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Relative sea-level change and evidence for the Holocene Storegga Slide tsunami from a high-energy coastal environment: Cocklemill Burn, Fife, Scotland, UK

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Abstract

A site in the Cocklemill Burn valley on the north shore of the Firth of Forth, Scotland, provides evidence of relative sea-level changes during the Holocene from ca. 7970 to ca. 5090 radiocarbon years BP, and of the Holocene Storegga Slide tsunami dated here as having taken place after ca. 7215 radiocarbon years BP. Marine sediments associated with two shorelines widely present in mainland Scotland, the Main Postglacial Shoreline and the Blairdrummond Shoreline, are recorded. The Holocene Storegga Slide tsunami deposits are unique here in the record of such sediments in eastern Scotland, in that they occur within marine sands, of which the upper horizons are intertidal sandflat deposits. The tsunami deposits probably accumulated shortly after a period of accelerated relative sea-level rise, the pattern and timing of which could have played a role in triggering the Holocene Storegga Slide.
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1. Introduction

In recent years, studies of relative sea-level change in NW Europe have concentrated upon low-energy environments, where sequences of marine and terrestrial sediments provide detailed evidence of coastal and relative sea-level changes, and where, in Scotland in particular, evidence of the Holocene Storegga Slide tsunami is frequently preserved. Open coastal environments are commonly not seen as providing comparably detailed evidence, yet the lack of information from such areas may compromise any detailed understanding of such events. In this paper an open coastal environment of relatively high-energy reveals surprisingly detailed information on both relative sea-level changes and an extreme coastal flooding event.

The area of investigation lies in SE Scotland on the north shore of the Firth of Forth along the lower reaches of a small stream, the Cocklemill Burn (Fig. 1). The surrounding area has long attracted sea-level investigations. Geikie (1902) summarised the evidence for relative sea-level changes and land uplift here, and observed that "the finest group of rock shelves (raised beaches) in the whole district is that which has been cut by the sea along the west and north fronts of Kincraig Hill". North of Kincraig Hill, he described a broad terrace of raised beach deposits made up of clays, sands and gravels. This terrace has been incised by the Cocklemill Burn, which rises on the eastern flank of Largo Law. The stream flows first east, then southeast through a deeply incised channel west of Pitcorthie House (UK National Grid Reference NO488041) then south and south–west through an extensive area of Late Devensian fluvioglacial and raised marine deposits associated with the last ice sheet and its limits (the Perth Stage Ice Limit and Loch Lomond Readvance Limit shown on Fig. 1) and the stages of deglaciation (Cullingford and Smith, 1966, 1980), before reaching the shores of Largo Bay. Around the bay, widespread coastal sand dunes overlie the raised Holocene marine deposits. Along the lower course of the burn, exposures

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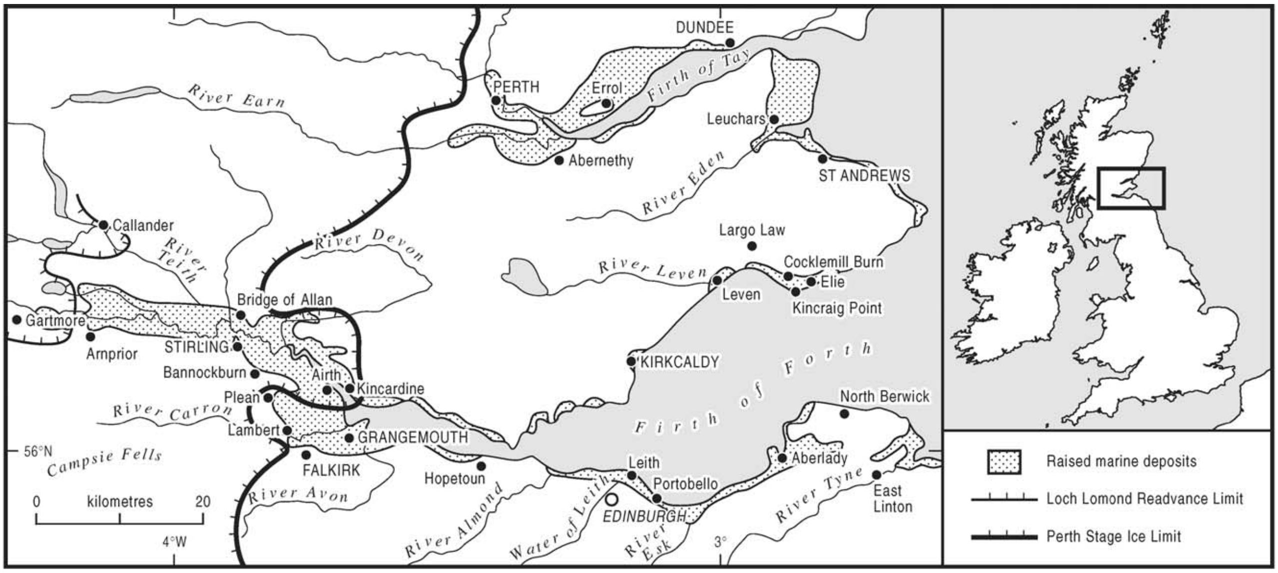

