009; Westaway, 2009a, 2010), and revision of the stratigraphic relations between glacial deposits assigned to this stage and deposits of the pre-Anglian Ingham River (Westaway, 2009b; cf. Lee *et al.*, 2004a; see also Lewis, 1993). However, the need for resolution of the contradictory estimates for the timing and extent of Saalian glaciation has attracted relatively little attention. Although recent publications (e.g., Clark *et al.*, 2004a; Toucanne *et al.*, 2009) have claimed that there is no evidence for glaciation in Britain or any adjoining region during MIS 8, this is not so; glacial deposits in the Netherlands sector of the North Sea (~150 km east of Cromer; Figure 1) are now securely dated to MIS 8 (e.g., Beets *et al.*, 2005; Meijer and Cleveringa, 2009). The aim of this note is to summarise evidence relevant to this issue, including that presented by West (2009) but not hitherto placed in any regional context.

The Lopham Fen outwash channel

Much of West's (2009) investigation concerns the Lopham Fen outwash channel, linking the catchments of the rivers Waveney and Little Ouse (Figure 1). The Waveney flows eastward into the North Sea, whereas the Little Ouse flows westward into the Fen Basin and then, after joining the Great Ouse, northward

into The Wash. However, the headwaters of these rivers adjoin across a low (~25 m O.D.) col at Lopham Fen. Other workers have previously noted this alignment of rivers and the disposition of Pleistocene sediments across this col, and have thus inferred former west-east drainage from the modern Little Ouse catchment into the Waveney. West's (2009) principal conclusions are, first, that there is a progressive east-west increase in the net fluvial incision between the Hoxnian (MIS 11) and Ipswichian (MIS 5e) interglacials, from ~10 m in the east (around Wortwell; Figure 1a) to ~30 m at the eastern margin of the Fen Basin. Westaway (2009b) explained such observations in terms of eastward tapering in regional uplift. Second, for a prolonged span of time between the Anglian and 'Wolstonian' glaciations the drainage divide between the Little Ouse and Waveney catchments was ~20 km east of its present location, near Brockdish. This means that Hoxne lay within the contemporaneous Little Ouse catchment (Figure 1), not the Waveney catchment as at present. Third, the southward advance of the 'Wolstonian' ice sheet blocked the Little Ouse valley near Brandon. This impounded a proglacial lake (which West calls the Little Ouse Lake) in the Little Ouse valley and resulted in deposition of sands (which he calls the Lopham Sands) and coarser sediments (interpreted as dropstones) within it. Fourth, this lake overflowed eastward into the pre-Wolstonian Waveney valley, cutting a channel that was up to ~1 km wide. Headward incision by the discharge in this overflow channel displaced the drainage divide westward to its present location.

Although previous schemes have attributed the landscape morphology and sedimentation in the Lopham Fen area to throughgoing eastward palaeoflow, it goes without saying that this proposal involves a radical reinterpretation of the study region. Previously, one view (e.g., Clark *et al.*, 2004a) has assigned the eastward palaeoflow to the Anglian. This interpretation is not discussed by West (2009), but it is nonetheless evident that his proposal requires the reassignment of large volumes of sediment over a substantial region from the Anglian to the 'Wolstonian'; this is feasible, given the lack of dating evidence (either way) from these deposits. Another view has assigned the palaeo-drainage between the Little Ouse and Waveney catchments to the LGM. For example, Clark *et al.* (2004b) suggested (as part of the recent 'BritIce' project) that a large ice-dammed lake was impounded in the Fen Basin during MIS2 as a result of ice to the north. In their view, the lake level was regulated at ~25m O.D. at its inferred outlet spillway into the Waveney; this is the basis for their inference that much of central and eastern England, below this level, was inundated by this lake (this includes localities as far away as Nottingham; Figure 2), where there is no evidence for any such lake). Although the Clark *et al.* (2004b) scheme is not considered, West discusses Tallantire's (1969) suggestion of a Devensian age for this outlet spillway, noting that such a young age is now precluded by abundant evidence (such as the fluvial terrace staircases of the Little Ouse and Waveney, which date back to the late Middle Pleistocene: e.g., Coxon, 1993;

Gibbard *et al.*, 2008; Westaway, 2009b). Furthermore, it now seems evident that the outlet spillway from the Devensian proglacial lake was farther north, adjoining the contemporaneous glacial limit near the modern north coast of Norfolk in the area between Brancaster and Weybourne (e.g., Moorlock *et al.*, 2002, 2008; Figure 1b).

West's (2009) coverage of dating evidence is restricted to consideration of pollen. A notable discussion concerns the evidence from Broome Heath, the type locality for the Broome terrace deposit of the Waveney. Coxon (1979) reported from these sediments low proportions of the 'Type X' palynomorph, which in Britain has been considered indicative of the Hoxnian (MIS 11) or Purfleet (MIS 9) interglacials but not the younger temperate stages (e.g., Thomas, 2001; Roe *et al.*, 2009). Coxon (1979) attributed the 'Type X' pollen in these sediments to reworking, an argument that West (2009) supports. This particular terrace deposit is indeed thought to be much younger than the Hoxnian; for instance, Westaway (2009b) assigned its upper part to MIS6 from its height of only ~2-3 m above the modern Waveney floodplain.

Discussion

West (2009) offers clues as to the age of the glaciation represented by the above evidence. First, he provides a stratigraphic column that appears to place it about halfway through the 'Wolstonian' (which would seem to imply an age of MIS 8), but elsewhere the text only assigns it to 'a later part' of the 'Wolstonian'. Second, from his detailed field observations in both the Waveney and Little Ouse valleys West recognises a complete cycle of incision and then fluvial aggradation between his 'Wolstonian' glaciation and the Ipswichian (MIS 5e) temperate stage; the cold stage fluvial deposits assigned to this span of time now form the Broome Terrace of the Waveney (Coxon, 1993; Westaway, 2009b) and what West calls the 'low terrace' of the Little Ouse. If one accepts that long-timescale fluvial terraces typically form in British rivers at intervals of ~100ka (e.g., Bridgland, 2000), this evidence implies that the 'Wolstonian' glaciation pre-dates MIS 6, suggesting MIS 8 as its probable age. This is essentially the same reasoning as White *et al.* (2010) used to assign this glaciation to MIS8 from the fluvial terrace evidence in the Lincoln area (Figure 2). However, it is unfortunate that West (2009) has left this issue hanging; he has strengthened the evidence for glaciation of eastern England during MIS8, thus reporting a significant discovery, but without actually saying so.

Taken as a whole, the evidence favours MIS 8 rather than MIS 6 as the age of the Saalian glaciation of eastern England. For example, temperate-stage sites in the Lincoln area (Norton Bottoms and Southrey; Figure 2), located well north of the MIS 6 glacial limit advocated by Gibbard *et al.* (2009) (Figure 1a), are now securely dated to MIS7 (the Aveley interglacial) using amino-acid analysis of *Bithynia opercula* (e.g., Penkman, 2007; Westaway, 2009a), and have clearly

not been overridden by ice. These localities, in the pre-Devensian River Trent (which drained eastward to the Wash; Figure 2), are discussed further by White *et al.* (2007, 2010). The evidence suggests that the Saalian ice sheet reached the vicinity of Tottenhill and, farther west, the vicinity of Peterborough (Figure 2). Conversely, West (2009) offers no supporting evidence for the idea that the 'Wolstonian' ice sheet reached as far south as the Little Ouse valley. Gibbard *et al.* (2009) report 'Wolstonian' glacial deposits at High Lodge in the Lark valley farther south (Figure 1), which would support the presence of ice in the adjacent Little Ouse valley. However, these High Lodge glacial deposits have been accepted by many workers (e.g., Cook *et al.*, 1991; Ashton *et al.*, 1992; Westaway, 2009b) as Anglian. Gibbard *et al.* (2009) reassigned these sediments to the 'Wolstonian' on the basis of a ~160 ka (i.e., MIS 6) OSL date; however, this date was from sands at the nearby Warren Hill site that many workers (e.g., Wymer *et al.*, 1991; Lee *et al.*, 2004; Westaway, 2009b) have regarded as emplaced by the pre-Anglian Ingham River, evidence for a pre-Anglian age being the absence of *Rhaxella* chert in the sediments. It is well-known that use of the OSL technique can result in underestimation of the age of any sample due to dose saturation (for instance, Westaway, 2004, discussed an example of this problem, regarding the chronology of Middle Pleistocene terraces of the River Loire). Furthermore, recent studies (e.g., Li *et al.*, 2007, 2008) suggest that OSL dating of relatively old sediments is susceptible to systematic error due to post-depositional uptake or leaching of radioactive elements; such uptake could likewise cause a systematically young numerical age (in this case, Saalian rather than pre-Anglian). When applied to the Middle Pleistocene of Britain, the OSL technique can evidently yield reliable ages for raised beaches (such as the MIS 7 dates for the Easington and Morston raised beaches; Davies *et al.*, 2009; Hoare *et al.*, 2009) but not necessarily for glacial deposits. The much greater flow of groundwater expected through the latter type of deposit (and, thus, the greater tendency for leaching or uptake of radioactive elements) may well be the cause of this problem.

As Figure 1a shows, Gibbard *et al.* (2009) envisage that most of the Fen Basin was ice-covered during the Saalian glacial maximum, with interconnected narrow proglacial lakes in tributary valleys of the Great Ouse, such as those of the Lark and Little Ouse. Following West (2007), they inferred that this Saalian proglacial lake overflowed eastward into the Waveney catchment. In contrast, the proglacial lake that developed around the LGM extended farther north (e.g., West *et al.*, 1999; Clark *et al.*, 2004b), being impounded by ice near the south coast of The Wash (e.g., Clark *et al.*, 2004a). Its Saalian counterpart may well thus have had a similar shape (Figure 1b), its northern margin adjoining the Tottenhill area where sands and gravels have been interpreted as forming a delta that prograded southward into this proglacial lake (Gibbard *et al.*, 1991, 1992, 2009).

The Saalian ice margin also requires demarcation farther east; Straw (1965, 1973) has indeed suggested possible locations for it, reflecting his interpretation that the Chalk-rich glacial deposits east and west of The Wash (historically known, respectively, as the 'Chalky Boulder-clay' and Wragby Till) are Saalian (long regarded by others as Anglian, these deposits are assigned to MIS 10 in the NGS; e.g., Hamblin *et al.*, 2005). Straw (1973) indeed envisaged that the modern rivers Bure and Wensum follow Saalian outwash channels (Figure 1b). It is apparent that this explanation is essentially the same as that proposed by West (2009) for the origin of the modern River Waveney farther south; West's arguments would thus have been strengthened if he had made this connection. Currently, the only dating evidence to refute such a suggestion for the age of these Norfolk rivers is the Hoxnian age assignment (West, 1991) of the sediments at Roosting Hill, which overlie the till and outwash gravel that Straw (1973) has assigned to the Saalian, and a set of OSL dates, which range from 391 ± 39 ka to 494 ± 42 ka, from within this outwash, which have been hitherto taken to indicate the Anglian glaciation (Pawley *et al.*, 2008). However, although Pawley *et al.* (2008) showed that one potential cause of these OSL dates exceeding the true ages of the samples - incomplete bleaching - can be excluded, they did not investigate whether these numerical ages might be affected by leaching or uptake of radioactive elements within the sediments. Loss of radioactive elements due to leaching would result in underestimation of radiation dose rate and, thus, overestimation of age; the possibility of this may be inferred because the concentrations of radioactive elements in these Middle Pleistocene sediments, which are the major contributor to the radiation dose rates, are much lower than in Devensian control samples at nearby localities (see Table 4 of Pawley *et al.*, 2008). West's (1991) Hoxnian age assignment, based on very low proportions of 'Type X' pollen and other Hoxnian indicators, could be readily adjusted to MIS 9 to accommodate these data (cf. Thomas, 2001; Roe *et al.*, 2009), consistent with the MIS 10 age of the underlying glacial deposits advocated in the NGS; the climatic fluctuations in the 'Hoxnian' part of the Roosting Hill record, recognised by West (1991), would thus represent the transition from late MIS 10 to MIS 9. However, if the glacial deposits at Roosting Hill date from MIS 8, as is now proposed, the 'Type X' and other 'Hoxnian' indicator pollen fall within temperate-stage deposits that must be assigned to part of MIS 7. Setting aside the possibility of reworking from older deposits, this would require the taxon that produced the 'Type X' palynomorph to have lived in Britain in MIS 7, possibly only during its early woodland phase (MIS 7e) that has rarely been preserved in the geological record. Hitherto, the only temperate-stage terrestrial deposits in Britain for which an MIS 7e age can be readily substantiated are in the early part of the succession at Aveley, which are differentiated from the later MIS 7 deposits at this and many other sites on the basis of mammalian biostratigraphy (e.g., Schreve, 2001). However, the extant pollen records from Aveley (e.g., West, 1969) are regarded as incomplete (e.g.,

Roe *et al.*, 2009); for example, West (1969) concluded that this succession is Ipswichian. Thorough re-examination of the pollen from the early part of this succession is thus necessary; evidence for 'Type X' and/or other 'Hoxnian' indicator pollen would support the proposed reinterpretation of Roosting Hill and, thus, the MIS 8 age for the preceding glaciation.

