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A MARINE ISOTOPE STAGE 4 AGE FOR PLEISTOCENE RAISED BEACH DEPOSITS NEAR FETHARD, SOUTHERN IRELAND

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ABSTRACT

Raised beach deposits around the Irish coast have been interpreted as interglacial or last glacial in age. On the south coast of Ireland, the Courtmacsherry Formation raised beach (CFB), near Fethard, Co. Wexford, was dated using Optically Stimulated Luminescence (OSL). This site was previously dated to Marine Isotope Stage (MIS) 6-5, but more recent dating of the CFB elsewhere along the south coast show it is considerably younger (MIS 4-3). The OSL analyses in this paper aimed to determine if new dating would support the greater age of the Fethard raised beach or realign it with the CFB. The new OSL ages place the formation of the Fethard raised beach between 57 ± 6 ka and 45 ± 6 ka, with 53 ± 5 ka the most likely age if a single depositional event is assumed. This is consistent with OSL dates of the CFB elsewhere. A MIS 4-3 age has important implications in understanding the palaeogeography and timing of glaciation in Ireland, and requires a reassessment of regional relative sea level history. As the eustatic response to global ice volume resulted in lowered relative sea-level during MIS 4-2, a crustal response to glaciation is implied by the new dates.

Key words: raised beach; OSL; sea level; glacio-isostasy; Ireland.

INTRODUCTION

Along the southwestern and southern coasts of Ireland bordering the Celtic Sea, fragmentary raised beach deposits, known as the Courtmacsherry Formation (Wright and Muff 1904; Martin, 1930; Bryant, 1966; Farrington, 1966; Orme, 1966; Synge, 1981) overlie a glacially moulded rock platform at 2 m to 4 m OD (Hull, 1872; McCabe and Ó Cofaigh, 1996; Gallagher and Thorp, 1997; Ó Cofaigh *et al*., 2012). The Courtmacsherry Formation raised beach (CFB) is a critical element in the Quaternary stratigraphy of Ireland and its age has long been debated with interpretations ranging from penultimate interglacial, to last interglacial to the last deglacial. The only measured ages for its formation differ markedly. Gallagher and Thorp (1997) determined from infra-red stimulated luminescence that the raised beach at Fethard, County Wexford, formed at the eustatic sea level peak of the Last Interglacial (MIS 5e). Subsequently, using OSL, Ó Cofaigh *et al*. (2012) concluded that the CFB in Co. Cork was deposited in high relative (isostatic) sea level conditions during stadial to interstadial conditions in MIS 4-3. In this paper we present the results of new OSL age determinations carried out on the CFB at Fethard, with the aim of understanding better both its chronostratigraphic relationship to the other CFB deposits along the south coast of Ireland and its regional palaeoenvironmental context. The results have an important bearing on our understanding both of glaciation in the far south of Ireland and Pleistocene sea level change in the Celtic Sea region.

The marine platform and raised beach of southern Ireland

The CFB underlies a terrestrial sequence reflecting periglacial and direct glacial depositional environments. Only in Ballybunnion, Co. Kerry, do raised beach deposits overlie sediments indicative of glacial conditions predating the formation of the raised beach (Synge, 1981; Warren 1985). Around the west Cork and Kerry coast, as far north as Ballybunnion, periglacial breccia (the “main head” of Farrington, 1966) is generally uppermost in the sequence. However, to the east of the Old Head of Kinsale, the main head is truncated by spatially discrete diamictons interpreted as tills of inland provenance (the Garryvoe Formation, the Bannow Formation and the Ballyvoyle Till) and Irish Sea Basin provenance (the Ballycroneen Formation) (Farrington, 1966; Culleton, 1978; Warren, 1985; Evans and Ó Cofaigh, 2009; Ó Cofaigh et al., 2012). These glacial formations are often overlain by a final periglacial unit (the “upper head” of Farrington, 1966).

The raised beach deposits overlying the rock platform comprise up to 6 m of stacked, horizontal to gently seaward-dipping beds of variably oxidised and variably sorted and textured gravels and sands commonly terminated by a bed of well sorted, sand (Bryant, 1966; Farrington, 1966; Orme, 1966; Devoy, 1983; Gallagher and Thorp, 1997). The latter has been variably interpreted as aeolian or shallow-marine. Faunal remains are not found in the Courtmacsherry Formation raised beach sediments. Ó Cofaigh *et al*. (2012) interpreted sub-rounded to rounded gravels with rubbly interbeds of angular gravels resting on the bedrock platform in Co. Cork, at Howe’s Strand, Broadstrand and Courtmacsherry Bay, to have formed in the beachface environment, with phases of periglacial mass wasting in an arctic setting. Variably stratified and sorted sands overlying the beachface gravels were interpreted to represent shallow marine, storm-influenced depositional environments, representing a hemi-cycle of marine transgression followed by regression (Ó Cofaigh *et al*., 2012). The raised beach sands at these three exposures are sharply truncated by a sequence reflecting periglacial slope processes and direct glacial deposition. At Kilfenora, County Kerry, peat deposits lie between the raised beach and the overlying head (Mitchell, 1970; Heijnis *et al*, 1993). In places, *e.g.* Preghane Cove, County Cork (Farrington, 1966) and along Wood Village Beach near Fethard, the main head generally oversteps the raised beach and rests directly on the rock platform; wedge-shaped remnants of raised beach deposits remain intact under the head, however, where the raised beach was deposited against rocky backing cliffs.

The coastal exposure at Fethard reflects a similar sequence of depositional environments to those in Co. Cork described and dated by Ó Cofaigh *et al*. (2012). Overlying the eroded rock platform at altitudes of between 2.5 m and 3.9 m OD is a sequence of generally stratified, variably oxidised gravels and sands, in turn overlain by a geliflucted breccia capped by a diamicton, interpreted to be a bed of the Blackhall Member of the Bannow Formation Till (Culleton, 1976 and 1978). Gallagher and Thorp (1997) interpreted this succession at Fethard, involving three facies associations, to reflect a temporal transition from marine transgression to regression followed unconformably by periglacial and then glacial deposition.