Fig. 1. A map of the Firth of Forth showing the location of the site north of Kincraig Point on the north shore of the Firth, the distribution of raised marine terraces adjacent to the Firths of Forth and Tay in relation to two Late Devensian ice limits: the Perth Stage and the Younger Dryas (Loch Lomond) Readvance. Modified after Sissons et al. (1966).

of up to 7 m, first described in the nineteenth century (e.g. Brown, 1867, see below) and still visible today disclose, beneath blown sand, detailed sequences of sediments from which inferences can be made about Holocene relative sea-level changes in the area.

2. Previous work

Early work in the area reflected conflicting evidence of both positive and negative movements of relative sea level. Thus, Fleming (1830) remarked upon the evidence of lower sea levels indicated by the presence of a "submerged forest" in Largo Bay; whilst Hamilton (1835) commented that beds of shells on Ruddons Point, south–west of the mouth of the Cocklemill Burn (Fig. 2), indicated that the land in the area had been uplifted. A particularly comprehensive study was undertaken by Brown (1867). From exposures along the Cocklemill Burn and at sites east of the area, Brown recorded a shelly clay overlain by peat, in turn overlain by sand and shells with blown sand at the surface. He concluded that the basal clay had been laid down in an "arctic" sea; that an uplift of the land had occurred allowing peat to accumulate; and that a marine transgression had occurred subsequently with the deposition of the sand and shells before the land had again been uplifted and coastal dunes had developed. Subsequent work by Etheridge (1881) and Bell (1890, 1892) supported Brown's observations. The evidence of these authors was summarised and further elaborated by Geikie (1900, 1902), exemplified by the quotation above. Forsyth and Chisholm (1977) remarked on the evidence, but added little new information on the marine sediments and stratigraphy in the area. The sedimentary record, history of sea-level changes and evidence for the Holocene Storegga Slide tsunami in the area were discussed in Tooley et al. (2003).

3. Methodology and techniques

The geomorphology of the area was mapped at a scale of 1:10,000, following the approach of Smith (e.g. Smith et al., 1992), and the terrace features are shown in Fig. 2. The altitudes of stratigraphical horizons in section, of boreholes, and of the highest points (generally the inner margins), of terraces, were levelled instrumentally from benchmarks related to Ordnance Datum Newlyn (OD), the UK levelling datum, and where appropriate were converted to mean high water spring tides (MHWS) from Admiralty Tide Tables (1996). Samples for laboratory analyses were collected from exposures using monolith tins and from boreholes using both a Stitz percussion sampler (Merkt and Streif, 1970) and a Dacknowski sampler (Tooley, 1981), with stratigraphic records compiled from a free face excavation and using an Eijkelkamp gouge sampler below the water table. Particle size analysis was undertaken using a Malvern 2600 laser granulometer for particles less than 1000 μm diameter and by sieving for larger particles. Pollen analysis was undertaken following routine procedures. Molluscs were identified by Professor D.H. Keen, and a list is provided in Appendix A and Table 3. Radiocarbon dating was undertaken by Beta Analytic Inc., and all dates quoted in the text are expressed in