According to West (1991), at Roosting Hill, chalky till is overlain by coarse outwash gravel (known as the Hungry Hill gravel), directed eastward through the Wensum catchment. This outwash is overlain by the organic deposits that West (1991) concluded are Hoxnian but which (it is now suggested) are younger; the stratigraphic relations between these deposits led West (1991) to conclude that the organic deposits immediately post-date the glacial deposits (so, if from MIS 7, they would be from its early, woodland, phase; i.e., MIS 7e). Post-dating the latter are three terrace deposits of the Wensum, forming in order of decreasing age the Beetley, Hoe and Worthing terraces; the tops of these are ~2 m apart, the latter ≤ 1 m above the modern floodplain. Ipswichian deposits (dated by pollen) post-date the emplacement of the Beetley gravel and pre-date the upper part of the Hoe gravel. The natural interpretation is that the upper parts of these terrace deposits were emplaced, respectively, during MIS 6, 4 and 2; the organic deposits date from early MIS 7 and the underlying chalky till and outwash gravel mark the MIS 8 glaciation.

Farther southwest, in the Nar valley (Figure 1), Hoxnian (e.g., Scourse *et al.*, 1999) temperate-stage freshwater and marine deposits reach ~20 m O.D. and are stratigraphically overlain by the Tottenhill succession (e.g., Ventris, 1986; Gibbard *et al.*, 1991, 1992). Inset into the latter deposit are the three terraces of the River Nar; in order of decreasing age, these are the Wormegay, Pentney and Marham terraces, the latter again ≤ 1 m above the modern floodplain, the vertical separations being 2-3 m (Ventris, 1986). The cold-stage deposits forming the Pentney terrace contain interbedded temperate-stage sediments, which Ventris (1986) assigned to the Ipswichian (MIS 5e) interglacial. The upper surfaces of the three Nar terrace deposits can thus be assigned, respectively, to MIS 6, 4 and 2 (cf. Boreham *et al.*, 2010). The Nar and Wensum terrace staircases are therefore strikingly similar to each other, consistent with the general similarity of the terrace staircases of the Fen Basin rivers noted by Boreham *et al.* (2010); moreover, the uplift rates indicated by the vertical separations and age assignments for these terraces are consistent with other fluvial sequences in the region (Westaway, 2009b). The same pattern of terrace formation is likewise evident in other rivers in the region; an example is the Trent, where (in the Newark area; Figure 2) the Balderton, Scarle and Holme Pierrepoint terrace deposits were emplaced during MIS 6, MIS 4 and MIS 2, as well as the Eagle Moor terrace deposit from MIS 8 (e.g., Boreham *et al.*, 2010; White *et al.*, 2010). This age model is consistent with the glaciation represented at Tottenhill having occurred in MIS 8. Conversely, it has been argued (e.g., by

Gibbard *et al.*, 2009) that this glaciation must date from MIS 6, because only a single interglacial palaeosol is present in the associated sediments; this would require the entire staircase of the River Nar to be post-Ipswichian. Lewis and Rose (1991) indeed documented extensive Ipswichian palaeosol development, then subsequent dramatic deformation of this soil by cryoturbation during the Devensian. By analogy it can be presumed that any palaeosol that developed during MIS 7 would have been disrupted by cryoturbation during MIS 6, and so would be no longer recognisable. This soil evidence is therefore not compelling; it only provides a minimum age for the Tottenhill succession.

It has repeatedly been proposed (e.g., Gibbard *et al.*, 1991, 1992, 2009; Lewis and Rose, 1991) that sands and gravels at Tottenhill, adjoining the lower reaches of the Nar at the eastern margin of the Fen Basin (Figures 1 and 2), represent ice-proximal Saalian outwash, forming a delta prograding southward into a proglacial lake. The disposition of these sediments relative to the Nar terrace staircase thus suggests that the glaciation can be no younger than MIS 8; it therefore pre-dates the MIS 6 age previously proposed (e.g., by Lewis, 1999; Gibbard *et al.*, 2009). Furthermore, Gallois (1978, 1994) reported two facies of flint-dominated gravel, the Lower and Upper Tottenhill gravels. In his view, the bulk of the deposit, comprising the lower gravel, is coarse, poorly-sorted and cryoturbated, with angular clasts and cross-bedding indicating palaeoflow to the south or SE; it corresponds to the lake foreset facies others (e.g., Gibbard *et al.*, 1992, 2009) have described. However, his ~4m thick Upper Tottenhill Gravel comprises typically smaller and better sorted clasts and is not cryoturbated; at West Winch (~5 km north of Tottenhill), correlative gravel has much more rounded clasts than the Lower Tottenhill Gravel and, along with associated sands, shows cross-bedding that dips towards the west. Gibbard *et al.* (1992) regarded this idea of two distinct gravels at Tottenhill as mistaken, but they did not investigate in detail the parts of the site (or any correlative sites, such as West Winch) where Gallois (1978) had reported the Upper Tottenhill Gravel. Ventris (1986) designated the upper surface of the Tottenhill gravels, at ~9 m O.D. (or ~10 m above the projected height of the Wormegay terrace of the Nar), as the 'Tottenhill terrace'. As Gibbard *et al.* (1991, 1992) noted, topset sediments are not present in the Tottenhill lacustrine delta facies. However, an upward-fining lacustrine succession has been reported ~5 km farther northeast at ~30 m O.D., at Blackborough End (Ventris, 1986), and may represent the lake surface level at the time when these deltaic sediments accumulated; this is the same altitude as for the deposits at Elton (Figure 2), which may well thus represent the opposite extremity of the same palaeolake. The Hoxnian Nar Valley Beds show no evidence of deformation due to being overridden by ice, suggesting that the Saalian ice margin lay to the north, as shown schematically in Figures 1b and 2. The greater height of the Blackborough End sediments than the inferred level of the Lopham Fen overflow channel (~30 m against ~25 m O.D.) suggests that the former were deposited while the area was

glacio-isostatically depressed, implying a nearby ice margin. Likewise, the ~10 m difference in height between the 'Tottenham terrace' and Wormegay terrace of the Nar suggests that the former deposit was emplaced while the area was glacio-isostatically depressed. Conceivably, the Upper Tottenham Gravel may have been deposited after the MIS 8 ice sheet melted and westward drainage into the Fen Basin was re-established, but before the subsequent glacio-isostatic recovery was complete (cf. Bridgland *et al.*, 2010).

Farther west there is, likewise, evidence for Saalian glaciation but disagreement as to its age and extent. The White *et al.* (2010) analysis of stratigraphic relations between glacial deposits and dated Trent terraces requires the glaciation to be no younger than MIS 8. Farther southwest, at Quinton, post-Hoxnian, pre-Devensian till, known as the Ridgacre Formation, is present (e.g., Horton, 1989); this has been assigned to MIS 6 using stratigraphic relations to terraces of the River Severn and cosmogenic dating (e.g., Maddy *et al.*, 1995). However, inspection of documentation (from, e.g., Maddy *et al.*, 1995; Goodwin *et al.*, 1997) indicates that the stratigraphy does not preclude an MIS 8 age, only a post-MIS 6 age. The cosmogenic dating (^{36}Cl dates of 170 ± 13 ka and 150 ± 9 ka on erratic boulders, the former at Moor Hall; Figure 2) is also not compelling; the calculations assume continuous exposure, whereas the alternative assumption of burial (e.g., within till, which was progressively eroded following the glaciation) for part of the time, followed by deflation, would make the glaciation older. Northeast of Birmingham, at Nechells, a succession similar to that at Quinton is evident, with temperate-stage deposits, biostratigraphically dated to the Hoxnian, both underlain and overlain by glacial deposits, thought to represent Anglian and Saalian glaciations (e.g., Kelly, 1964; Thomas, 1997). There is nothing to preclude an MIS 8 age (or, indeed, a MIS 10 age) for the Saalian glaciation recorded at this site. Farther northeast, Rice (1968) and others have proposed that the most recent glaciation of the Leicester area was during the Saalian. The subsequent development of quantitative chronologies for the River Trent and its tributary, the Soar (e.g., Maddy, 1999a; Westaway, 2007), enables this suggestion to be tested. The oldest terrace of the Soar, known as the Knighton terrace and thought to immediately post-date the glaciation (Rice, 1968), is at a height consistent with deposits of the Trent that are now assigned to MIS 8 (Westaway, 2007), thus implying glaciation of much of the modern Trent catchment (upstream of the Jurassic limestone escarpment; Figure 2) during MIS 8. Overriding by Saalian ice would explain the near-total absence of fluvial terrace deposits emplaced within this catchment before MIS 8, noted by White *et al.* (2010).

Nonetheless, the southeastern limit of this putative Saalian glaciation of the Midlands remains problematic. At Frog Hall, near Coventry, outwash gravel (the Dunsmore Gravel) is inset by the younger Frog Hall sand and gravel; both these deposits can be traced downstream to the southwest across the catchment

of the River Avon, where they have been projected to the levels of Avon terraces 5 and 4 (e.g., Sumbler, 1989). In modern nomenclature, these are the Pershore and Ailstone terraces; near the Severn-Avon confluence, they are ~45 m and ~25 m above the modern rivers (e.g., De Rouffignac *et al.*, 1995; Maddy *et al.*, 1995; Bridgland and Schreve, 2001), the upper parts of the two terrace deposits having been dated to MIS 8 and MIS 6 from interbedded temperate-stage sediments that are assigned to MIS 9 and MIS 7 using biostratigraphy and aminostratigraphy (e.g., Bridgland and Schreve, 2001). Alternatively, the Frog Hall sand and gravel may correlate with the deposits of the unnumbered Strensham terrace farther downstream in the Avon; the latter is not resolved from the Ailstone terrace throughout the catchment but, where resolved, is up to ~7 m higher (e.g., De Rouffignac *et al.*, 1995; Bridgland and Schreve, 2001).

Both these correlations with the Avon terraces thus imply that the Dunsmore Gravel dates from MIS8 (rather than from the Anglian, as hitherto thought) and therefore indicates routing of outwash from the glaciated region farther north at that time. Nonetheless, temperate-stage deposits within the Frog Hall sands and gravels have hitherto been assigned to MIS 9 or MIS 11 (e.g., Keen *et al.*, 1997; Thomas, 2001). Westaway (2009a) indeed suggested an MIS 11 age for these temperate-stage deposits from amino-acid analysis of *Bithynia* opercula; nonetheless, as few (only 4) opercula were analysed (by Penkman, 2005), the possibility exists that they were reworked to Frog Hall from a Hoxnian deposit elsewhere. However, alternative stratigraphic correlation schemes for this locality have been proposed (Keen *et al.*, 1997; Maddy, 1999b), which do not support Sumbler's (1989) interpretation. For example, Keen *et al.* (1997) argued that although the uppermost gravel at Frog Hall may correlate with Avon terrace 4, as Sumbler (1989) suggested, the underlying temperate-stage deposits may be much older (i.e., Hoxnian), being separated from the overlying gravel by an erosional unconformity. Furthermore, these temperate-stage deposits have yielded biostratigraphic evidence considered indicative of the Hoxnian, including 'Type X' pollen and characteristic ostracods (e.g., Keen *et al.*, 1997; Thomas, 1997). However, the potential chronological range of 'Type X' pollen has already been discussed, and it is difficult to know what significance to assign to the other biostratigraphic indicators when so little is known of early MIS 7 palaeoenvironments in Britain; if Frog Hall dates from MIS 7 is must (e.g., from the woodland pollen present; Thomas, 1997) be from the poorly-known MIS 7e substage. Further dating work and stratigraphic analysis are necessary to resolve this issue (as well as many other points discussed in this note). However, it is apparent that as things stand either the Dunsmore Gravel dates from MIS 8 and indicates glaciation of the region farther north at that time, or it and the Frog Hall temperate-stage deposits are older, in which case (given the evidence for Saalian glaciation at nearby sites, including Nechells and the sites in the Leicester area) the margin of the Saalian ice-sheet was not far away, but apparently with no routing of outwash into the Avon. As a result,

either way, thorough study of this key locality will help to constrain the extent of Saalian glaciation of the Midlands.

Hitherto, analysis of the pre-Devensian glacial deposits of Britain has been dominated by the use of till lithology for both local and regional correlation; use of this approach has persisted even in recent publications such as that by Lee *et al.* (2004b). However, it should now be apparent that ice advances in the same direction over the same bedrock during different cold stages can produce indistinguishable till lithologies and fabrics (cf. Shotton, 1976). Likewise, ice advances from different directions during the same cold stage will produce different till lithologies and fabrics. The likelihood, now evident, that much of central and eastern England has been overridden by ice during multiple glaciations, means that other methods must be applied to assign glacial deposits to cold stages, such as the use of their dispositions relative to fluvial terrace deposits that is adopted here. For example, decades ago, the 'Chalky Boulder-clay' east of The Wash was assigned to the 'Gipping' glaciation (e.g., Baden-Powell, 1948; West and Donner, 1956). It was subsequently reassigned to the Anglian (e.g., Bristow and Cox, 1973), and more recently reassigned again to MIS 10 as part of the NGS (e.g., Hamblin *et al.*, 2000, 2005; Clark *et al.*, 2004b; Lee *et al.*, 2004b, 2008), although Straw (e.g., Straw, 1965, 1973, 2000) has consistently regarded it as Saalian. The present reassessment indicates that these glacial deposits in west Norfolk may well indeed be Saalian, although the glacial evidence from the 'Gipping' type area in SE Suffolk is Anglian.