Uranium-Thorium Disequilibrium (UTD) dating of peat underlying the Fenit Formation but overlying the Courtmacsherry Formation at Kilfenora, Co. Kerry, gave an age range of 123 ka to 114 ka (Heijnis *et al.*,1993); the dated peats were interpreted to represent the onset of cool conditions following the MIS 5e climatic optimum and eustatic sea level peak. Infrared stimulated luminescence (IRSL) dating of the Courtmacsherry Formation at Fethard, Co. Wexford by Gallagher and Thorp (1997), the first direct dating of the raised beach itself, indicated an age range of 161,785 ± 18,462 to 128,610 ± 16,795 years. The older date was interpreted as constraining the formation of a high tide run-up beach deposit, the younger a wind accretion beach deposit, representing peak eustatic sea level, predating the first appearance of interdigitating aeolian sands and periglacial breccia. These dates indicated that the Courtmacsherry Formation broadly bridged the MIS 6-5 boundary, but that its uppermost sands represented aeolian beach processes operating in MIS 5e, the peak of the Last Interglacial. Moreover, the Fethard dates (Gallagher and Thorp, 1997) indicated that the periglacial breccia and overlying tills belonged to periglacial and then glacial environments post-dating the Last Interglacial in Ireland. This was a significant finding, for the established morphostratigraphic framework of the Irish Pleistocene (Mitchell *et al*., 1973) required that all glacial deposits south of the Southern Irish End Moraine, including the deposits overlying the rock platform along the south coast, belonged to the Munsterian Glaciation. The Munsterian was inferred to be a separate cold stage predating the last (i.e. Midlandian) glaciation (MIS 4-2). In this way, the IRSL dates of the Courtmacsherry Formation at Fethard indicated that Warren's (1985) lithostratigraphic interpretation of the Pleistocene sequence along the south coast was broadly correct, especially his contention that the various tills and the periglacial Fenit Formation overlying the raised beach along the south coast belong to the last glacial (MIS 4-2). Both Warren's (1985) lithostratigraphy and the IRSL dates of Gallagher and Thorp (1997) cast doubt on the widely accepted morphostratigraphic concept in which the last Irish Ice Sheet terminated at a fully terrestrial margin, the Southern Irish End Moraine (Carvill-Lewis, 1914;

Charlesworth, 1928; Mitchell *et al*., 1973; Synge, 1979), leaving the far south of Ireland unglaciated during the last glaciation.

Optically stimulated luminescence (OSL) dating by Ó Cofaigh *et al*. (2012) of the CFB in Co. Cork, at Howe's Strand, Broadstrand and Courtmacsherry Bay, but not including the Fethard exposure, indicated deposition during MIS 4-3. Moreover, AMS radiocarbon dates on reworked shells from the 'Irish Sea Till' (i.e. the Ballycroneen Formation), and OSL dates of overlying outwash sediments dated these deposits to MIS 2 (Ó Cofaigh and Evans, 2007; Ó Cofaigh *et al*., 2012). Collectively, the dates of Gallagher and Thorp (1997) and Ó Cofaigh *et al*. (2012) confirm that the glacigenic deposits overlying the CFB along the south coast are of last glacial age and that most of southern Ireland as far as the Celtic Sea coast was glaciated during the LGM in MIS 2, severely undermining the SIEM concept and its associated chronological inferences. However, although the age of the glacigenic deposits along the south coast is well constrained by Ó Cofaigh *et al*. (2012), it remains to be determined if the MIS 6-5e age of the CFB at Fethard (Gallagher and Thorp, 1997), which was consistent with the inferred date for the Courtmacsherry Formation in Co. Kerry at Fenit (Heijnis *et al*., 1993), can be reconciled with the MIS 4-3 age reported by Ó Cofaigh *et al*. (2012) at CFB sites further west in Co. Cork. This paper reports new age determinations of the CFB at Fethard using OSL with the aim of resolving this chronostratigraphic problem and providing a better understanding the succession of sedimentary environments represented by the Pleistocene succession along the south coast of Ireland.

STUDY SITE AND METHODS

The study area and exposure

The Fethard exposure is located on Wood Village beach (NGR S804 063, W6°49'40" N52°12'25"), near Fethard On Sea, County Wexford (Fig. 1). The site is located in a low lying coastal plain dissected by deeply incised channels indicative of meltwater flowing towards the present coastline from areas inland (Culleton, 1978). The bedrock geology of the Fethard area is dominated by Devonian slates, shales and grits which are surrounded by Old Red Sandstone, Avonian shales (both Devonian) and Carboniferous limestone to the south, by Devonian volcanics and small intrusions of Ordovician Leinster granite to the north and by a complex assemblage of Pre-Cambrian to Cambrian gneisses, schists and metasediments and Carboniferous dolomites, limestones and conglomerates to the northeast and east (Culleton, 1978).

Optical Luminescence Dating methods

New samples for OSL dating were analysed at the Oxford Luminescence Dating Laboratory, using a Risø TL-DA-15 automated luminescence reader, using a single-aliquot regenerative (SAR) protocol (Murray and Wintle 2000, 2003) on quartz isolated from the samples. Samples were prepared in subdued lighting with initial treatment with 37% HCl and 30% H_2O_2 until the cessation of any reaction. Wet-sieving was used to isolate the 125-210 µm fraction, and heavy minerals were separated using sodium polytungstate flotation at 2.72 gcm^{-3}. The quartz grains were etched for 45 minutes with 40% HF to remove both the alpha-irradiated rind and feldspars. Samples for analysis were mounted onto steel discs with silicone oil using a 3 mm mask.

Analysis parameters included a 240°C preheat (selected following plateau test) with a 20 second pause before measurement of the natural signal at 130°C using blue LED stimulation. A test dose of 8.92 Gy was measured following a preheat at 220°C, and a post-IR blue measurement was used to test for feldspar contamination (Duller, 2003). Any aliquots failing feldspar contamination, recycling ratio and recuperation tests were excluded from further analysis, as were any saturated aliquots (defined by D_e > $2D_0$, where D_0 is the dose saturation of the exponential function used to fit the growth response curve). This resulted in the rejection of a total of eight out of 68 aliquots (Table 1). At least fifteen acceptable aliquots were used for each sample, and the Central Age Model (CAM) of Galbraith *et al*. (1999) was used to derive a single equivalent dose (D_e) for each sample. Dose recovery tests (DRTs) were used to test the applicability of the SAR protocol, and characterize the distribution of dose estimates under well-bleached conditions, using two 60 s room-temperature stimulations from blue LEDs with a 10000 second pause in between (Murray and Wintle, 2003). Four aliquots of each sample were given a known dose of 100 Gy after bleaching, and the overall mean recovery ratio (0.96 ± 0.06 by CAM and 1.01 ± 0.10 by arithmetic mean) suggests that the protocol is broadly working. However, there is also substantial scatter within the DRT results, suggesting that at least 22% overdispersion (*sensu* Galbraith *et al*., 1999) might be expected from experimental procedures alone.