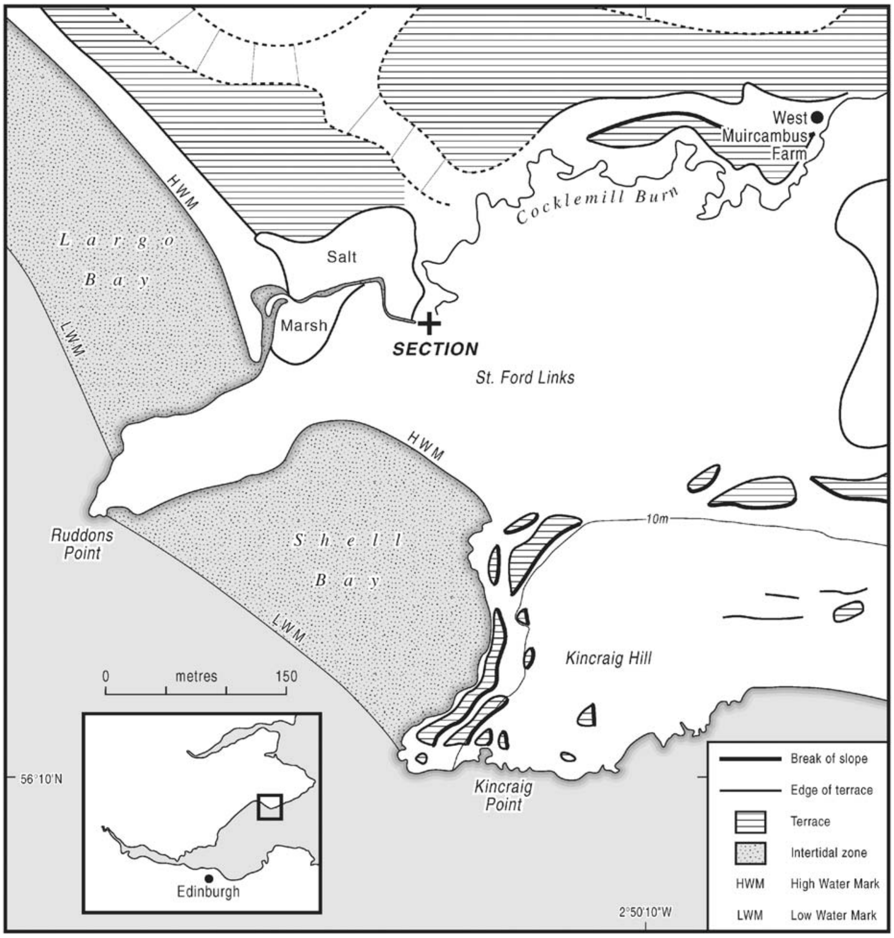

Fig. 2. A map showing the location of the section in the context of marine terraces on Kincraig Point and east of Largo Bay.

radiocarbon years BP (equivalent calibrated ages for the dates obtained in this study are given in Table 2). Latitude and longitude of the site were established using a Magellan GPS 310.

4. Geomorphology

The lower reaches of the Cocklemill Burn west of West Muircambus Farm (Fig. 2) are surrounded by a gently undulating surface of aeolian sand, known as St. Ford Links. In exposures along the burn, the blown sand is up to ca. 2 m thick and forms a surface with altitudes up to +10 m OD, although on average it is ca. +7.5 m OD. The blown sand lies above mainly horizontally bedded sand with fine gravel and horizons of shells (see below). To the south of the area, the sand and fine gravel form a terrace measured at 6.2–6.9 m over a distance of 200 m along the western flanks of Kincraig Hill, where at higher elevations (+45, +24.5 and +22 m OD) several Late Devensian terraces recorded by Cullingford and Smith (1966) predate the Main Perth Shoreline and Perth Stage Ice Limit (Fig. 1). On Kincraig Point, a lower terrace at 3.7–4.0 m also occurs (Fig. 2). The origins of this latter feature are uncertain, and it is cut at least partially in rock.