It is nonetheless clear that many of the localities discussed above provide evidence of glaciation that post-dates MIS 11 and precedes MIS 7 or MIS 6. In principle, the glaciation could thus have occurred during either MIS 10 or MIS 8. MIS 8 is favoured, primarily because of stratigraphic relations between glacial deposits and younger fluvial terrace staircases; if the glaciation were in MIS 10, there would in many localities be a gap in the fluvial records spanning a complete climate cycle, which would be inexplicable given the excellent preservation of the post-MIS 8 fluvial successions. However, given the lack of quantitative dating evidence, an MIS 10 age cannot be excluded at this stage; such an age would indeed be more readily reconcilable with some of the evidence, notably, the presence of 'Type X' pollen in temperate-stage deposits that post-date the glaciation. Furthermore, regardless of whether this glaciation was in MIS 10 or MIS 8, its extent differed from those envisaged for both the MIS 10 and MIS 6 glaciations of the NGS.

Conclusions

A great deal of evidence, consistent with Saalian glaciation of much of eastern and central England, is now available. This has not hitherto been apparent, due to the piecemeal manner in which localities have been documented. Although there is as yet no demonstrably reliable direct dating of any glacial deposits

from this stage, there is clear evidence in many localities for a glaciation that post-dates the Hoxnian (MIS 11) and pre-dates MIS 7 or 6. Possible candidate ages for this glaciation are either MIS 10 or MIS 8; the dispositions of glacial deposits relative to dated fluvial terrace staircases favour MIS 8 as the age of the glaciation.

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Rob Westaway
Faculty of Mathematics,
Computing and Technology
The Open University
Abbots Hill
Gateshead
NE8 3DF

Also at: IRES
Newcastle University
Newcastle-upon-Tyne
NE1 7RU

REPORTS

GLACIAL LANDSYSTEMS WORKING GROUP (GLWG) DURHAM AND YORKSHIRE COAST MEETING, 23-25th OCTOBER 2009

Following on from the success of the revived Glacial LandSystems Working Group in 2008, GLWG was met with a substantial following of 38 people from all over the UK (Aberdeen to Southampton, Durham to Aberystwyth). The group assembled at Whitley Bay Caravan Park on the Durham coast on Friday 23rd October, 2009, to taste the local beer and listen to an introductory talk by Bethan Davies and Dave Roberts. The weekend began at the Durham coastline at Whitburn and Warren House Gill, focusing on a glacial and interglacial record stretching back to the Middle Pleistocene, before moving south to the Devensian glacial sediments at Uppgang, North Yorkshire.

Saturday 24th October

Although storms were forecast, the morning started off dry, but windy and once the group had assembled, a convoy headed out to the first site, Whitburn Bay. There are a number of issues regarding the behaviour of the British and Irish Ice Sheet (BIIS) along this coastline and the lack of chronostratigraphic control associated with both advance and retreat phases. Whitburn Bay is located in an area of coalescence of several competing ice lobes, making it useful for understanding east coast ice-sheet flow dynamics.

The group was introduced to the Late Devensian tills by Bethan Davies. Glacigenic sediments were well exposed above the Magnesian Limestone bedrock with the lower Blackhall Member and the upper Horden Member clearly identified, separated by a boulder pavement. The glaciofluvial sands and gravels sparked a lively debate regarding their possible subglacial and proglacial origin. The two tills represented ice flow from two different locations during the Late Devensian, supporting the existence of multiple competing ice lobes in the eastern sector of the BIIS. The dynamic group discussions continued despite the ensuing rain and increasing winds. Fortunately, the next stop was to sample the delightful Whitburn fish & chips and dry off.

The afternoon saw the convoy bracing the high winds to assemble at Warren House Gill to discuss the Middle Pleistocene, Warren House Gill Formation (WHF). GLWG members were impressed by the vast sections cleared along the cliff by a JCB, courtesy of the QRA! These sediments have previously

been interpreted as indicating the onshore presence of the Scandinavian ice sheet during MIS 6. However, the WHF apparently pre-dates a raised beach dated to MIS 7. In short, the age, genesis and provenance of the WHF remains unresolved. The revised lithostratigraphy proposed by Bethan Davies provoked much discussion. Bethan suggested that the basal deposit was a glaciomarine diamicton that had been overridden by an ice sheet, that was deposited at some point between MIS 8 and 12, and which contained almost entirely British and North Sea detrital material. There was no evidence of an onshore Scandinavian ice sheet at Warren House Gill. Bethan Davies and Dave Roberts concluded the afternoon by suggesting that the Fennoscandian ice had interacted with the BIIS in the North Sea possibly twice during the Quaternary, during MIS 6 and MIS 12, with the precise chronostratigraphical framework for the site still under development - so watch this space!

After a day blowing the cobwebs away, the evening was spent tasting the local pub grub and Ale, only moving on once last orders was called. The GLWGers then had the excellent idea to go to the Whitley Bay Caravan Park karaoke night, which we could only get into after some quick-talking from Dave Roberts. This was quite an experience and although none of the group volunteered to sing, we could tell Dave Evans was close!

Sunday 25th October

The following morning, the high winds continued. The bright eyed group from the night before said a few goodbyes before some people started the long journey home. After some unpredictable convoy driving, the remaining crowd arrived at Upgang, North Yorkshire, led by Dave Roberts. We discussed Late Devensian tills and ice marginal environments, aiming to resolve some of the issues of glaciation along the east coast.

With the sun now shining, the group was led down to the beach and was in awe of the impressive section 750 metres long and 30 meters high. They were even more amazed that it was discovered by a friend on a stag night! Upgang displayed four lithofacies associations, with an initial ice advance from the north, followed by ice recession and the formation of an ice marginal lake. Ice later readvanced into the area, infilling the lake and eventually the entire site. As the rain started to fall, the talks progressed to dating control. A crude chronostratigraphic framework was suggested, with the initial ice advance occurring at ca. 21,000 cal. years BP, and the second advance at ca. 16,000 cal. years BP, with speculative correlation to Heinrich Event 1.



Figure 1. The GLWGers at Uppang, North Yorkshire

In summary, Bethan Davies' Ph.D. field sites stimulated interesting discussions about the genesis of the LGM sediments and the behaviour of the British Ice Sheet along this coastline. An excellent meeting and look forward to seeing you all next year for the QRA GLWG in Anglesey.

Danni Pearce
Department of Geography
Queen Mary University of London

AGLWG website is now hosted at Durham University Geography Department, where you can read more about the group and find reports on all of the past meetings and links information about future meetings:

http://www.dur.ac.uk/geography/qec/research_groups/glwg/

QRA ANNUAL DISCUSSION MEETING, UNIVERSITY OF DURHAM, 5-8TH JANUARY 2010

The QRA Annual Discussion Meeting 2010 was hosted by the Department of Geography, Durham University under the broad title of '**Sea-level Changes: the Science of a Changing World**'. The theme brought together researchers from what might be described as near (majority) and far-field (minority) sites, to discuss issues related to past and future sea-level reconstruction. The subject matter is both highly relevant - as the community debates the range of possible future predictions and contemplates their potential societal, economic and environmental impacts, and wide ranging - drawing upon a host of different skills, approaches and archives. There was new and challenging material for all and it is fair to say that the conference represented a 'vigorous intellectual workout', to use the words of Rhodes W. Fairbridge, the first to report the 20th century rise in global sea level in the 1960s,



Figure 1. Durham Cathedral and Castle, 5th January 2010

The meeting was organised by **Sarah Woodroffe, Dave Roberts Ian, Shennan** and **Antony Long** and was attended by over 120 delegates. It is testament to the commitment of Quaternary scientists that there were very few absences despite the significant snowfalls and temperatures $< -10^{\circ}\text{C}$ experienced across Britain that put a strain on the UK transport network (Figure 1). This report focuses solely on oral presentations, but I must congratulate those individuals who put together high-quality posters detailing future initiatives, postgraduate research efforts, international collaborations as well as local and global projects.

Kurt Lambeck (Australian National University) provided a fitting start to the conference with a global view of ice sheet and sea level interactions from present to beyond the Eemian in the Wiley-Blackwell Journal of Quaternary Science Keynote Lecture. He presented the latest of his continuing efforts to obtain 'ice equivalent sea level' using iteration between geophysical model solutions and a comprehensive observational database of relative sea levels from across the globe. Discussion focussed on dynamic picture in the Eurasian sector, which was related to the draining of the Baltic Sea and whether one considers the Arctic to be open or closed during the Eemian. This first session continued with a suite of talks based on observational data from mid- to high-latitude regions that have been used to constrain past relative sea levels (RSL). **Rebecca Rixon** (University of Exeter) presented a sample collection strategy that takes advantage of cosmogenic isotope, geomorphological and biological techniques to define ice-free areas and constrain the deglaciation of Antarctic Peninsula Ice Sheet. It is hoped that work during this PhD study will constrain sea levels in this 'data-poor region' with wide range of model estimates and perhaps have some bearing on the possible contribution of the Larson Ice Shelf to Meltwater Pulse 1A. **Emma Watcham** (Durham University) presented data from another high-latitude southern hemisphere setting – South Shetland Islands - where raised beach and isolation basin data are being used to refine existing relative sea level curves for the area. **Marc Hijma** (Utrecht University) discussed attempts to define the magnitude of sea level change prior to the 8.2 ka event related to the draining of glacial lakes Agassiz and Ojibway. Peat and gyttjaic mud deposits from the Rhine-Meuse delta were recognised as challenging settings to define relative sea levels, but groundwater index points have been used to define a jump > 2 m at 8450 BP. Discussion focussed on tidal influence at the end of an elongated English Channel. Looking at more recent sea level change, **Antony Long** (Durham University) summarised ongoing work on isolation basins and salt marshes of west-central and southern Greenland to put the recent dynamic phase of ice sheet mass balance in context. The data 'bridges the gap' between longer-term geological evidence and recent direct observations from satellites by providing a curve for the past 600 years with c. 1.4 m of RSL rise. **Anders Romundset** presented a similar strategy using isolation basins in Finnmark, northern Norway, to define a Holocene RSL curve. Tsunami deposits (dated at 8100 BP) are found in these sediments some 1300 km distant from the Storegga slide to the south.

The final two talks of the first theme presented data from lower latitudes. **Gina Moseley** (University of Bristol) illustrated the way that stalagmites and flowstones from karst settings can be used as sea level indicators. U-series ages have been used to constrain periods of serpulid worm overgrowths, calcite growth and hiatuses in circum-Caribbean submerged caves. These data are combined to suggest sea level fluctuations of up to 6 m between 9 and 6 ka, at odds with other evidence from the region. **Ben Horton** (University of Pennsylvania)

has spearheaded efforts to compile a large database of RSL indicators from the North Atlantic seaboard of the United States. Considerable effort has been devoted to defining 'indicative meaning and uncertainty' of salt marsh data and comparison was made with tide gauge data of the past 100 years to constrain the sea level change. In this region, highest sea level change during the Holocene ($> 5 \text{ mm a}^{-1}$) is found in the mid-Atlantic region associated with the collapse of the glacial forebulge.

The second theme – Quaternary sea-level changes, past people and their environments – started with a keynote talk by **Colin Murray-Wallace**, who took us back to the early and middle Pleistocene and the glacial-interglacial fluctuations that resulted in the impressive suite of laterally-persistent coastal barriers distinctive of the Coorong Coastal Plain in southern Australia. Uplift-corrected interglacial sea levels based on evidence from this region are considered to be consistently within 6 m of present sea level since the Brunhes-Matuyama reversal (780 ka). Accurate dating of these older interglacials is challenging and **Morten Anderson** (University of Bristol) demonstrated how state-of-the-art MC-ICPMS U-Th methods have been used to date fossil corals from emergent coral atolls of the South Pacific. Continuing with glacial-interglacial cycles, **Mark Bateman** (University of Sheffield) presented data from the tectonically active coastal setting of the Atacama Desert, northern Chile. Here, cemented dune deposits can be related to former high sea levels. OSL ages constrain tectonic uplift rates, while stable isotope and sedimentological data indicate evidence that can be related to environmental setting and paleowind direction, respectively.

After dinner, many of the delegates reconvened for a public "Any Questions" style session at Hatfield College to discuss the impact that our Quaternary sea level research has on science and society. This novel session was chaired by **Jim Rose** (Royal Holloway) and panel members were **Iain Stewart** (University of Plymouth, television presenter), **Fabienne Marret-Davies** (University of Liverpool, QRA Publicity), **Carl Stiansen** (Durham University, media relations), **Antony Long** (University of Durham), **Colin Murray-Wallace** (Editor, Quaternary Science Reviews) and a noble volunteer from the audience, **Margot Saher** (University of Plymouth). Among the key issues discussed were: How do we make our science generate impact? How do we disseminate our research effectively? What influence do we have on policy? Does Quaternary science need a blog or twitter? Many suggestions were made and I reiterate one here. There was a call for open-access summaries for lay interest of the academic papers provided on journal websites. Such material will add impact by informing the general public of our results in a context they should understand. The discussion throughout was open and informal, and became even more so after we drifted to the college bar.