Dosimetry was derived from in-situ field gamma spectrometry using a Canberra Inspector 1000™, with a 2” NaI detector. Dose rate conversion factors from Guérin et al. (2011) were used. Moisture content was assumed at 15 ± 5 %, giving a 95% confidence range of 5-25 %, which is typical of studies in similar sedimentary settings where moisture contents have been repeatedly measured (e.g. Derese *et al*. 2009, Jankowski *et al*. 2015). The cosmic contribution to dose rate was derived from the methods of Prescott and Hutton (1994).

RESULTS

Sedimentology

Pleistocene sediments are exposed along a coastal cliff up to *ca.* 20 m high running roughly northeast to southwest. The Pleistocene sediments rest on a rock platform, cut into the Devonian metasediments. The platform is generally low-lying, resting *ca.* 2.5 m OD (Malin Head Datum), but rises into two elevated rock spurs, lying 2.5 m to 3.9 m OD and sloping gently towards the east-southeast (Fig. 2). In places, the lower platform surface exhibits linear abrasions, elliptical scours and cross-sectionally asymmetric fractures of uncertain but possibly glacial origin (Dahl, 1965; McCabe and Ó Cofaigh, 1996). Three lithofacies associations are exposed at the site overlying the bedrock platform.

Lithofacies Association A (LFA A) – bedded sand and gravel

On the two elevated spurs of the rock platform, each ending abruptly against the bedrock cliff in a sharp notch, the bedrock is overlain by gently-dipping beds of sand and gravel which reach an altitude of 5 m OD and thickness of 2.5-3.0 m (Fig. 2, LFA A). Differences in the thickness of LFA A are due to it being overstepped by the breccia of Facies Association B where the rock platform is lowest. We now focus in detail on the sands and gravels of LFA A which is also the target of our OSL sampling and dating. LFA A is composed of four main facies (Fig. 3).

Much of the exposure described by Gallagher and Thorp in 1997 has been lost due to erosion but the general sedimentary sequence is still evident (Figs 4 and 5). The best remaining exposure shows a 0.25-0.4 m basal unit of coarse, rounded to angular fine to medium pebble gravels and cobbles in a poorly developed matrix of medium to coarse sand (F1). Overlying this are 0.25-0.45 m of planar to seaward dipping beds of fine to medium pebble gravels and occasional coarse blades, fining upwards to oxidised sands (F2), from which two samples were taken for dating in this study (Fet 12-3 and -4, Fig. 5). Above this is 0.15 m of medium to coarse gravels fining upwards to fine gravels and then 0.85 - 0.95 m of seaward dipping beds and laminae of medium sands alternating with thinly bedded, seaward dipping coarse sands and fine gravels (F3). Gallagher and Thorp (1997) obtained a date of 161,785 ±18,462 yr from coarse, horizontally laminated coarse sand and fine gravel at 3.4 m OD in this unit. F3 terminates in horizontally laminated sands, from which sample Fet12-1 was taken for this study (Fig. 5). At the top of LFA A, is up to 1.1 m of well sorted, massive to cross-laminated fine to medium sand with occasional fine gravel clasts (F4), which was dated by Gallagher and Thorp (1997) to 128,610 ±16,795 yr (their sample FOSL4, 4.4 m OD). Sample Fet12-2 was taken from this unit for this study. F4 also occurs in the cliff notch and within crevices and joints. The uppermost sands of F4 have been incorporated along with angular rock fragments into thin, moderately to steeply-dipping pseudo-beds at the base of Lithofacies Association B.

Lithofacies Association B (LFA B) – massive to crudely stratified clast-supported diamicton/breccia

LFA A is overlain by up to 10 m of red, clast-, to locally matrix-supported diamicton (LFA B). The diamicton ranges from massive to crudely stratified, and locally has the appearance of brecciated bedrock. Clasts within the diamicton are steeply dipping, predominantly angular, and the matrix, where present, is sandy. The lower contact with the underlying sand and gravel of LFA A is erosional, with the uppermost sands of LFA A being incorporated into the base of LFA B. In places the beds within the upper 1 m of LFA B are folded (Evans and Ó Cofaigh, 2008). In its lower part the sands of LFA A are partially incorporated into the diamicton of LFA B.

Lithofacies Association C (LFA C) – massive, matrix-supported diamicton

LFA B is overlain sharply by a massive to crudely-bedded, matrix-supported diamicton, up to 5 m thick, containing mainly local petrographies but also including clasts of Leinster granite, shales and sandstones. Gallagher and Thorp (1997) noted that the platform metasediments have been granitised along some fault planes in the rock but concluded that the greater silica content and angularity of clasts derived from these small intrusions make them clearly distinguishable from erratic clasts of the main Leinster granite.

Lithofacies Associations - Interpretation

Lithofacies Association A comprises a sequence of generally stratified, variably oxidised gravels and sands overlying the eroded rock platform. It is interpreted to be part of the CFB (Mitchell, 1962; Warren, 1985; Ó Cofaigh at al., 2012). The horizontal stratification, seaward dipping bedding and imbrication, sorting and alignment of gravel clasts within the sands are consistent with deposition in a beachface environment. Occasional angular local lithologies within LFA A may either reflect wave erosion of the platform or, alternatively, periglacial weathering and downslope mass-movement onto the beach and thus interbedding with the beach sediments (Fig. 2). This interbedding of angular local lithologies and in some locations units of 'head' preserved in the beach deposits is commonly observed in the Courtmacsherry Raised Beach Formation along the south coast of Ireland (Wright and Muff, 1904; Farrington, 1966; Ó Cofaigh *et al*., 2012).

Lithofacies Association B crops out consistently along the south coast of Ireland and has been discussed in numerous publications stretching back over a century.It is interpreted as a periglacial slope deposit (e.g., Wright and Muff, 1904; Farrington, 1966; Synge, 1978; Warren 1985). The characteristics of LFA B at Fethard, namely the clast-supported diamicton to breccia, the dominance of angular clasts of local lithology and its frequently crudely bedded appearance are consistent with this previous interpretation.