5. Site stratigraphy and environmental changes

The sediments examined in detail in this paper are exposed in sections exposed along the left bank of the Cocklemill Burn between West Muircambus Farm and Largo Bay. These sections were first visited by the authors in 1995 and shell samples taken for radiocarbon assay. The samples yielded ages that ranged from 7140 to 4100 years BP (Vita-Finzi, personal communication) and placed the exposed sediment sequence as having accumulated during and following the Main Postglacial Transgression, at the time of the Main Postglacial Shoreline (Sissons, 1974) and the later Blairdrummond Shoreline (Smith et al., 2000) in mainland Scotland.

The section examined in detail in this paper is shown in Fig. 3 and described in Table 1. The sedimentary record is based upon a vertical face (0–520 cm) and gouge and piston core samples taken at the base of this

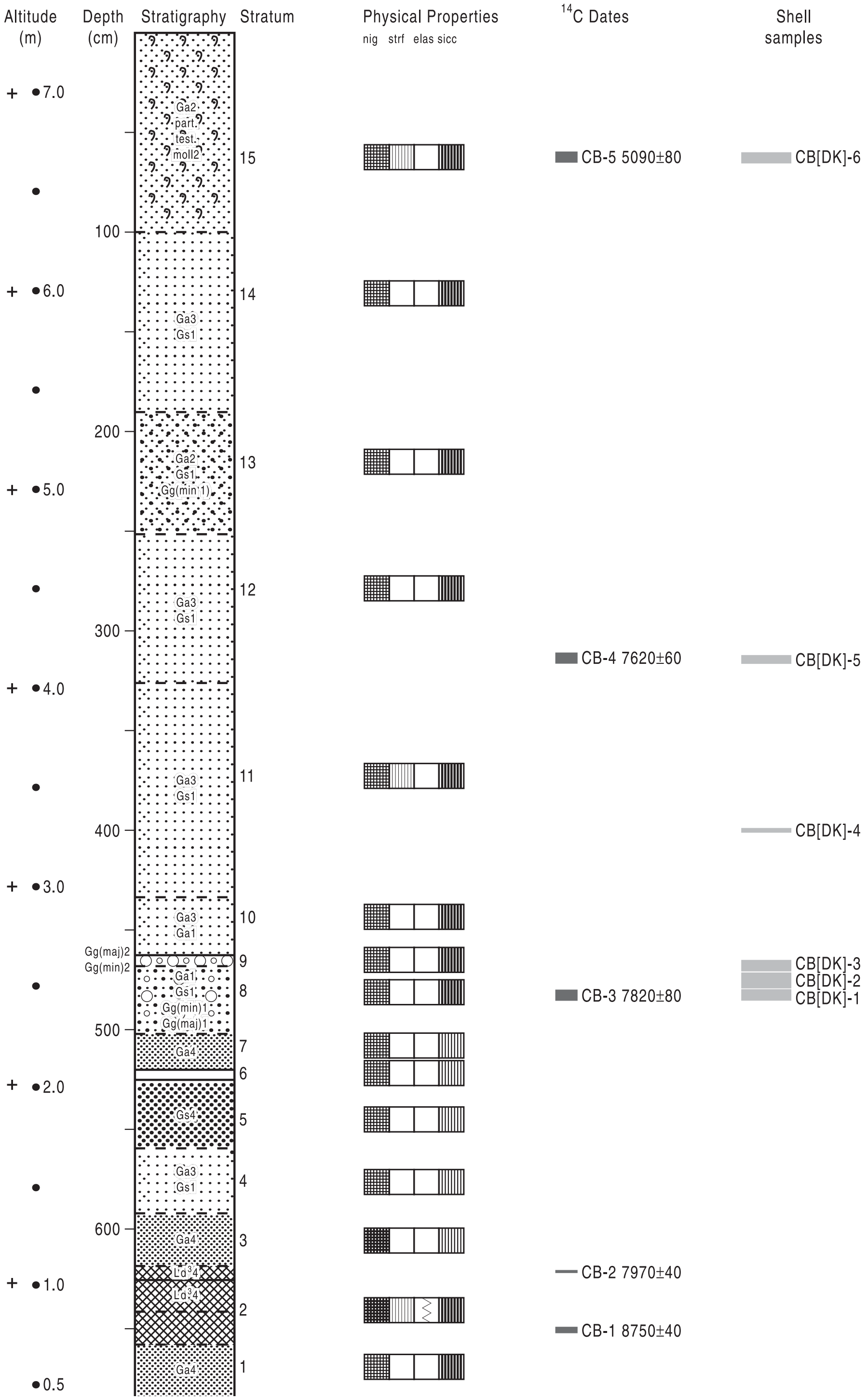

Fig. 3. The stratigraphy at the section from the south bank of the Cocklemill Burn. The stratigraphic signatures and symbols for the physical properties follow the scheme of Troels-Smith (1955). *Ga—Grana arenosa*: mineral particles 0.06–0.6 mm; *Gs—Grana saburralia*: mineral particles 0.7–2 mm; *Gg(min)—Grana glareosa minora*: mineral particles 2.1–6 mm; *Gg(maj)—Grana glareosa majora*: mineral particles 6.1–20 mm. *Ld*^{3}*—Limus detrituosus*: a mudlike, homogeneous, non-plastic deposit consisting of microscopic particles of ±decayed micro-organisms or parts of plants; the superscript numeral indicates the degree of humification of the particles on a scale 0–4. The physical properties comprise: nig—nigror degrees of darkness on a scale 0–4 where 0 is the lightest shade; strf—stratificatio, the degree of stratification on a scale 0–4 where 0 is no stratification and 4 is well stratified; elas—elasticitas, the degree of elasticity of the sediment on a scale 0–4 where 0 is no elasticity and sicc—siccitas is the degree of dryness on a scale 0–4 where 0 is water and 4 is an air dry deposit. Limes is the boundary between strata on a scale 0–4 where 0 is a boundary zone >1 cm and 4 is a sharp boundary <0.5 mm. Details of the radiocarbon assays CB-1–5 are given in Table 2 and of the molluscan assemblages CB[DK]-1 CB[DK]-6 in Table 3 Appendix A.