First up on the second day of talks was **Mark Siddall** (University of Bristol), who provided a QRA Keynote Lecture that summarised a range of empirical modelling attempts based on paleosea-level data and used to inform future predictions. Examples were taken from the penultimate deglaciation and the last few interglacial periods to look at the sensitivity of sea level to global temperature variation. These estimates add confidence to the predictions at centennial scale from coupled global climate models, but it is well-recognised that there remain some non-linearities and unresolved spatial disparities in the paleorecord. This talk provided an excellent back-drop for the wide variety of sea-level evidence that followed. **Matt Williams** (University of York) illustrated the use of coastal shell middens of fish gatherers on the Farasan Islands in southern Red Sea to investigate the interplay between uplift, sea level change and patterns of resource exploitation. **Dan Charman** (University of Exeter) promoted the use of testate amoebae to supplement standard methods of sea-level reconstruction in salt marsh habitats. Test cases from both sides of the North Atlantic provide encouraging evidence that the addition of such data to modern multi-proxy transfer functions will provide higher-resolution and more robust sea level data. This is particularly so for higher zones, nearer Highest Astronomical Tides, where forams are less successful. **David Bridgland** (Durham University) presented river terrace evidence from the Ouse, Humber and Trent drainage systems of northern England that has been amassed during recent years in projects funded by the Aggregates Levy Sustainability Fund. Reconciliation of the different terrace records draws upon the interplay between climate change and crustal process via epeirogenic uplift. **Andrew Cooper** encouraged the community to consider the evidence for sea level change in offshore waters of Britain. The risks may be higher, but careful targeting with multi-beam and seismic bathymetry can be used to improve upon the paucity of data for sea level minima or the rapidly changing elevations during the last deglaciation: low stand deltas and submerged isolation basins are particularly useful here. By way of example, comparison between geophysical and core methods were illustrated for the sites of Belfast Lough and Causeway Coast, Northern Ireland.

Morphological mapping, combined with stratigraphical and diatom analysis at two nearby coastal sites on Harris, Outer Hebrides, have been conducted by **Jason Jordan** (Coventry University) and others. They expected to obtain different estimates of post-glacial uplift at this site, which is peripheral to the main glacio-eustatic centre, but similar fluctuations were observed. **Eilat Toker** (University of Haifa) presented archaeological evidence from sites of Hellenistic, Roman and Byzantine occupation on the coast of Israel to illustrate fluctuating sea levels: Wells, cisterns and fortifications provide dated sea level evidence and indicate that levels were near present during the Roman period but dropped to perhaps -1.0 m during the 13th century and rose subsequently. Rob Westaway (Open University) closed what was a morning packed with

variety with a discussion of the role that erosional isostasy plays in the uplift of marine terraces of southeast Italy. A region that appears to have seen a shift to isostatic uplift after the "Mid Pleistocene Revolution" when climate change brought about that enhanced erosion.

The afternoon of day two provided a range of talks on modelling global to local sea levels. In his Quaternary Science Review/Elsevier Keynote Lecture, **Richard Peltier** took us back to some of the background theory to assess visco-elastic adjustment of the Earth and then reinforced the notion that one also needs to include 'rotational feedback' in the 'sea level equation', which provides one of the most fundamental tests of our understanding of ice-ocean-solid earth interaction. Recent modelling efforts were presented (ICE-5G and 6G) that are informed by results from space geodesy (GRACE). It was suggested that attention should be devoted to linking ice sheet models incorporating realistic ice mechanics to the glacial isostatic adjustment (GIA) models constrained by time-dependent geomorphological data.

The British Isles has a high density of RSL data that is used to constrain GIA models. Until recently, however, the data from North Wales were difficult to reconcile and **Michael Roberts** (Bangor University) presented new tidally-corrected RSL data from offshore in the Menai Straits that are extremely useful in this regard. **Sarah Bradley** (Durham University) reinforces the particular importance of the RSL data from the British Isles by highlighting the combined effect of the global signal and that related to the local British Isles Ice Sheet (BIIS). Latest GIA model iterations are constrained by the regional GPS velocity field and far-field Holocene sea level data (from China and Thailand). **Ian Shennan** (Durham University) presents estimates of the baseline rates of relative sea level change using these improved models. Latest GIA models include terrain, which is a major fraction of the local component of load that includes the BIIS, and a non-equilibrium last-glacial maximum ice sheet. Easily interpreted maps have been produced for practitioners that have local or national-scale concerns. Future versions of the models illustrated here are expected to be 'glaciologically-driven'.

James Scourse (Bangor University) illustrates the feedbacks between sea level and climate by highlighting the impact of post-glacial flooding of continental shelves on the productivity of oceans and dissipation of tidal energy, tidal mixing and seasonal stratification. Among the excellent visualisations displayed were those of the European Palaeotidal Visualisation Model. ([// www.hpv.cs.bangor.ac.uk/palaeo.php](http://www.hpv.cs.bangor.ac.uk/palaeo.php)). In separate presentations, **Anne Le Brocq** and **Pippa Whitehouse** (both Durham University) illustrated the use of numerical ice sheet modelling (GLIMMER) constrained by field evidence to consider ice sheet configuration and mass balance in Antarctica. The former looked at the last glacial maximum and deglaciation in the Weddell Sea sector

and suggested a limited contribution of 2 ± 1 m to MWPIa, but it was recognised that better grounding line definition and bed topography are needed to provide more robust results. The latter looked at the recent mass balance and compares results with the full range predicted by GRACE, satellite altimetry, INSAR. The variety of field constraints used in Antarctica was illustrated by **Dominic Hodgson** (British Antarctic Survey). It comes as no surprise that data from this continent are rare because only 0.32% is ice free, but seal skins, penguin remains, whalebones, isolation basins and raised marine landforms have been utilised effectively to constrain RSL. Of particular interest are data from prior to the last glacial maximum located in the Syowa Coast region that has been used to shed light on the marine transgressions of marine isotope stage 3. **Jeff Ridley** (Met Office) concluded the modelling section by discussing critical thresholds of ice volume. Forward modelling using climate and off-line ice-sheet models indicates that there are some critical thresholds in ice volume that are 'points of no return'. In some greenhouse-gas projections scenario these are reached in a few hundred years. To improve the robustness of future projections, incorporation of snow and regional climate models are required.



Figure 2. Conference dinner in the Great Hall, University College, Durham University

Day three focussed on recent and future sea level changes. **Jason Lowe** (Met Office) provided the QRA Keynote Lecture for the session and discussed strategies to 'operationalise' or 'tailor' sea level projections. Combinations of GCM ensemble results, regional model downscaling and surge models are used to predict elevations with appropriate uncertainties. The goal here is provide information to decision makers and this is being delivered by the

AVOID programme, which addresses such critical questions as 'How much climate change is too much?' and 'What are the upper limits on sea level rise for the next century?'

One of the impacts of sea level rise and increasing storm occurrence is accelerated coastal cliff erosion. **Michael Lim** (Durham University) detailed attempts to characterise the nature and rate of erosion on rocky coasts using laser scanning, microseismic measurements and water level sensors. Processes are captured and fed into future predictions of volume loss/unit area. **Natasha Barlow** (Durham University) took the opportunity of a gap in the programme to highlight her PhD research comparing model and field evidence from south central Alaska where the combined influence of GIA and earthquake deformation cycles are evident. **Dissanayake Sampath** (Universidade do Algarve) described attempts to use the GIS-based Estuarine Sediment Model to predict the long-term morphological evolution of the lower Guadiana estuary, Portugal, in response to a range of sea level rise scenarios and also decreased sediment supply.

Against a backdrop of discussion about glacio-hydro-isostatic adjustments, **Matthew Brain** (Durham University) illustrates the problems associated with determination of sea level index points and, specifically, issues related to autocompaction of coastal sediments. Sea level data need careful correction for this process and both geotechnical 'laws' and experimental effort are being used to improve the situation for both minerogenic and organogenic sediments. Methods for the former are better developed. Looking at more precise estimates of recent sea level change, one might expect tide gauge data for the past few centuries to provide robust data for decadal and interannual variability, but as illustrated by **Philip Woodworth** (Proudman Oceanographic Laboratory) there is much more effort required to account for redistribution of water. Gyre-scale spin-up/down of the North Atlantic, for example, is known to have influenced low-frequency variability of sea level observed in the UK.

A body of evidence indicates accelerating sea level rise during the past two centuries, but such data is often overshadowed by the concern that baseline rates for longer time-scales are not sufficiently robust. Salt marsh data represent the best, widely-distributed candidates for this exercise and **Andrew Kemp** (University of Pennsylvania) presented a comprehensive compilation of data from North Carolina, USA, for the past two millennia using modern transfer functions based on cluster analysis. The rates of sea level rise obtained for the period since the end of the 19th century are the highest for the period of under investigation. Highest current rates of recent sea level rise in the UK are expected in South-west England and **David Dawson** (University of Plymouth) revealed sea-level index points based on a shallow basal intertidal sequence from South Devon that enable better reconstructions for the past 2000 years.

As the demands on precision and accuracy of tide gauge measurements is ramped up, corrections for GIA alone are not sufficient and all vertical tide gauge motions must be accommodated for. **Matt King** (Newcastle University) discussed the significant advances made in GPS geodesy, particularly reference frames, which now allow more robust estimates of sea-level change based on tide gauge data to be calculated. The final talk of the conference was presented by **Svetlana Jevrejeva** (Proudman Oceanographic Laboratory), who has used statistical inverse models that incorporates natural (volcanic and solar) and anthropogenic (greenhouse gases and aerosols) forcings to look at past sea level change. It was shown that the latter forcings dominate after 1800 AD and that continued emissions in a range of six IPCC scenarios results in a sea-level rise at the end of the 21st century of 0.5 to 1.7 m. The salient point was made that stratospheric injection of SO₂ equivalent to a Pinatubo eruption every 4 years would only delay sea-level rise by 12-20 years because of inertia in the system.

Inertia, thresholds, non-linearities in the Earth system were key themes of the meeting and represent major concerns. It is evident from the quality and diversity of subject material presented at this conference that these concerns are well-served by the research community. Geophysical modelling results and observational evidence must be used in concert and a wide range of excellent examples of this practice were presented here

The remaining delegates dispersed quickly after the last talk, conscious that the journey home would be challenging with the continuing weather disruption; there was buzz on the railway platform after the enjoyable meeting, despite the delays. The Durham team – organising committee and assistants – are to be congratulated for their enthusiasm and hospitality during the conference. They coordinated a stimulating and varied programme. For those unable to make the trip, you can get a flavour of the meeting by accessing online versions of the keynote talks hosted by the Sea Level Research Unit at Durham University (see <http://tinyurl.com?DurhamSLvideos>).

David A. Richards
School of Geographical Sciences,
University of Bristol

QUATERNARY RESEARCH FUND

OSL DATING OF KEY MIDDLE AND LATE PLEISTOCENE GLACIAL STRATIGRAPHIC UNITS IN BUCHAN, NE SCOTLAND

Introduction

A grant from the Quaternary Research Fund facilitated field work at three important sites close to the Ugie valley, central Buchan, NE Scotland during April 2009. Details of the sites and the work undertaken to address a number of chronological issues within the glacial stratigraphy of the area, and more widely, are given below.

Leys Quarry (NK 005 525), NW of Peterhead

The longest onshore record of Middle and Late Pleistocene climate change in Scotland is preserved in the sequence of sediments and buried soils at Kirkhill and Leys quarries (Hall and Connell, Appendix 1.7 in Merritt *et al.*, 2003). A single luminescence age estimate, two buried soils of interglacial status, together with optically stimulated luminescence (OSL) dates from a nearby site (Gemmell *et al.*, 2007) indicates that the upper two glacial episodes at the site date to MIS 6 and MIS 2. The earliest glacial event has tentatively been assigned to MIS 8. Sand-rich glaciofluvial, and probable periglacial fluvial, sediments (Pitscow Sand and Gravel Formation) occur within this earliest sequence and three samples for OSL dating were recovered in an attempt to provide a robust age estimate for this cold stage. Glaciation of the UK during MIS 8 is controversial, though deposits in eastern England have recently been assigned to this stage (Straw, 2005; Boreham *et al.*, in press). Glacial sediments of MIS 8 age have tentatively been recognised in the southern North Sea basin and are thought to be present on Jæren, SW Norway (Lee, Busschers and Sejrup, in press).