Lithofacies Association C is interpreted as a subglacial till on the basis of its massive, matrix-supported character, the sharp basal contact, folding of the underlying periglacial head deposits, and presence of erratic clasts (Leinster granites) (Culleton, 1976, 1978; Evans and Ó Cofaigh, 2008).

Chronology - Field Sampling

Four samples for optical dating were taken from cleaned sections within the sequence, in light-tight plastic or steel tubing, dependent on the degree of induration of the sediment. Field dosimetry was conducted with a portable gamma spectrometer in the holes left by the sample tubes. All samples were taken from LFA A, the CFB deposits. One sample (Fet12-2) was taken from the uppermost sands of F4, one (Fet 12-1) from the laminated sands of F3 and two (Fet12-3 and Fet12-4) from the indurated upper sands of F2.

Ages

The results from the OSL dating at Fethard are presented in Table 1 and Fig. 6 and example shinedown curves, dose response and dose distributions are shown in Fig. 7. The luminescence response of the samples, in general, was relatively dim, and three of the four samples (Fet 12-1, Fet12-2 and Fet12-4) show substantial (> 30%) overdispersion, implying that dispersal of the D_e estimates is not solely due to the uncertainties of individual estimates. The undisturbed bedding within F2 and F3 suggests that bioturbation is unlikely in these sediments. Partial bleaching cannot be categorically ruled out, although Fet12-3 has an overdispersion value consistent with well-bleached sediment (16%) and is well within the range which has been demonstrated by the dose recovery tests as inherent for these samples. This suggests that, at the very least, deposition of the sands within F2 occurred under well-bleached conditions, in keeping with studies which have shown that modern beach sands tend to have low residual quartz OSL signals (e.g. Sommerville *et al.* 2001; Singarayer *et al*., 2005). In the high Arctic, quartz beach sands in a glacier-proximal setting (ice margins within ~500 m) have shown negligible residual OSL signals (Alexanderson and Murray, 2011), except immediately adjacent (< 100 m) to the ice margins, where maximum residuals of ~12 Gy were identified. Even this would represent only a ~10% overestimation on the ages presented in this study, which would not substantially alter the interpretations. Moreover, partial bleaching of these samples would result in age over-estimation; as the subsequent discussion shows, this would be highly problematic from a geomorphological perspective due to the characteristics of sea-level during the peak of the last glacial. The presence of clasts and differing petrographies within both units, however, is very likely and would lead to heterogeneity within the beta dose environment, which may well account for the observed scatter in the data. In the light of this, the use of a central age estimate for D_e estimation seems most justified. The ages of 45 ± 6 ka and 56 ± 8 ka for the upper sands (units F3 and F4) lie just within unity at one sigma and are broadly consistent with the ages for the lower unit F2 of 55 ± 5 ka and 57 ± 6 ka. If near-synchronous deposition (within the multi-millennial margins of uncertainty indicated) is assumed, it is possible to construct a single age for the deposition of the Fethard raised beach by deriving age estimates for each aliquot, and then using the CAM to derive a most probable deposition age, assuming a single construction event for the beach (at the millennial scale that the resolution of the methodology employed here permits). This results in a single CAM age of 53 ± 5 ka for the Fethard raised beach.

DISCUSSION

The age, stratigraphic position and palaeoenvironmental context of the raised beach at Fethard

The new age estimates of the Fethard exposure require a reassessment of the ages presented by Gallagher and Thorp (1997). The original age estimates (MIS 6-5) were derived from the Infrared Stimulated Luminescence (IRSL) signal from potassium feldspars, using a single aliquot additive dose protocol. It is unclear whether any fading testing and/or correction was applied. Despite repeat aliquots demonstrating fair coherence in establishing the D_e, Gallagher and Thorp (1997) noted that the feldspar IRSL signal may not have been adequately bleached at the time of deposition, and thus their ages may have been overestimates. Similar overestimates have been reported from other studies in which sites have been investigated using both feldspar IRSL and quartz OSL (e.g. Hansen *et al*., 1999; Alexanderson *et al*., 2008), and are typically attributed to the slower bleaching of the feldspar IRSL signal in comparison to the quartz OSL signal (Godfrey-Smith *et al*., 1988; Fuchs *et al*., 2005).

The Fethard raised beach was deposited within the interval from 57 ± 6 ka to 45 ± 6 ka, with a most likely central date of 53 ± 5 ka, in the MIS 4-3 interval, an age range consistent with dates for the CFB further west in Co. Cork (Ó Cofaigh *et al*., 2012) (Table 2). The periglacial deposits and till overlying the raised beach at Fethard are thus of MIS 3 or MIS 2 age. All Pleistocene deposits above the Courtmacsherry Formation between Co. Wexford and Co. Cork (Ó Cofaigh *et al*., 2012) therefore belong to the last glacial cycle, and post-date MIS 5. By inference, southern Ireland was glaciated during the last glaciation and the concept of LGM ice terminating at the SIEM, leaving the far south of Ireland unglaciated during the LGM, is no longer tenable (cf. Warren, 1985; Gallagher and Thorp, 1997; Ó Cofaigh and Evans 2001, 2007; Ballantyne, 2010; Ó Cofaigh *et al*., 2012).

Although the CFB was deposited in MIS 4-3, the relatively poor precision of the dates means that it cannot be determined whether these dates indicate that the CFB relates to a single formation event or to several. However, the coherence between the dates does imply that the entire south coast of Ireland experienced an episode(s) of sufficient isostatic depression to allow a local positive relative sea level, peaking at ca. +5 m OD, during an interval in which glacio-eustatic sea level was consistently below present (see Siddall *et al*., 2008).