Table 1
Stratigraphy of the section examined at the Cocklemill Burn, Fife

Altitude (m) OD	Depth (cm)	Stratum	Description
+7.29 to +6.29	0–100	15	Well-laminated shelly sand with rare rounded pebbles and organic detritus, including seaweed. Shells included *Littorina, Cerastoderma edule, Donax vittatus* and *Ensis arcuatus.* Ga2, part.test.moll.2, test.moll.+, Dg+, Gg(maj)+Gg(min)+, part.test.moll.+nig2, strf4, elas0, sicc2
+6.29 to +5.39	100–190	14	Pink to buff sand with bioturbated horizons at 155–170 and 130–148. Grit and lightly iron stained shell hash in the burrows. Ga3, Gs1, Gg(min)+, part.test.moll.+, Lf+nig2, strf0, elas0, sicc2
+5.39 to +4.78	190–251	13	Sand with gravel. Strongly bioturbated with burrows at 190–210, 220–235 and 250 cm. Grit, gravel and shell hash infilled burrows. Ga2, Gs1, Gg(min)1, Gg(maj)+, part.test.moll.+nig2, strf0, elas0, sicc2
+4.78 to +4.03	251–326	12	Buff coloured sand with rare organic detrit, us rare gravel and rare shells, including *Arctica islandica*, *Anomia* and *Mytilus* Ga3, Gs1, Dg+, test.moll+, part.test.moll.+ Gg(min)+, Gg(maj)+ nig2, strf+, elas0, sicc2
+4.03 to +2.95	326–434	11	Buff coloured sand with clasts of organic detritus, rare sand and iron stained sandy clasts. Some of the organic detritus is woody: some is seaweed. Organic detritus in layers—338–335, 351–349, 374–359 and 388–391 cm. At the top of the stratum is a lag deposit of grit, gravel, pebbles and shells, such as *Littorina littorea*, *Cerastoderma edule* and *Scrobicularia plana* Ga3, Gs1, test.moll.+, Dg+, Ag+, Lf+, Gg(min)+Gg(maj)+, part.test.moll.+nig2, strf4, elas0, sicc2
+2.95 to +2.66	434–463	10	Bleached sand with ironstained dipping beds of grit Gs1, Ga3, Gg(min)++, part.test.moll+, Lf+nig2, strf0, elas0, sicc2
+2.66 to +2.62	463–467	9	Iron stained grit and gravel with rare shells and shell fragments, such as *Littorina saxatilis, Mytilus edulis* and *Cerastoderma edule* Gg(maj)2, Gg(min)2, Gs+, test.moll+, part.test.moll.+ Lf+nig2, strf0. elas0, sicc2
+2.62 to +2.26	467–503	8	Gravelly and gritty sand with shells and shell fragments and organic detritus ironstained towards the base Shells include *Cerastoderma edule*, *Mytilus edule* and *Scrobicularia plana* Ga1, Gs1, Gg(min)1, Gg(maj)1, Dg+, test.moll.+ part.test.moll+, Lf+nig2, strf 0, elas0, sicc2
+2.26 to +2.09	503–520	7	Buff coloured sand with organic and shelly clasts. Shell fragments towards the top of the stratum Ga4, Dg+, part.test.moll.+nig2, strf 0, elas0, sicc1+
+2.09 to +2.04	520–525	6	Water
+2.04 to +1.69	525–560	5	Coarse sand with grit and gravel and rare shell fragments Gs4, Gg(min)+, Gg(maj)+, part.test.moll+ nig2, strf0, elas0 sicc2
+1.69 to +1.37	560–592	4	Fine, medium and coarse sand with grit and gravel and rare shell fragments Ga3, Gs1, Gg(maj)+, Gg(min)+, part.test.moll+nig2, strf 0, elas0, sicc1
+1.37 to +1.09	592–620	3	Fine sand with rare shell fragments and organic detritus Ga4, part.test.moll+, Dg+ nig3, strf0, elas0, sicc1
+1.09 to +0.71	620–627 and 642–645	2	Strongly laminated, dark brown limus with rare herbaceous detritus and rare fine to medium sand grains *Menyanthes* seeds and *Chara* in laminations. 627–642 unsampled. Ld^{3}4, Dh+, Ga+nig3, strf4, elas1, sicc2, ls4
+0.71 to +0.44	645–687	1	Fine to medium sand with rare woody roots and diffuse organic material Ga4, Tl^2+, Sh++ nig 2, strf0, elas0, sicc2, ls0

exposure adjacent to the bed of the Cocklemill Burn (525–685 cm). The sediments were described using the scheme of Troels-Smith (1955). Samples were taken from the section for pollen, diatom and foraminiferal analyses, as well as for further radiocarbon dating (Table 2) and malacological analyses (Appendix A).

In the section examined (Fig. 3), the basal stratum 1, from 687 to 645 cm depth (+0.44–+0.71 m OD), consists of a medium sand with organic material. This is overlain by stratum 2, a well-laminated *limus* (a type of peat which is mudlike, homogeneous and non-plastic, consisting of particles of more or less decomposed micro-organisms or plant fragments), from 645 to 620 cm depth (+0.71 to +1.09 m OD). A sample from the *limus* was the only one which contained countable amounts of pollen. Although the pollen was poorly preserved, eroded, broken and folded, the tree pollen present included *Pinus, Betula, Salix, Ulmus* and *Quercus.* Shrubs present included *Corylus* and herbaceous taxa included Poaceae, Cyperaceae, Pteropsida, *Rumex, Artemisia, Typha angustifolia* and Chenopodiaceae. The presence of *Menyanthes* fruit and encrustations of *Chara* bear witness to the freshwater conditions under which the sediment was laid down. Samples were prepared for diatom analysis, but no frustules were recovered. The upper boundary of stratum 2 is sharp (*limes* 4) and is clearly erosional: fragments of organic detritus and intraclasts of peat apparently eroded from this stratum occur in the overlying stratum. Radiocarbon dates of 8750±40 and 7970±40 BP were