Oldmill Quarry (NK 024 439), W of Peterhead

Here till of the Whitehills Glacigenic Formation (WGF), derived from the Moray Firth basin is known to be younger than MIS 4 (Merritt and Connell, Appendix 1.8 in Merritt *et al.*, 2003; Gemmell *et al.*, 2007). However, it is uncertain if the till is of MIS 3 or 2 age. In the past amino acid and C¹⁴ analyses of sparse shell fragments within the till at other sites have proven inconclusive. At Oldmill the till incorporates rafts (>2m in diameter) of sand and silty sand. These sediments are texturally distinct from the underlying

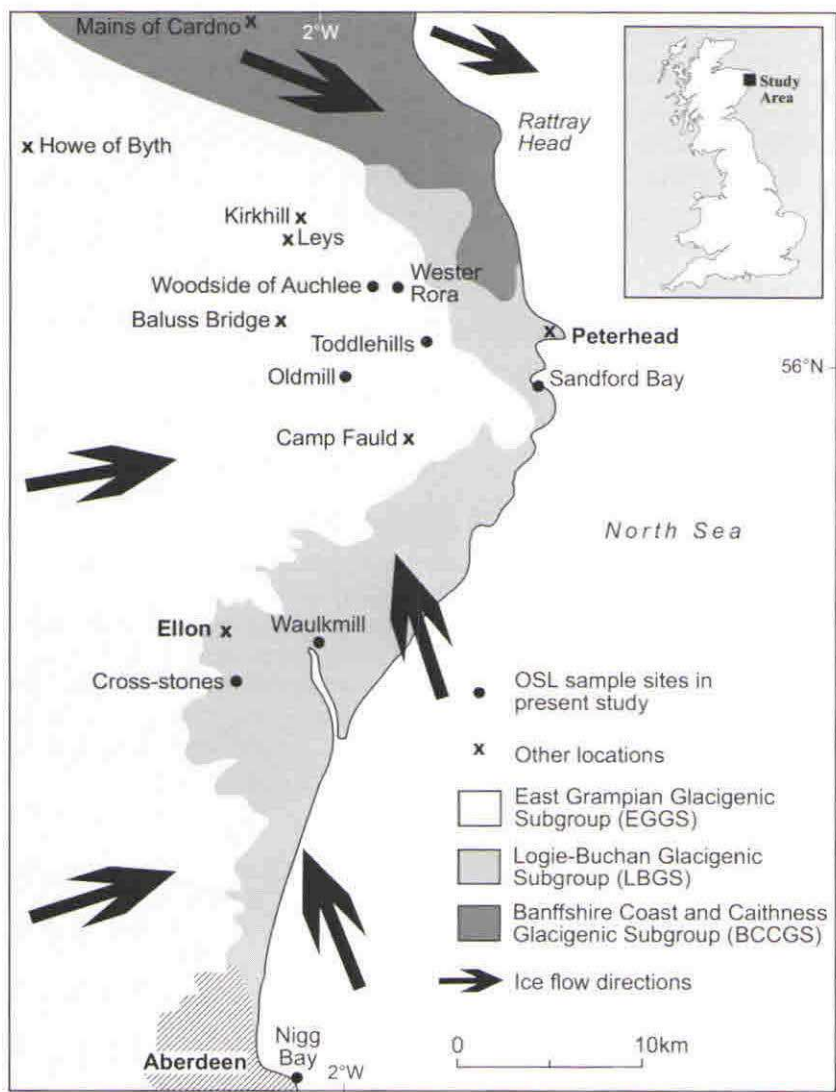


Figure 1. Location map of Buchan, NE Scotland, showing sites mentioned in the text and the surface distribution of major glacigenic lithostratigraphic subgroups.

glaciodeltaic sediments which provided the MIS 4 OSL age estimate. Two samples for OSL dating were collected from the rafts in an attempt to further constrain the age of the WGF.

Sandford Bay cliff (NK 125 434), S of Peterhead

Cliff exposures have revealed laminated silts, clays and sands, with minor diamicton beds, between regionally important till sheets (Connell, Appendix 1.12 in Merritt *et al.*, 2003). During the 19th century bird, fish and seal bones were apparently recovered from correlative laminated deposits at an adjacent brick pit now long abandoned. In the late 1970s small samples were analysed to determine if a marine microfauna was present but proved barren, leaving the question of the depositional environment of these sediments (glaciolacustrine or glaciomarine) uncertain. It had been hoped to excavate a section in the laminated sediments to collect large volume samples for microfaunal analysis, C¹⁴ and OSL dating. It was anticipated that these samples could provide bounding age estimates for the Hatton Till Formation and Sandford Bay Till Member. Recent work at the site (Connell and Gemmell, 2007) recovered an OSL sample from sands overlying both tills. An age estimate from that sample is awaited.

Unfortunately significant slumping on the upper cliff had obscured all outcrops of the laminated inter-till sediments and digging failed to locate any suitable material. However, recent erosion of the lower cliff face produced good exposures of the lower till (Sandford Bay Till Member) and underlying glaciotectonised bedrock. The opportunity was taken to log that exposure in detail. Due to the disappointing situation at Sandford Bay it was decided to search sections at Nigg Bay, Aberdeen (NJ 966 051) and an area near Cults (NJ 876 035) for large boulders suitable for cosmogenic nuclide exposure dating. A number of suitable boulders were found at both sites for future analysis of landform age/deglaciation timing.

Interpretation of all three sites will be prepared when the new OSL age estimates are available.

Acknowledgements

We would especially like to thank Dr Andrew Murray (The Nordic Laboratory for Luminescence Dating, Department of Earth Sciences, Aarhus University, Risø National Laboratory, Denmark) for his interest and continued support of OSL dating in NE Scotland. Thanks to Mrs Alison Sandison for drawing the figure. ERC is most grateful to the QRA for a grant from the Quaternary Research Fund that contributed to the costs of the fieldwork. He would like to thank June and Al Gemmell, Colin Turner, and Sheila and Adrian Hall for their very generous hospitality. He would also like to thank Mrs B. Connell for her interest and support and Derek Melling for helping to prepare sampling tubes.

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E.R. Connell
A.M.D. Gemmell

GeoSciences School
Geography and Environment
University of Aberdeen
St Mary's
Elphinstone Road
Aberdeen
AB24 3UF
UK

NEW RESEARCHERS AWARD SCHEME

FAST GLACIER FLOW IN SOUTH-EAST ICELAND: THE SEDIMENTARY SIGNATURE

Background and rationale

Research into subglacial processes is crucial for an understanding of glacier dynamics. Processes at the ice-substrate interface are still poorly understood, and, as a consequence, the 'basal boundary' still constitutes a major uncertainty in ice sheet modelling. While recent glaciological research highlights the importance of understanding fast glacier flow, notably in the context of ice sheet stability and future sea level rise (Stokes and Clark, 2001), knowledge of what controls sudden accelerations (surging) and ice streaming is mostly theoretical and mainly conceptual in character. There seems to be a general consensus that variations in glacier velocity are related to changes in subglacial hydrology and substrate rheology (Evans *et al.*, 2008, Luckman *et al.*, 2006, Smith *et al.*, 2007, Tulaczyk *et al.*, 2001.) but convincing empirical evidence has yet to be presented.

This study investigates sedimentary sequences in glacier forelands that are known to have experienced surging events, and compares them to sedimentary sequences associated with non-surging glacial movement. This project seeks to discover the differences that are preserved in the sedimentary record and to see if this can be linked to current theories on ice-substrate dynamics.

Methodology

Outlet glaciers around the south-side of the Vatnajökull Icecap, Iceland, were selected for this study. In this area there is an excellent historical record of surge events (Bjornsson *et al.*, 2003) and a range of types of glaciers, in terms of surging and non-surging behaviour, but also in terms of flow velocity. Furthermore, almost all field areas are easily accessible. Key localities in the field were identified for extensive and systematic analysis, including detailed sediment logging, geotechnical measurements (penetrometer tests) and clast fabrics analysis. Bulk samples were taken for the purpose of grain size analysis and undisturbed block samples were taken for thin section micromorphological analysis of the sediment.

Preliminary results

Preliminary results suggest that surge-affected areas show a deformation signature that overwrites the yearly advance and retreat cycles found in other glacial foreland sites. Logs taken through sedimentary sequences in the surge-

affected foreland of Breiðamerkurjökull for example, show a silty clay sediment with an interpreted shear-induced anastomosing foliation superimposed on what has been identified as a typical A-B horizon deformation profile. A suite of structures consisting of stringers of sand and coarser gravel lenses and inclusions of sediment with a conspicuous blocky structure (Figure 1) was frequently observed. In places where the anastomosing units become decimeter-scale the maximum grain-size within the unit increases and the individual branches start to show a secondary internal shear foliation. Some parts show an association with conjugate fault sets that affect a multiple unit sequence. The amount of sediment reworking that has occurred at the surge-affected sites appears to be more pervasive and deeper than normal deformation profiles, which is evidenced by incorporation of older sediment sequences throughout the stratigraphy.



Figure 1. Thirty centimeters of cleared section from *Breiða Windows* location showing the presence of multiple black sand lenses and thin inter-bedded layer. Note the blocky structure.

Conclusions

The preliminary results of this project are promising and qualitatively there appears to be a difference in deformation signature between the sediments in

surge-affected and non-surge affected areas. It is anticipated that the ongoing quantitative analyses of data will produce a set of diagnostic characteristics which will aid in differentiating surge-affected and non-surge affected sediments in this part of Iceland.

Acknowledgements

The QRA's New Research Worker's Award contribution to the cost of fieldwork in Iceland is gratefully acknowledged. Thanks are also due to Swansea University for partially funding the fieldwork and to numerous staff within the Geography department for help with organisation and equipment. I would like to thank the Icelandic Glacier Guide company for numerous lifts between field sites. I would also like to thank specifically John Hiemstra and Dave Evans for their help in the field and Paul Moore, not only for his help in the field but also his patience in heavy rain.

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Iain Leighton
Department of Geography
Swansea University
Singleton Park
Swansea
SA2 8PP
529026@Swansea.ac.uk

2D NUMERICAL MODELLING OF CENTRAL NEW ZEALAND'S LAST GLACIAL MAXIMUM AND CLIMATICALLY-DRIVEN DRAINAGE CAPTURE

Background and rationale

This research is part of a PhD project investigating the controls of glacial-interglacial climate cycles on braided river stratigraphy. The Canterbury Plains of eastern South Island, New Zealand have been built by braided river systems active during the last 30 ka (Ashworth *et al.*, 1999), which includes the Last Glacial Maximum (LGM) between 22-18 ka (Alloway *et al.*, 2007). This aspect of the project investigates the glacial history of the Rakaia, Ashburton and Rangitata river basins using a 2D numerical glacial model (Plummer and Phillips, 2003). The aim is to understand changes in discharge and sediment flux that occur due to changing climate and the effect of climatically-driven drainage capture on braided river processes. Fieldwork indicates that drainage capture occurs when transfluent ice (Golledge, 2007) crosses the modern drainage divides and potentially causes substantial changes to the discharges downstream. The modeling effort aims to quantify this effect at various stages of glaciation. This numerical model first calculates the mass balance of the study area under modern conditions and recreates the ice extents that this would be expected to produce using the physical properties of ice flow. When the modern ice extents can be realistically reproduced, the temperature and precipitation inputs can be adjusted to recreate LGM and postglacial ice extents. Model output is verified using both the observed glacial geomorphology (Mabin, 1980) and published data quantifying climatic changes in New Zealand. We are fortunate that New Zealand has a well-constrained climate event chronology in place for the last 30 ka (Alloway *et al.*, 2007) to which we can tie our modelling efforts.

Preliminary results

The model has been adapted to the Southern Hemisphere and we are now working to refine estimates of modern and ancient precipitation patterns and likely temperature changes to understand the ice dynamics at various times, as reflected by glacial moraines. Figure 1 shows a timeslice of model output for a one year period during a postglacial advance due to cooling of -4°C . This research is very much still ongoing, with the aim of producing realistic, ground-truthed models showing glacial advances and retreats, as well as ice extents and dynamics in the study area for key periods of New Zealand's history. We are currently developing a robust model of modern precipitation as a key input into this glacial model, and thinking about how micro- to meso-scale climate would have varied over the last 30 ka. Ultimately we will be able to quantify the precise changes in climate that have initiated glacial advances and retreats in New Zealand, and the resulting changes in discharge and sediment flux. The

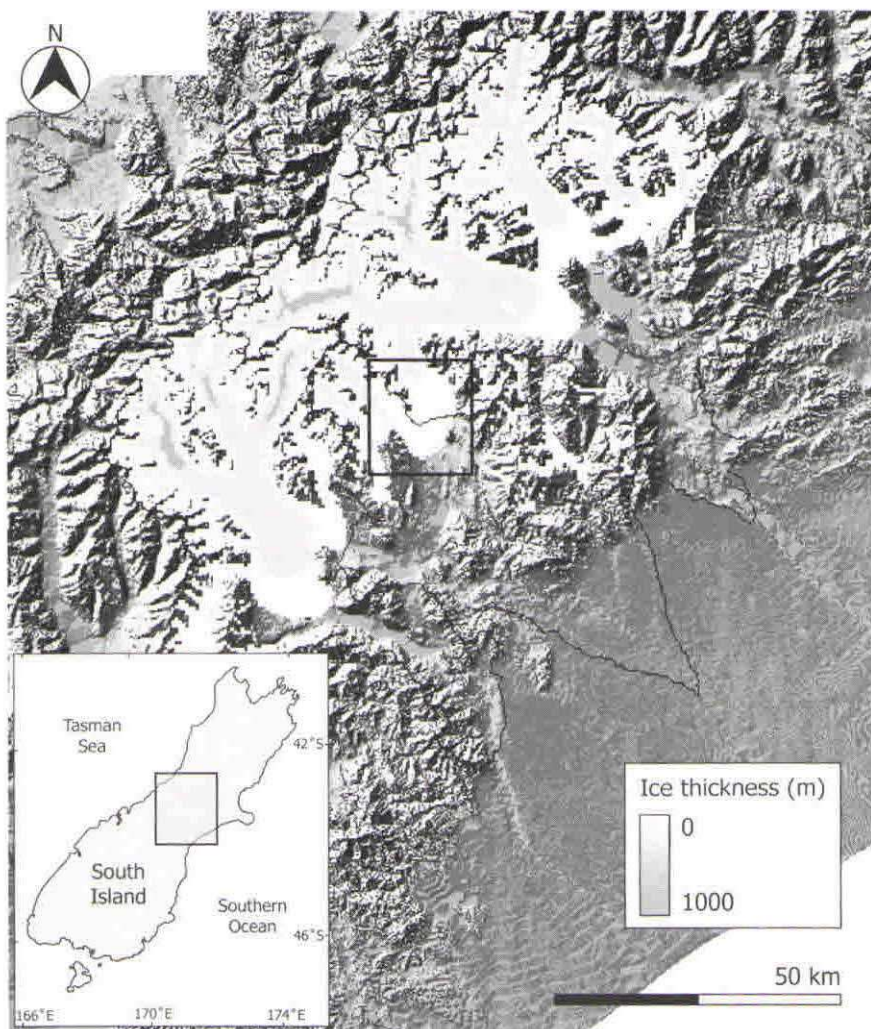


Figure 1. Modelled ice extents in the three study basins during a major postglacial advance, showing maximum ice thicknesses of ~1000 m. Drainage divides are indicated by black lines. The box in centre indicates a zone of confluent ice.

results will be used to better understand how these fluxes affect braided river processes and their resulting stratigraphy.