An extensive record of iceberg production, in the form of ice rafted debris (IRD), from the calving margins of ice sheets originating in western Scotland and in Ireland provides the best regional timescale of glacial and deglacial events and allows a wider contextualisation of those events with external forcing functions (Scourse et al., 2009; Haapaniemi *et al*., 2010). To the northwest of Ireland, ocean core records from the Barra–Donegal Fan record IRD production from ca. 57 ka (MIS 4) until deglaciation in MIS 2 (Scourse *et al*., 2009). Before ca. 30 ka, the record is dominated by iceberg calving from ice margins that terminated on the inner continental shelf. After 30 ka, dominantly coarse lithic IRD reflects a calving ice front that was located at the continental shelf break. To the west and southwest of Ireland, in the Porcupine Sea Bight region, pulses of IRD delivery are recorded between ca. 57 ka and 48 ka, with continuous IRD production from 48 ka until deglaciation in MIS 2 (Scourse *et al*., 2009). Overall, the IRD record points to the development of a small ice sheet in western Scotland by 59 ka, during Heinrich Event 6 (H6) and its continuous presence from 46 ka until full deglaciation in MIS 2. Between 60 ka and 30 ka a strong millennial-frequency in IRD from western Scotland reflects the development of a significant glacimarine margin around Scotland. The IRD record points to extensive ice on the continental shelf west of Scotland by 40 ka with high relative sea level, moderate isostatic depression and moderately high glacio-eustatic sea level forcing strongly coupled behaviour (i.e. forcing and feedbacks) between the ice sheet and the North Atlantic climate system and sea level. A similar pattern is recorded on the western Irish margin where IRD records from the Porcupine Sea Bight and Barra-Donegal Fan indicate regional ice cover in Ireland, during the central age range of of 53 ± 7 ka for the Fethard raised beach and a continuous IRD flux originating on the Irish land mass beginning ca. 46 ka (Scourse *et al*., 2009).

In the MIS 4-3 transition, glacio-eustatic sea level rose by 20-40 m from a lowstand at ca. -90 to -80 m (Siddall *et al*. 2008). The MIS 4 -3 sea level transition occurred between 60 ka and 57 ka (SPECMAP modelling suggests 59 ka), with an initial sea level rise to ca. - 60 m for the first half of MIS 3 but then a fall to -80 m for the remainder. Superimposed on this broad trend are four sea level fluctuations of between 20 m and 30 m magnitude during MIS 3 (Siddall *et al*., 2008; Shackleton *et al*., 2000). These enhanced sea-level rises are associated with the end of Heinrich events, occurring at the transitions between stadial and interstadial conditions, and are consistent with the timing of the IRD maxima around the eastern Atlantic Ocean (Sierro *et al*., 2009). So, it is clear that several sea level excursions occurred in the MIS 4-3 interval when the Courtmacsherry Raised Beach was deposited. None of these was of sufficient magnitude to allow a fully glacio-eustatic explanantion for formation of the Fethard raised beach in the time interval indicated by the new dates. However, given that glaciation on Ireland was persistent during MIS4-3 (e.g. Scourse *et al*., 2009), it is probable that glacio-isostatic crustal depression played an important role in determining regional relative sea level. With glacio-eustatic sea level peaking between -40 m and -70 m in the MIS 4-3 transition and through the first half of MIS 3 (Siddall *et al*., 2008), an isostatic depression of 45 m to 75 m would have been required to attain a relative sea level of +5 m, the maximum altitude of the Fethard raised beach. However, if the raised beach was associated with the end of a Heinrich Event, in which glacio-eustatic sea level rose an extra 20-30 m above the background level (Siddall *et al*., 2008), an isostatic depression of only 45-35 m could account for the elevation of the raised beach. Moreover, the sea level reconstructions for this period typically have uncertainties of the order of ±30 m, so it is possible that the adjustment necessary could be considerably less. Given that the IRD evidence indicates regional ice coverage within the time interval in which the Fethard raised beach was deposited, glacio-isostatic depression in that period is probable (although as yet unquantifiable) and, therefore, a MIS 4-3 raised beach a reasonable consequence. This interpretation, if correct, points to considerable gaps in our knowledge of the mechanisms, timing and amplitude of crustal response to glaciation in Ireland.

For the period from 32 ka (approximately the MIS 3-2 transition) to the local last glacial maximum ~22 ka (MIS 2), Bradley *et al*. (2009) and Brooks *et al*. (2011) inferred ice thickness of ~125 m increasing to 200-250 m along the south coast of Ireland, thinning rapidly to ~125 m immediately after the local last glacial maximum. Using a 3.6:1 ratio of ice thickness to isostatic depression as a broad guide (from simple buoyancy relations between glacial ice of density 0.9 g cm^{-3} and a mantle density of 3.3 g cm^{-3}), the 35-45 m of crustal depression inferred for the formation of the Fethard raised beach equates to an estimated ice thickness over the region of 128-165 m. For the MIS 4-3 interval represented by the raised beach, these estimates imply the presence of an ice sheet intermediate in thickness between that of the local last glacial maximum and both the MIS 3-2 transition and the immediate post-glacial maximum. The submerged glacimarine limit represented by arcuate clastic landforms (moraines) on the seabed at -60 m, south-southwest of Fethard (Gallagher *et al*., 2004), if deposited during minimum glacio-eustatic sea at -130 m in MIS 2 (Lambeck, 1993a, 1993b), implies up to 70 m of glacio-isostatic crustal depression by ice ~257 m thick. If the submerged margin formed after the local glacial maximum, when ice had thinned to only 125 m, glacio-isostatic crustal depression could have been only ~34m. Thus, the presence of the submerged moraines brackets crustal depression to between ~70 m and ~34 m, in reasonable agreement with the models of Bradley *et al*. (2009) and Brooks *et al*. (2011). However, changes in ice thickess due to ice-dynamical considerations (e.g. from marine drawdown due to ice streaming) are not considered in these estimates.

Conservative conclusions from these estimates of glacio-isostatic adjustment, together with the new dates, are that the Fethard raised beach formed on a shoreline depressed by ice up to ~165 m thick during MIS 4-3, with subsequent significant glacial thinning in MIS 3 (> ⅓ loss), before regrowth to maximum thickness, and a terminus on the continental shelf south of the present coastline, in MIS 2. Moreover, the age and sedimentology of CFB (Wright and Muff, 1904), indicate that it was deposited in cold conditions in MIS 4-3 (O'Cofaigh *et al*., 2012), by implication along a coastline still under the influence of calving glaciers.

This accords with the inference of Bates *et al*. (2003) that, along the English Channel, raised beach deposits containing erratics were deposited during high sea levels at the end of cold stages.