Acknowledgements

The author gratefully acknowledges the QRA New Research Worker's Award for funding travel to Idaho National Laboratory, USA to develop this model for use in New Zealand. Additional support for this work was also received from the Dudley Stamp Memorial Award and the British Sedimentological Research Group. This work was undertaken whilst the author was in receipt of NERC studentship NE/F008295/1. Many thanks to Mitch Plummer not only for this collaboration, but also for the warm welcome in Idaho Falls, and David Schultz for insights into orographic precipitation. Further thanks to project supervisors Simon Brocklehurst, Merren Jones and Stephen Covey-Crump.

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Ann V. Rowan
Basin Studies and Petroleum Geoscience
School of Earth, Atmospheric and Environmental Sciences
University of Manchester
Manchester M13 9PL
Tel: +44 161 306 9360
Email: ann.rowan@postgrad.manchester.ac.uk

A PALAEOCLIMATIC INVESTIGATION USING OXYGEN ISOTOPE ANALYSIS OF FAUNAL REMAINS AT KOSTENKI XIV, RUSSIA

Background and rationale

Kostenki XIV is an Upper Palaeolithic site located on the Russian Plain, c. 500km to the south of Moscow. The site contains some of the earliest evidence for the Early Upper Palaeolithic in Europe, with at least two cultural levels (4a and 4b) assigned to the period between c. 40-50kya. Climatic records for this period have revealed a series of rapid oscillations known as Dansgaard-Oeschger events, and their impacts have been detected in climatic proxies all over Europe (Voelker, 2002). Falling within the scope of a larger PhD project and with the help of this QRA grant, the climatic context of two human occupations at Kostenki XIV were investigated using oxygen isotope analysis of horse teeth found in the layers, to determine the relationship of the occupations to these climatic events. $\delta^{18}\text{O}$ in tooth enamel has been shown to reflect changes in the isotopic composition of environmental waters ingested by animals during the period of tooth growth, which in turn reflects local temperature conditions in the continental mid-latitudes (Luz and Kolodny, 1984; Rozanski *et al.*, 1992). $\delta^{18}\text{O}_{\text{enamel}}$ can therefore be used as a proxy of climatic changes in past environments. The two investigated layers (4a and 4b) are separated stratigraphically by around 2m, and chronologically by around 3,000 years, although a new radiocarbon dating programme is currently in progress to refine the dates. Layers 4a and 4b have been interpreted respectively as the remains of a horse-hunting and butchery event, and as the remains of an occupation event redeposited across a hill-slope (Sinitsyn, 2003).

Results

The results of tooth enamel $\delta^{18}\text{O}$ analysis at the two sites were extremely similar (Figure 1), revealing virtually identical population-level averages, and intra-population variability that differed by only 1‰. By converting the $\delta^{18}\text{O}_{\text{enamel}}$ values to $\delta^{18}\text{O}_{\text{ingested water}}$ (achieved using a modified version of the relationship proposed by Delgado Huertas *et al.*, 1995), it is possible to compare past climates with those of today. Current precipitation in the area has an annual weighted average of -9.4‰, with summer and winter averages of -7.6‰ and -16.4‰ respectively (IAEA website). These results estimate that the annual average isotopic composition of environmental waters at the time of the occupations at Kostenki XIV was similar to the modern winter mean, equating to an annual average temperature in Kostenki of below 0°C.

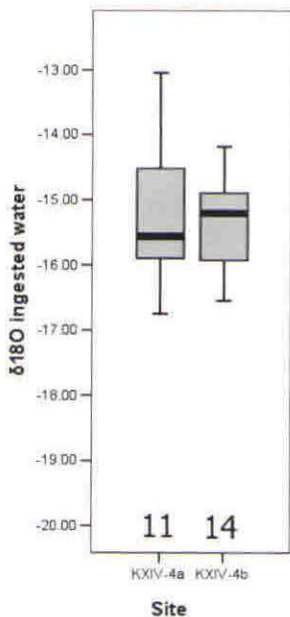


Figure 1. Box-plot of $\delta^{18}\text{O}$ results measured on horse teeth from human occupation levels at Kostenki XIV. Sample numbers are indicated at the bottom of the plot.

Significance

On the basis of these results alone it is not possible to say whether the occupations in layers 4a and 4b correspond to a D-O warm or cold event, however the overall similarity between the levels is striking, and imply that the two human occupations at Kostenki XIV were made during similar climatic conditions. The climatic variability observed in the Greenland ice cores indicates that periods of stability lasted for no longer than 1,000-2,000 years at a time. This suggests the possibility that the climatically-similar occupations at Kostenki may have been separated by a period of significantly different climates – a D-O cycle. An isotopic context for these data is currently being built using comparative analyses at other Kostenki sites, to determine how faunal isotopic values have changed through time in the area. This will allow a more complete interpretation of the results from Kostenki XIV.

Acknowledgements

I would like to thank Prof. Andrey Sinitsyn for arranging access to samples, and the QRA for providing financial assistance towards the cost of undertaking the isotopic analyses presented in this report. I am also grateful to Prof. Martin Jones and the Moravia Gates Project for contributions towards travel expenses, and to my supervisors Dr. Tamsin O'Connell, Dr. Lila Janik, and Dr. Rhiannon Stevens for their continuing support and advice throughout this research.

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Alexander J. E. Pryor
Department of Archaeology
University of Cambridge
ajep2@cam.ac.uk

THE MICROMORPHOLOGY OF ICEBERG SCOURS: CLAY MINERALOGY ANALYSIS

Background and Rationale

Icebergs plough through unconsolidated lake/sea sediments gouging out kilometre long grooves, 100m's wide and ten's of metres deep. Little is known about what scours look like in stratigraphic section (where surface characteristics are absent e.g. through burial or deterioration) (Woodworth-Lynas and Landva, 1988; Woodworth-Lynas, 1988; Longva and Bakkejord, 1990; Linch, 2009). Such information is important for palaeoenvironmental reconstructions (e.g. calving glacial margins, wind direction, extent of subglacial environment etc.) in addition to aiding structural engineering on Arctic shelves, which could be of great value to oil and gas companies given the anticipated increase in number, size and frequency of icebergs as a result of climate change. The primary aim of this investigation is to establish a definitive set of diagnostic keys for identifying iceberg scours in the Quaternary and pre-Quaternary rock record by macroscopically and microscopically (2D thin sections and Metripol birefringence stress mapping) examining sediment deformation below onshore (former glacial lakes) and offshore iceberg scours.

Oriented clay domains (plasmic fabric) as seen during thin section analysis under the microscope can be developed by processes other than mechanical deformation. Clay mineralogy plays a role through the capacity of certain clays to incorporate water into their crystal lattice. Wetting and drying of swelling clay (e.g. during subaerial exposure during lake retreat), such as smectite clay, affects the presence and strength of plasmic fabric, particularly skelsepic plasmic fabric (Dalrymple and Jim, 1984). Furthermore, increased water content (and pore water pressure) associated with swelling clay, changes less rapidly because it is more difficult to remove than absorbed water. As a result, concentration of particular types of clay often form the plane of decollement along which movement is concentrated and deformation is easiest. It is therefore, essential to know the mineralogy of clay samples in order to assess the extent of sediment deformation caused by iceberg scouring and that by swelling clay. The QRA New Researchers Award was used to part-fund the total cost of clay mineralogical analysis on iceberg scoured sediment samples from Glacial Lake Agassiz (Manitoba), Scarborough Bluffs (Ontario), and The Witch Ground (North Sea), all of which were carried out at Royal Holloway University of London.

Results and discussion

Glacial Lake Agassiz: Clay mineralogy of iceberg scoured sediment (clay) sampled from (former) Glacial Lake Agassiz, Manitoba, Canada, consistently

shows (relatively) high quantities of smectite clay (c. 5-6°) between values of over 200 x-ray counts to over 600 x-ray counts (Velde, 1992) (Figure 1). Smectite, illite (c. 8.9°) and kaolinite (c. 12.5°) are particularly high in group 1 samples (Velde, B) (Figure 1). High smectite content indicates that some deformation structures, particularly skelsepic plasmic fabric, may be attributable to swelling clay during shrink-swell associated with 1) lake retreat and subaerial exposure (sediment shrinks); and 2) lake advance and inundation (sediment swells). Major peaks between 20 and 30° are attributed to quartz content.

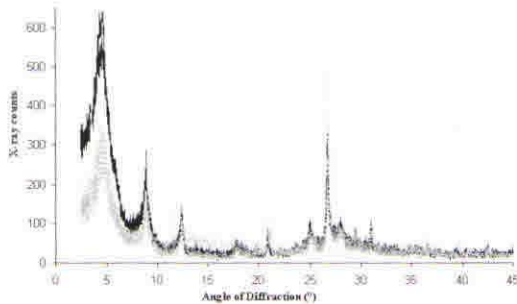


Figure 1. Clay mineralogy: Glacial Lake Agassiz, Manitoba, Canada (black line indicates group 1 samples and grey-dashed line indicates group 2 samples).

Sunnybrook Formation, Scarborough Bluffs, Ontario: Clay mineralogy of iceberg scoured Sunnybrook Formation (sandy clay) from Scarborough Bluffs, Ontario, Canada, shows minor smectite (c. 5-6°) and illite content (c. 8.9°) below c. 60 x-ray counts and no indication of a kaolinite peak. (Velde, 1992) (Figure 2). Therefore, it is unlikely that deformation structures observed in thin section, including plasmic fabric, can be attributed to swelling smectite clay during lake retreat and subaerial exposure. Major peaks between 20 and 30° are attributed to quartz content.

The Witch Ground, North Sea: Clay mineralogy of iceberg scoured diamict from The Witch Ground, North Sea (sample numbers correspond to depth in metres), remains relatively consistent down-core with low relative proportions of smectite, illite and kaolinite, which are all below c. 60 x-ray counts (Figure 3). Therefore, it is unlikely that any deformation structures observed in thin section, including plasmic fabric, can be attributed to swelling smectite clays. Major peaks between 20 and 30° are attributed to quartz content.

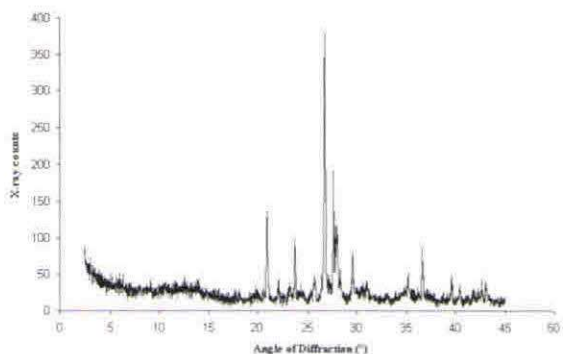


Figure 2. Clay mineralogy: Sunnybrook Formation, Scarborough Bluffs, Ontario, Canada.

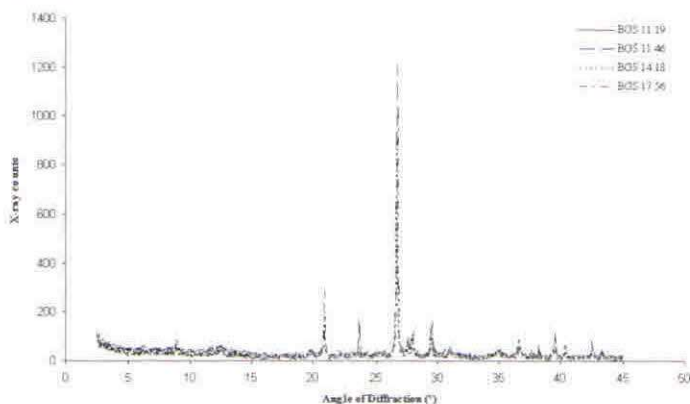


Figure 3. Clay mineralogy: The Witch Ground, North Sea

Acknowledgements

Many thanks to the Quaternary Research Association for the New Researchers Award, which contributed to the cost of clay mineralogy analysis. Further thanks are extended to Dr David Alderton (Royal Holloway University of London) for carrying out all necessary X-ray diffraction techniques, and to the supervisors of this Ph.D. research: Professor Jaap van der Meer (Queen Mary University of London), Dr Simon Carr (QMUL) and Professor John Menzies (Brock, Ontario). This is a NERC funded Ph.D. NER/S/A/2006/14030.

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Lorna Linch
Department of Geography
Queen Mary University of London
Mile End Road
London
E1 4NS

LINKS BETWEEN ONSHORE EROSION AND OFFSHORE GEOMORPHOLOGY AROUND THE COASTS OF SICILY AND CALABRIA, ITALY

Background and Rationale

This project aims to examine links between subaerial and submarine geomorphology around the coasts of southern Italy, in particular whether differences in the rates at which sediments are supplied to the coasts from subaerial erosion are reflected in different submarine deposits and channels. Submarine continental slopes have a great diversity of gullies and canyons, but how these features develop is still not well understood. Marine-geoscientists suspect that sediments delivered from the adjacent land strongly influence these submarine landscapes by supplying erosive density flows and suspended sediment fallout. Such connections are usually difficult to assess, however, as most continental shelves are too wide to allow us to assign individual canyons to rivers, and we have a poor idea of sediment supply. In contrast, the coasts of NE Sicily and SW Calabria have narrow shelves (Figure 1) and many rivers are clearly related to adjacent offshore channels. Furthermore, in this area, it is possible to assess the long term sediment flux in rivers from a combination of uplift rates (e.g. Antonioli *et al.*, 2006), exhumation rates, and landslide flux estimates from sequences of aerial photographs.

In the Ionian Sea between Sicily and Calabria, a geophysical dataset was collected in 2006 aboard the Italian research vessel, *Urania*, including multi-beam echo-sounder, sediment profiler and seismic reflection data. As the data reach to within 100 m depth along the coasts, they include areas that were exposed during the Last Glacial Maximum (when sea-level was depressed by ~120 m), thus allowing an assessment of how rivers delivered sediment during glacial times. A visit to the Italian group based in the ISMAR/Bologna (Andrea Argnani and others) who ran the 2006 cruise allowed discussions on the geomorphology of the region and the marine dataset.

Results

A number of geomorphic features were interpreted from the multi-beam bathymetric data (Figure 1). The central feature (Messina Channel) is somewhat similar to Monterey Canyon and adjacent channels, which have been more intensively studied (e.g. Greene *et al.*, 2002), so the Messina data interpretation was assisted by analogy with Monterey Canyon. The continental slopes are heavily gullied with prominent converging patterns of rills and gullies forming confluences at canyon heads. Notches in the canyon heads and gullies lie at similar depths to the shelf edge. The Messina Channel runs from the Strait of

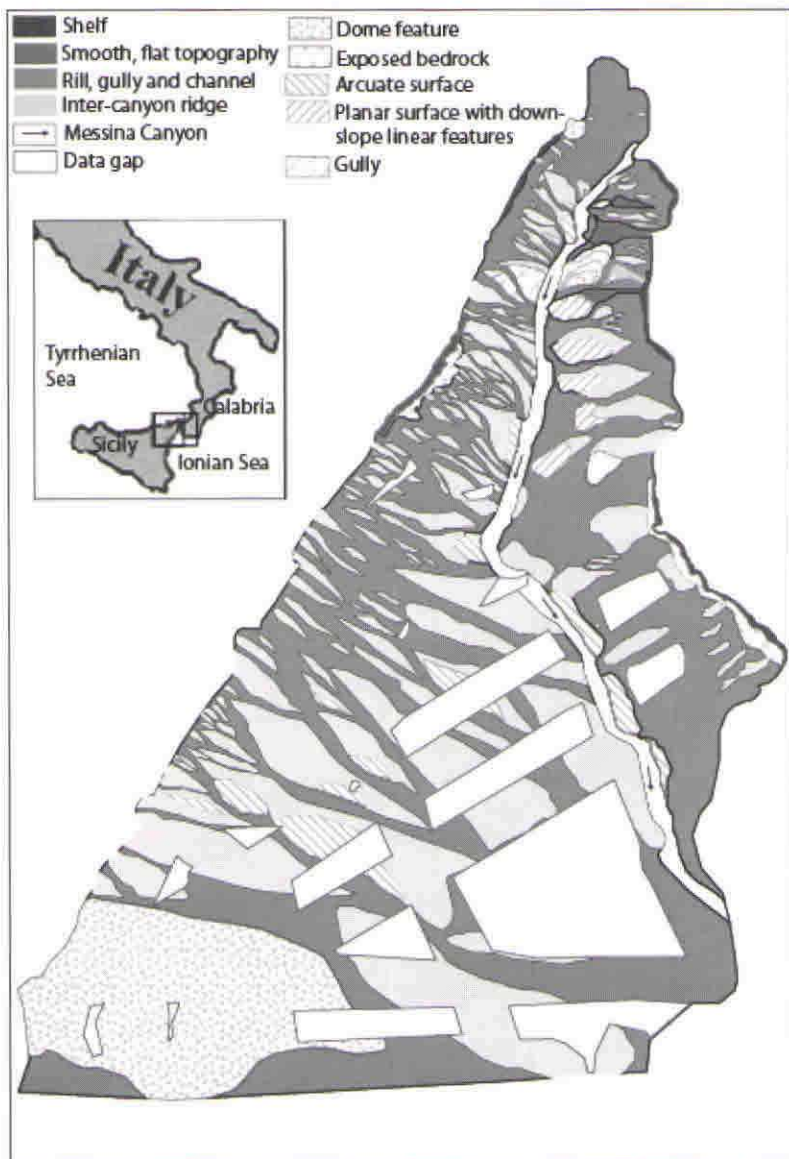


Figure 1. Geomorphological map of the submarine Messina Cone, Ionian Sea, Italy.

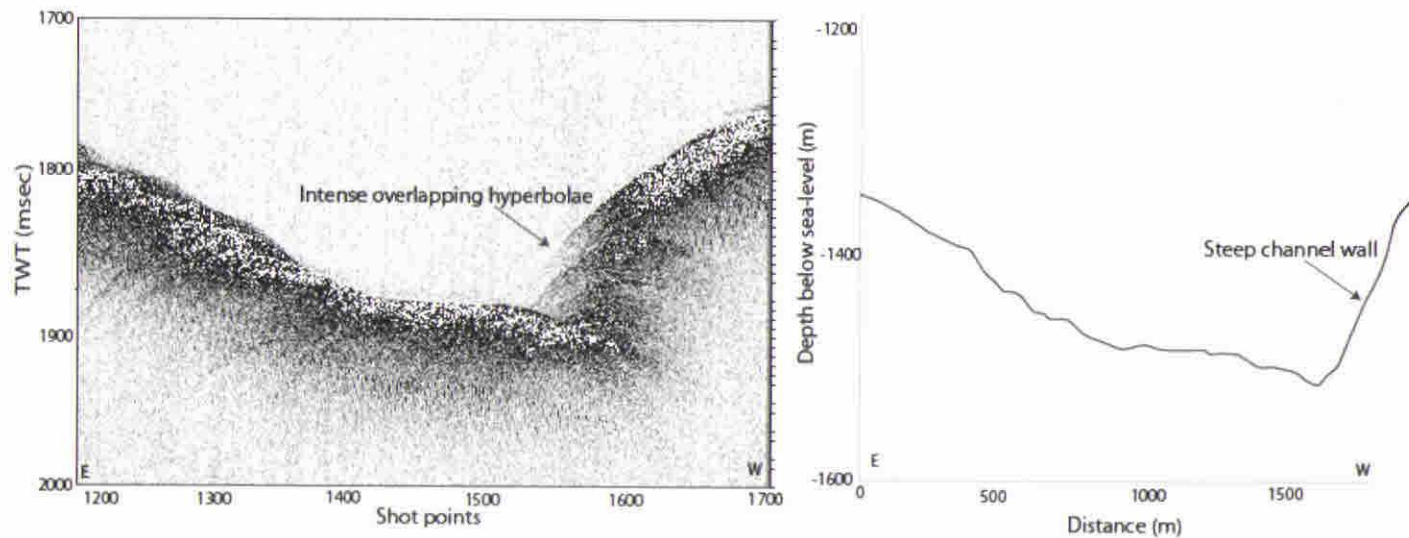


Figure 2. Coincident cross-sections of Messina Channel: (left) in the Chirp data and (right) in the multi-beam bathymetric data. Note the steep right wall with overlapping diffraction hyperbolae in the Chirp data, which reveal an undermined embankment of the channel not resolved in the multi-beam data.

Messina, north to south. Although the channel does not meander prominently, alterations of its course due to slumping and mass wasting are inferred from arcuate surfaces bounding it. The general absence of meanders could also explain the apparently vigorous flow dynamics in the channel, evidenced from under-mining at the outer-bends of the channel wall.

The duration of the echo in Chirp (sediment profiler) records gives an indication of the seabed character at scales smaller than the multi-beam topography. Different echo characters were therefore mapped based on previous interpretations on similar data (e.g. Damuth, 1974). The most common echo-character observed is overlapping diffraction hyperbolae, implying a rough seabed. The example in Figure 2 shows cross-section profiles of the Messina Canyon both in the Chirp data and the bathymetry. The bathymetry profile shows a steep right wall without much structure, whereas the Chirp profile shows discrete diffraction hyperbolae covering a very steep, possibly overhanging wall. This is potential evidence for undermining of the channel wall by sedimentary flows passing down the channel.

There is a sharp bend of the Messina Canyon at the centre of the dataset. Interpretation of the seismic reflection data collected here by Argnani *et al.* (2009) revealed a prominent fault escarpment offshore Calabria. The orientation of the lower part of the canyon is aligned parallel to this fault, which indicates possible evidence for strong structural control.

Significance

Tectonic and sedimentary processes both contribute to the development of the Messina Canyon. The analysis in this project is on-going but initial findings suggest that channels lying offshore large rivers with rapid uplift rates, receive higher sediment flux and are characterised by canyons with broad channels with “graded” longitudinal profiles. These channels are located away from the Strait of Messina. In contrast, channels that lie offshore small rivers (near the Strait) are characterised by small relief channels with steep gradient. The combination of multi-beam bathymetry and Chirp data allows us to evaluate the interaction between active tectonics, large currents descending the Messina Canyon, and sediments derived from the Sicilian and Calabrian coasts in shaping the evolving morphology of the Ionian Sea floor.

Acknowledgements

The author gratefully acknowledges the QRANew Research Worker’s Award for financial support towards her visit to the CNR, Bologna, Italy in 2009. Thanks to Andrea Argnani (co-supervisor) and Marzia Rovore for their valuable insight during discussion on the dataset. Thanks to Luca Gasperini for the hands-on introduction to his software, Seispro, which has been very useful for analysing

the Chirp profiles. Finally, the author is grateful to her PhD supervisors Neil Mitchell and Simon Brocklehurst for their constant support.

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Rajasmitha Goswami
Basin Studies and Petroleum Geoscience
School of Earth, Atmos. and Env. Sc.
University of Manchester

REVIEW

AYR (SHEET 14W)¹ : SUPERFICIAL DEPOSITS AND
SIMPLIFIED BEDROCK (SCOTLAND)

DUNOON AND MILLPORT (SHEET 29E AND PART 21E)² :
BEDROCK AND SUPERFICIAL DEPOSITS (SCOTLAND)

ROTHBURY (SHEET 9)³, KENDAL (SHEET 39)⁴
ROCHDALE (SHEET 76)⁵
: BEDROCK AND SUPERFICIAL DEPOSITS EDITIONS
(ENGLAND AND WALES)

GEOLOGY OF THE KENDAL DISTRICT : SHEET
EXPLANATION (39) 34PP⁶

D. Millward, M. McCormac, N.J. Soper, N.H. Woodcock, R.B.
Rickards, A. Butcher, D. Entwisle and M.G. Rains

GEOLOGY OF THE ROCHDALE : SHEET EXPLANATION
(76) 30PP⁷

R.G. Crofts, E. Hough and K.J. Northmore

Published by : British Geological Survey 2008^{2,4,5} 2009^{1,3} 2010^{6,7}

ISBN 978 0 7518 3531 1 flat	978 0 7518 3532 8 folded and cased ¹
ISBN 978 0 7518 3415 4 flat	978 0 7518 3416 1 folded and cased ²
ISBN 978 0 7518 3579 3 flat	978 0 7518 3580 9 folded and cased ³
ISBN 978 0 7518 3564 9 flat	978 0 7518 3565 6 folded and cased ⁴
ISBN 978 0 7518 3557 1 flat	978 0 7518 3558 8 folded and cased ⁵
ISBN 978 085272649 5 ⁶	
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The Ayr (14W) sheet has been completely resurveyed and offshore geology added, even if the uncoloured late glacial deposits simply blanket the seabed on which the simplified pre-Quaternary bedrock geology is shown without any underwater depth contours. Along the coastline a series of tidal deposits, blown sand and three successive raised beaches extending to about 25 m above sea level are clearly shown. Inland, very large areas of bedrock are blanketed by till, plus associated areas of hummocky glacial deposits along with patches of glaciofluvial and lacustrine deposits. This is supplemented by blue lines depicting drumlins, the inferred flow direction of former glacial meltwater channels, and movement of past ice sheets from glacial striae and crag and tail features. In addition, the extent of artificially modified ground is marked with ruled lines that show the colour of the underlying unit, apart from small uncoloured landslips. Furthermore, a diagram shows high and low water levels along with chart datum (lowest astronomical tide used on navigational charts) relative to Ordnance Datum, which is useful information to have easily at hand. In the margins there are two vertically exaggerated schematic cross-sections outlining the relationships of the superficial deposits and a radar image showing how ice flow moulded the local topography, along with extensive details about the mainly Palaeozoic bedrock geology.