Gallagher and Thorp (1997) concluded that both the restricted altitudinal range of the CFB and the coherent sequence of facies overlying it along the south coast of Ireland implied a spatial uniformity of environment that is unlikely to be the product of sedimentation into a series of isolated, glacially enclosed bays. Similarly, if sedimentation had been in glacio-isostically enclosed basins, the restricted altitude of the CFB along the south coast would require an extremely uniform crustal response over *ca.* 200 km of geologically and glaciologically variable coastline. Instead, the CFB most probably reflects high relative sea level forced by a *combination* of glacio-isostatic depression resulting from ice sheet growth in MIS 4 (Scourse *et al*., 2009; Ó Cofaigh *et al*., 2012) and the increased contribution of glacio-eustatic sea level occurring in the first half of MIS 3 (Siddall, 2008). This conclusion suggests that the retreat of marine-terminating Irish ice was at a rate that, at least initially, out-paced regional isostatic recovery, perhaps pointing to different response times and lags within the marine, cryospheric and lithospheric systems. If the CFB was deposited between MIS 4 and early MIS 3, during the glacio-eustatic high stand (Siddall, 2008), the beach deposits would have been abandoned in the glacio-eustatic fall in sea level characterising the second half of MIS 3, the preserved and dated exposures having been opportunistically protected from glacial erosion by a combination of rocky backing cliffs and the overlying periglacial breccia (Gallagher and Thorp, 1997). The regional occurrence of the periglacial breccia, either overlying and interdigitating with raised beach deposits spanning the transition between MIS 4-3, or deposited early in MIS 3, is consistent with a palaeoenvironmental event in which both temperature and glacio-eustatic sea level peaked at onset and then declined consistently afterward until glaciation became re-established.

CONCLUSIONS

- Bedded gravels and sands resting on a raised marine rock platform at Fethard, Co. Wexford, south Ireland are interpreted as raised beach deposits and form part of the Courtmacsherry Pleistocene raised beach that has been documented at numerous sites along the south coast of Ireland.
- OSL dating of the Fethard raised beach yielded ages from 57 ± 6 ka to 45 ± 6 ka, with a central age of 53 ± 5 ka considered the most likely time of deposition. This is consistent with recent OSL dates of MIS 4-3 for the CFB at other sites along the south coast of Ireland (O'Cofaigh *et al*., 2012).
- Collectively OSL dates on the CFB along the south coast of Ireland indicate that it formed during a period(s) or high relative sea level during MIS 4-3. The CFB is therefore not an interglacial raised beach as has been previously proposed. This is consistent with the last glaciation of southern Ireland occurring during MIS 2 and with the Southern Ireland End Moraine representing a recessional position rather than the maximum limit of the last ice sheet in Ireland.
- An MIS 4-3 age for the CFB in southern Ireland implies that the south coast experienced an episode(s) of sufficient glacio-isostatic depression to allow a local positive relative sea level, peaking at ca. +5 m OD, during an

interval in which glacio-eustatic sea level was consistently below present. This in turns implies the presence of an Irish Ice Sheet by the time of MIS 4, an interpretation consistent with the deep sea record of ice-rafted debris from around Ireland and Britain.

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Figure Captions

Figure 1. The location of the exposure of the Courtmacsherry Raised Beach near Fethard, southeast Ireland.

Figure 2. Lithofacies Association (LFA) A - the raised beach overlying the marine platform extends vertically from the solid to the dotted lines but is not uniformly preserved. Note the coarse, angular to sub-angular clasts at the base of the raised beach sediments (examples arrowed) and the smoothed planar (a), to undulatory (b) surface of the platform exposed beneath the raised beach. The platform and raised beach continue in a notch behind the small promontory indicated by the dased line.

Figure 3. Composite vertical log of the exposure in 2012. Because the absolute height of the platform surface varies, heights shown in the log are relative.

Figure 4. Facies units F1-F4 comprising the Courtmacsherry Raised Beach near Fethard. The graphic scale is is 1.0m long in 0.1 m increments.

Figure 5. Detail of units F1, F2 and F3 and locations of samples (Fet 12-4 with gamma spectrometer inserted). For scale, the trowel is 0.3 m long.

Figure 6. The results from the OSL dating at Fethard in their straigraphic context.

Figure 7. Quartz OSL characteristic of representative aliquots of the samples from Fethard, comprising: a) OSL decay curves are typified by rapid signal depletion associated with dominance of the quartz fast component. This aliquot is brighter than many analysed. b) A typical dose response curve with a single saturating exponential fit. The vast majority of aliquots have D_e estimates below $2D_0$, and the few that failed this test were rejected from further analysis. c) and d) Dose distributions for samples Fet12-1 and Fet12-4, revealing moderately overdispersed but broadly symmetrical spread in the data.

Tables

Sample details		Dosimetry*					D_e analysis			
Sample code	Lab code	K (%)	U (ppm)	Th (ppm)	Cosmic dose rate (Gy/ka)	Total dose rate (Gy/ka)	Aliquots**	D_e (Gy)	Over-dispersion (sigma, %)	Age (ka)
Fet12-1	OxL-2272	1.36 ± 0.07	1.57 ± 0.16	4.77 ± 0.48	0.14 ± 0.011	1.843 ± 0.136	15/15	83.26 ± 8.23	37	45.2 ± 5.6
Fet12-2	OxL-2273	1.28 ± 0.06	0.87 ± 0.09	3.74 ± 0.37	0.164 ± 0.015	1.604 ± 0.120	15/17	89.51 ± 10.11	42	55.8 ± 7.6
Fet12-3	OxL-2274	1.35 ± 0.07	1.64 ± 0.16	4.35 ± 0.44	0.123 ± 0.009	1.808 ± 0.136	15/18	99.19 ± 5.19	16	54.9 ± 5.2
Fet12-4	OxL-2275	1.36 ± 0.07	3.21 ± 0.32	4.54 ± 0.45	0.123 ± 0.009	2.136 ± 0.162	15/18	121.63 ± 10.2	31	57.0 ± 6.4

*Assumed moisture content all samples 15 ± 5%
**Aliquots accepted / analysed

Table 1.

Courtmacsherry Bay*	Howes Strand*	Broad Strand*	Fethard**
62.5 ± 16.3 (45.1 ± 9)	56.7 ± 12.2	77.3 ± 11.8	55.8 ± 7.6 (F4; Fet 12-2)
44.0 ± 7.6 (100.8 ± 17.4)	56.7 ± 9.8	66.2 ± 15.4	45.2 ± 5.6 (F3; Fet12-1)
36.1 ± 7.9 (59.6 ± 9.6)	61.2 ± 9.5	63.4 ± 15.8	54.9 ± 5.2 (F2; Fet 12-3)
67.1 ± 11.9 (71.5 ± 11.8)	59.8 ± 12.2	68.5 ± 13.8	57.0 ± 6.4 (F2; Fet 12-4)
54.8 ± 11	53.1 ± 7.4		
70.8 ± 13.2			

* Ó Cofaigh et al., 2012
**This paper

Table 2.

Table Captions

Table 1. The results of the OSL analysis.

Table 2. OSL ages (ka) of dated exposures of the Courtmacsherry Formation. For each site, ages are given in stratigraphic sequence. For the Fethard ages, the facies units and sample names within LFA A are indicated in parentheses. For Courtmacsherry Bay, ages in parentheses refer to single grain analyses (O'Cofaigh et al., 2012).

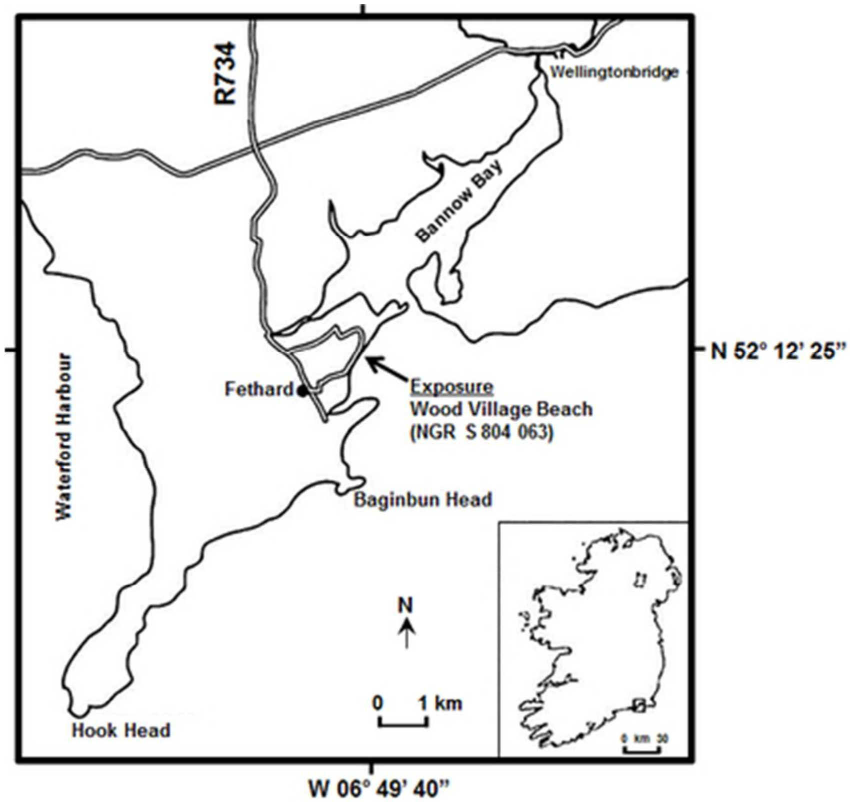


Figure 1. The location of the exposure of the Courtmacsherry Raised Beach near Fethard, southeast Ireland.
18x17mm (600 x 600 DPI)

Figure 2. Lithofacies Association (LFA) A - the raised beach overlying the marine platform extends vertically from the solid to the dotted lines but is not uniformly preserved. Note the coarse, angular to sub-angular clasts at the base of the raised beach sediments (examples arrowed) and the smoothed planar (a), to undulatory (b) surface of the platform exposed beneath the raised beach. The platform and raised beach continue in a notch behind the small promontory indicated by the dased line.
36x27mm (300 x 300 DPI)

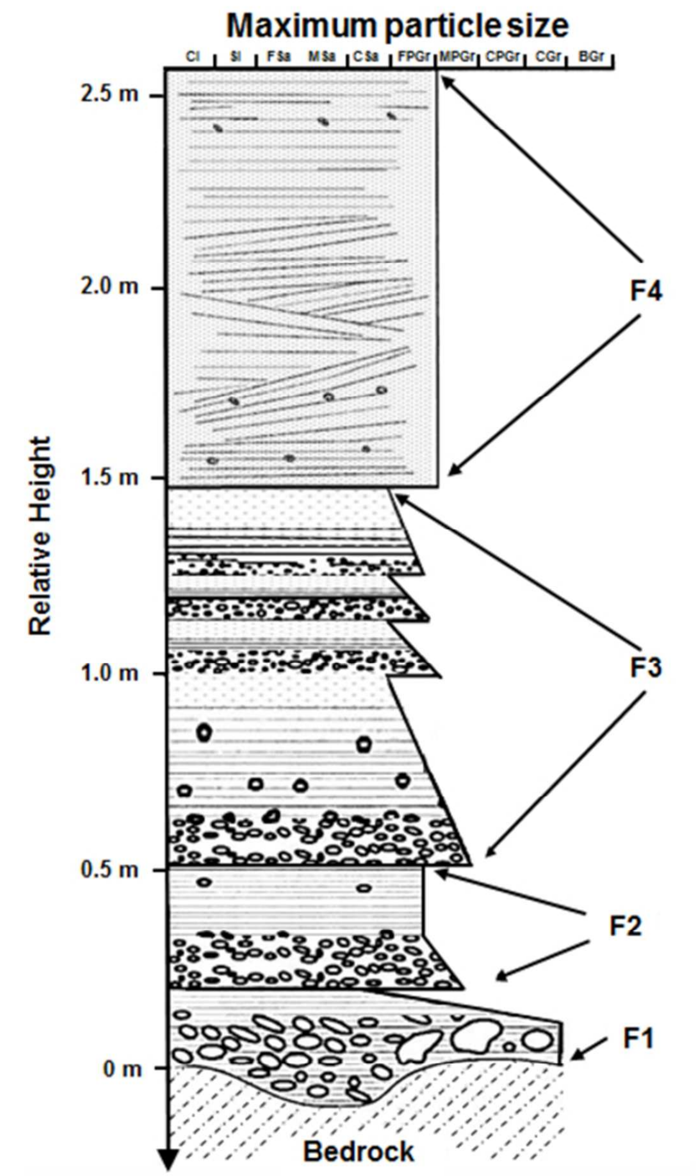


Figure 3. Composite vertical log of the exposure in 2012. Because the absolute height of the platform surface varies, heights shown in the log are relative.
22x34mm (600 x 600 DPI)