Further up the Firth of Clyde, the Dunoon and Millport sheet (29E and part 21E) covers a relatively narrow extended strip of land on its western shores, including most of the Isle of Bute, along with the Cumbrae islands shown as an insert. This edition has been stitched together from the original survey and various published sources, in addition to some resurveying and limited desktop revision based on aerial photography. With a modern base map, this provides an up-to-date synthesis, even in supposedly unrevised areas such as the raised marine deposits and alluvium at the head of Holy Loch which have been amended. This includes often quite extensive landslips, alongside spreads and patches of till usually confined to the valleys. While it is stated that there is insufficient data to map fully the offshore geology at 1:50,000, even an outline coupled with offshore depth contours would have been better than nothing, as such information puts the onshore landscape into context. This is not helped by this map not being a normal half sheet (*QN* 109, 58), so that the eastern shore of the Firth of Clyde is not shown. With a slightly larger paper size, like the one used for the Ayr sheet, it would then have been possible to show the Cumbrae islands in their true position and have room for more marginalia.

South of the border, the Rothbury sheet (9) in Northumberland has been completely resurveyed, so, while much of the mainly Carboniferous bedrock

apart from the higher ground around the town of Rothbury is still shown as being blanketed by large spreads of Devensian till, there are many significant changes. Most obviously, contemporary opencast coalmining has pot-marked the eastern margin of the sheet. Elsewhere, the finer detail is reflected by often completely revised boundaries for the glaciofluvial deposits associated with the till along with later terrace, alluvial and peat deposits. Swallow-holes and landslides are marked in addition to the usual glacial features in blue. In addition to the sections illustrating the underlying Carboniferous sediments, there is a schematic cross-section for the superficial deposits and a simplified map of the bedrock geology. Ideally, this map would have been extended a few km to cover the small portions of land on the neighbouring Newbiggin sheet (10) beside the North Sea, as this arbitrary cut-off makes the thin cordon of coastal deposits which straddles these two sheets particularly hard to comprehend easily.

The Kendal sheet (39) covers part of the southern Lake District and mainly shows till and associated glaciofluvial deposits irregularly spread over extensive areas of Palaeozoic sediments with hummocky glacial deposits confined to the valleys beneath the more ancient upland fells composed of Ordovician Borrowdale volcanics. As this map provides high quality coverage of the superficial deposits this makes it potentially too complex, and so a separate bedrock edition is available showing these units in much greater detail. Separate editions allow the marginalia to be filled with really useful material beyond the very well drawn conventional and schematic cross-sections. Thus there is an impressive map outlining a number of Quaternary domains. Within each one, the superficial deposits are related to different depositional environments. In addition there is a slightly smaller map showing ice movement indicators, including the southward distribution of distinctive erratics from the Shap Granite, and drumlin axis directions. This insert map in particular would have benefited from the inclusion of simplified contours, as this would have shown the influence of topography on these indicators. In the sheet explanation colour booklet that comes with these maps the superficial deposits get relatively little coverage. Furthermore, the outline geological succession inside the front cover and introduction refers to radiocarbon time for events around the end of the last ice age, rather than real time used in the excellent Quaternary chapter in the new British Regional Geology of Northern England also published by the BGS. However, this booklet does provide local details, including grid references, and the applied geology section provides comments about foundation conditions, including the limitations of boreholes in site investigations for buried Carboniferous limestone karst features where geophysical methods are best used to provide continuous coverage.

Further south, the Rochdale sheet (76) covers a number of Lancashire towns in between areas of moorland up to 474 m high. Given a long industrial past including coal mining and quarrying, along with scattered landslips on many

slopes, coupled with extensive spreads of till and other superficial deposits, this map provides a very useful synthesis, while a separate edition shows the Carboniferous bedrock in much more detail. The map shows a number of glacial meltwater channels and the approximate margins of wider buried channels in the south of the district. However, the estimated extent of concealed glaciolacustrine clay deposits proved in boreholes is only shown on an insert map, which mainly shows rockhead contours, the level of bedrock beneath superficial deposits. Also the main rivers are clearly shown including the Pennine watershed, with the Yorkshire Calder draining eastwards through the town of Todmorden in the northeast of the sheet. In addition to an over-exaggerated schematic cross-section, there is an excellent colour radar image of the area's topography, also with a welcome overlap, and an extended caption explaining some of the key landscape features. The accompanying sheet explanation has a concise and well written description of the superficial deposits, but it would have been better if the Quaternary account had started after the tabulations listing sandstones and coal seams rather than having the opening paragraph split over three pages. Along with two landscape photographs there is a map of meltwater channels and drift filled valleys to provide further information besides a table setting out the nature of the local superficial deposits and another in the applied geology section outlining their engineering characteristics.

David Nowell
2 Tudor Road
New Barnet
Herts.
EN5 5PA

ABSTRACTS

QRA AND RGS-IBG UNDERGRADUATE DISSERTATION PRIZE WINNER 2009

PALAEOCLIMATIC IMPLICATIONS OF TEPHRA AT A NEW SITE WITHIN THE MENTEITH MORAINE OF THE LOCH LOMOND READVANCE GLACIER

Mark Grosvenor (BSc)
University of Exeter

The identification of tephra at a new site within the Western Highland Boundary allows reconstruction of the termination of the Loch Lomond Stadial at the moraine of the Menteith Lobe. The termination of the Loch Lomond Stadial, also known as the Younger Dryas, has seen a vast range of studies due to its abrupt nature. Palaeoclimatic data is extremely important as by investigating how ice reacted to a climatic forcing in the past, it is possible to infer how contemporary ice may react in the future and can assist in adaptation and mitigation strategies with respect to climate change. There are still many unanswered issues and areas which have not been investigated. This study aims to assist by providing palaeoenvironmental data for a new site which can be used for comparison with similar studies. The location of the tephra (*most likely* Vedde Ash, $10,310 \pm 50$ BP) within the core suggests that by the time of eruption organic colonisation had already begun, meaning that climate had already shifted.

The site, at Inchie, has not previously been cored. A multiproxy approach is used focussing upon the changes in organic content of sediment, magnetic susceptibility and trends in the particle-size distribution through the moraine.

MULTI-PROXY RECONSTRUCTIONS OF LATE QUATERNARY ENVIRONMENTS IN WESTERN SOUTHERN AFRICA

Abi Stone (DPhil)

School of Geography and the Environment, University of Oxford

The position of the southern African subcontinent in the mid-latitudes means this region was influenced by fluctuations in a number of atmospheric and oceanic climate circulation systems during the late Quaternary. Whilst the reconstruction of palaeoenvironmental and palaeoclimatic conditions in southern Africa has developed rapidly over half a century, our understanding remains limited by poor spatial coverage and sources of uncertainty within our existing data. The availability of terrestrial proxy archives is restricted by the arid nature of the environment. Sedimentary landforms, such as aeolian dunes and the silt, mudstone and tufa deposits associated with fluvial systems are vital sources of palaeoenvironmental information.

This thesis considers the dimensions of uncertainty in three key terrestrial proxy archives. Linear sand dunes, interdune water-lain deposits and tufa are used to reconstruct palaeoenvironmental conditions at three sites in Namibia. The uncertainty relates to sampling strategies, chronological control and palaeoenvironmental interpretation. Optically stimulated luminescence (OSL) dating has been applied to linear dunes in the west of the southern Kalahari linear dunefield and to interdune deposits in the northern Namib Sand Sea, whilst the utility of ^{234}U - ^{230}Th dating was tested for tufa deposits in the Naukluft Mountains.

This study demonstrates the influence of sampling strategy on the dunefield-scale record of linear dune accumulation; the choice of vertical sampling interval is important, a young bias is introduced in datasets with a shallow sampling bias, and small datasets demonstrate a reliance on individual sites. This study also provides a revision of radiocarbon based chronologies for water-lain units in the northern Namib Sand Sea. This adds further evidence to avoid radiocarbon-based humidity-proxy histograms using inorganic carbonates for reconstructing palaeoenvironments. This study establishes a rigorous methodology for increasing confidence in ^{234}U - ^{230}Th dating of fluvial tufa deposits.

The record of environmental change preserved at these three sites provides insight into the dynamic response of these terrestrial proxy archives to Quaternary climatic fluctuations since MIS 5. Southern Kalahari linear dunes record a period of accumulation at the transition from MIS 2 to the Holocene, centred on ~10 ka. The Tsondab River progressively retreated eastward from MIS 5 to present. The Naukluft tufa include deposits of considerable antiquity, deposition of barrages prior to MIS 5 and some Holocene deposition inside the channel.

LEAD AND NEODYMIUM ISOTOPE CONSTRAINTS ON CONTINENTAL WEATHERING AND OCEAN CIRCULATION IN THE NORTH ATLANTIC DURING THE LAST GLACIAL/INTERGLACIAL CYCLE

Kirsty Clare Crocket (PhD)
University of Bristol

Changes in circum-North Atlantic continental weathering regime and ocean circulation for the last glacial/interglacial cycle were examined in this study using Pb and Nd isotopic compositions of the FeMn oxyhydroxide fraction in terrestrial and marine sediments. The isotopic composition of this leachable sediment fraction reflects that of labile inputs to the ocean released during weathering of the continental detrital sediments. The northern North Atlantic was selected on the basis that major changes in the physical and chemical weathering regime took place on the surrounding landmasses during glacial advance and retreat.

Pb and Nd isotope compositions of the FeMn oxyhydroxide fraction were determined using sequential leaching methods and MC-ICPMS techniques. Sediments collected from a variety of terrestrial glacial settings from Antarctica, continental Europe, North America, Iceland and Greenland, were analysed to provide an analogue for the isotope compositions of labile continental inputs to the ocean during glacial maximum conditions. A positive correlation was observed between radiogenic Pb isotope composition in the FeMn oxyhydroxide fraction and age of bedrock from which the glacial debris derived. No discernible trend in Nd isotope composition of the FeMn oxyhydroxide fraction was found. The Nd isotope compositions of the FeMn oxyhydroxide and detrital fractions tended to be very similar, with the FeMn oxyhydroxide fraction having both more positive and negative Nd isotope compositions relative to the detrital fraction.

Two marine core locations were selected (1) Orphan Knoll in the NW Atlantic - to capture changes in the weathering regime pertaining to the Laurentide Ice Sheet, and (2) Feni Drift in the NE Atlantic - to capture changes driven by glaciation of North Western Europe. Interpretation of the Pb isotope data from each was aided by corresponding Nd isotope results, which provided information on ocean circulation changes. The Pb isotope records highlighted the importance of transport pathways of Pb, and hence of changes in Pb flux associated with different climate modes. They demonstrated that the most radiogenic Pb isotope compositions in the FeMn oxyhydroxide fraction ($^{206}\text{Pb}/^{204}\text{Pb}$ up to ~ 21.0 at both core sites), and therefore solute and nutrient fluxes also, are associated with terrestrial ice delivery to the ocean and ice sheet disintegration.

The Nd isotope record at Orphan Knoll exhibits changes that support a slowdown in circulation during Heinrich Events, during which times it is postulated that vertical transport of Nd from the surface ocean became more important than the lateral flux delivered by deep water currents. Large excursions to negative Nd isotope compositions in the FeMn oxyhydroxide fraction ($\sim -20 \text{ } \epsilon_{\text{Nd}}$) occurred during periods of circulation slow down. The Feni Drift record indicates either an absence or shoaling of overflow water from the Norwegian Sea during Heinrich Events and during other meltwater events. At these times, the Nd isotope compositions of the FeMn oxyhydroxide fraction deviated from an average $\sim -10.2 \text{ } \epsilon_{\text{Nd}}$ to more radiogenic values of $\sim -7.5 \text{ } \epsilon_{\text{Nd}}$, due to incursion of Antarctic Bottom Water to the depth of the core site.

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The Quaternary Research Association is an organisation comprising archaeologists, botanists, civil engineers, geographers, geologists, soil scientists, zoologists and others interested in research into the problems of the Quaternary. The majority of members reside in Great Britain, but membership also extends to most European countries, North America, Africa, Asia and Australasia. Membership (currently *c.* 1,000) is open to all interested in the objectives of the Association. The annual subscription is £20 with reduced rates (£10) for students and unwaged members and an Institutional rate of £35.

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