Figure 4. Facies units F1-F4 comprising the Courtmacsherry Raised Beach near Fethard. The graphic scale is is 1.0m long in 0.1 m increments.
36x27mm (300 x 300 DPI)

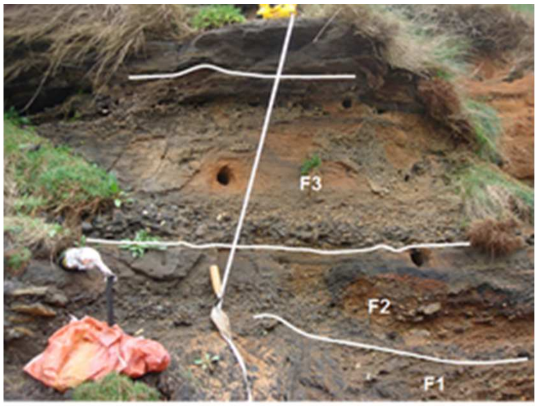
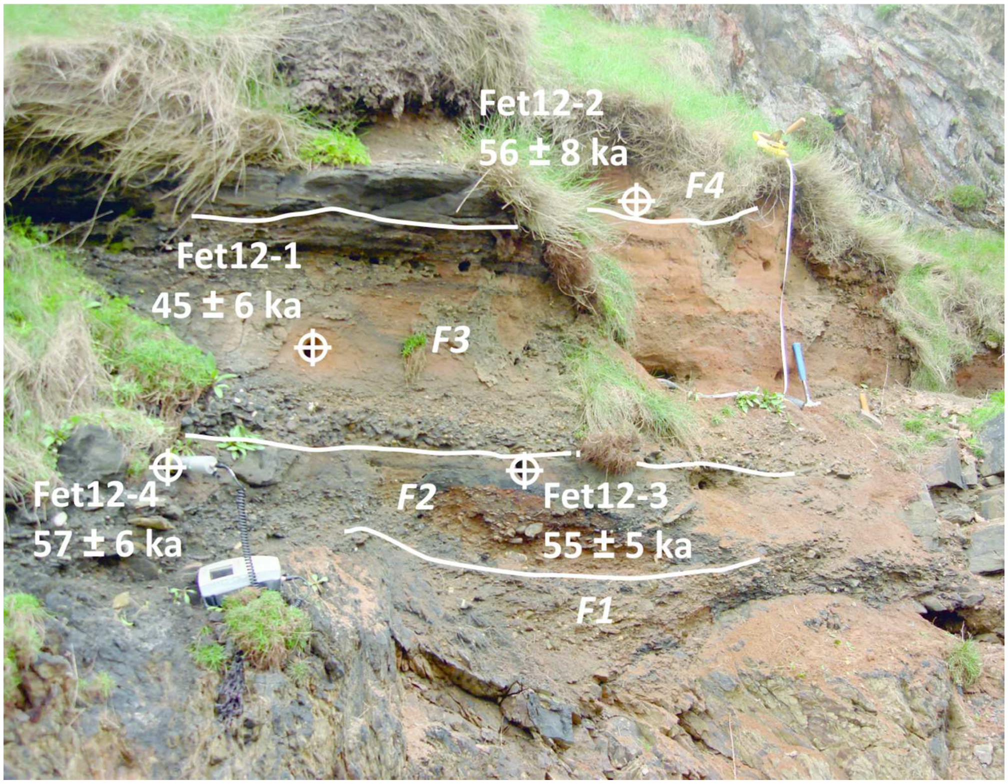
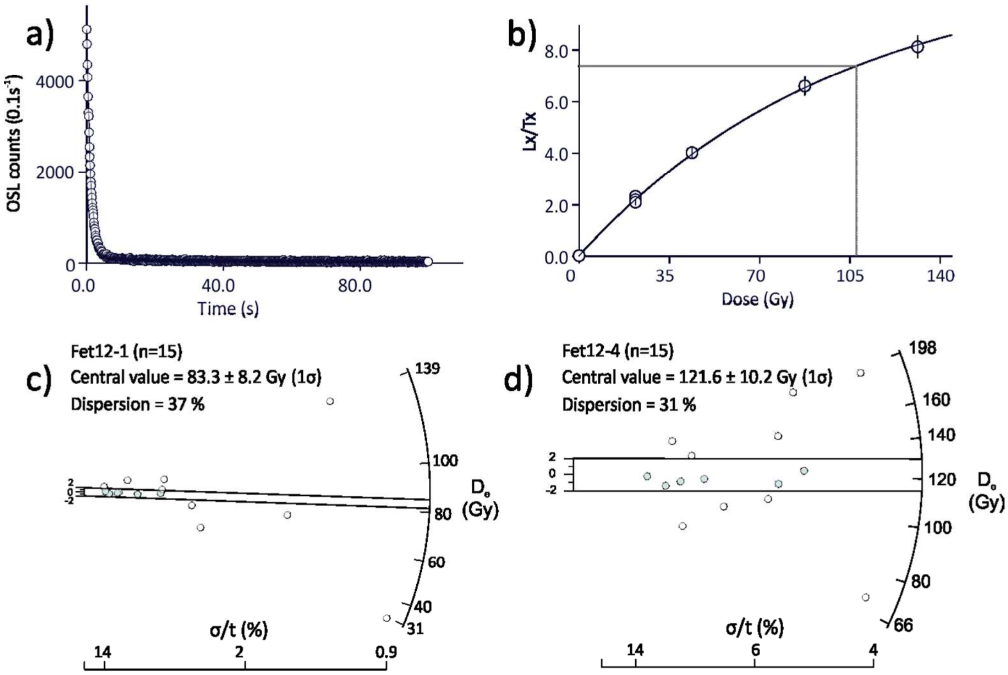


Figure 5. Detail of units F1, F2 and F3 and locations of samples (Fet 12-4 with gamma spectrometer inserted). For scale, the trowel is 0.3 m long.
22x17mm (300 x 300 DPI)



117x91mm (300 x 300 DPI)



116x125mm (300 x 300 DPI)