Table 2
Radiocarbon dates from the Cocklemill Burn section

Sampling Code	Laboratory Code	Material	Stratum	Depth (cm)	Altitude (m) OD	Weight (g)	Conventional 14-C age	Calibrated age (BP)
CB-5	Beta 179976	Shell *Cerastoderma edule*	15	60	+6.69	19	5090±80	5600–5280
CB-4	Beta 179975	Shell *Arctica islandica*	12	313–315	+4.46 to +4.44	55	7620±60	8180–7940
CB-3	Beta 169869	Shell *Cerastoderma edule*	8	480–485	+2.49 to +2.44	26	7820±80	8360–8180
CB-2	Beta 179974	*Limus detrituosus* [3]	2	621–622	+1.08 to +1.07	10	7970±40	9000–8640
CB-1	Beta 179973	*Limus detrituosus* [3]	2	648-652	+0.81 to +0.77	10	8750±40	9570–9900

obtained from the base and top of stratum 2, respectively (Table 2). Given that the overlying strata were laid down in a marine environment, that these strata contain peat apparently eroded from stratum 2 (see below) and that pollen of salt marsh taxa (*Artemisia* and Chenopodiaceae) have been recorded, it is likely that marine conditions were close to the site ca. 8000 BP.

Above the basal sequence, strata 3–12 (620–251 cm depth; +1.09–+4.78 m OD) comprise largely unsorted sands with marine shells, both broken and entire, and display little or no sedimentary structure except in parts of stratum 10 and possibly stratum 11 (where some coarse bedding dipping westwards can occasionally be seen). From stratum 3 to the water table (shown as stratum 6 on Fig. 3), and in stratum 7, above it, the sediments are predominantly of fine to coarse sand. The deposit changes markedly above stratum 7. Fig. 4 shows monolith samples from the top of stratum 7, strata 8 and 9, and the lower part of stratum 10, with the results of particle size analyses on consecutive 1-cm thick subsamples across these monoliths (the monoliths were taken from a face 5 m from the section, and disclose slightly different altitudes from those in Table 1 and Fig. 3). At the base of the sequence in the monoliths, in the top of stratum 7 (the lowest two samples), the buff coloured sand contains only small quantities of gravel. Above this, the gravelly sand with shells (stratum 8) discloses an initial coarsening-upwards sequence which reaches almost 60% gravel before fining-upwards (with a thin sand horizon) to stratum 9, an iron-stained grit with predominantly sand-size particles. Above the grit, a bleached sand (stratum 10), contains noticeable quantities of gravel, which rapidly increase at the base then gradually decrease to the top (not shown in Fig. 4). Above stratum 10, the buff coloured sand of stratum 11 (also not shown in Fig. 4) contains intraclasts of organic material and is marked at the top by a lag horizon of predominantly gravel and shells. Stratum 12 exhibits no intraclasts and is a massive deposit of buff-coloured sand.

Strata 3–12 are believed to include an episode of high-energy deposition represented by strata 8–11. Strata 3–7, with their shells and shell fragments, were probably laid down as marine conditions reached the site. The coarse and fine sequence of deposits in strata 8–11 probably indicates fluctuating high-energy conditions, with the lag horizon at the top of stratum 11 indicating cessation of this episode with some erosion of the deposit. The duration of this erosive episode is unknown, but there is no evidence of terrestrial conditions developing, so it seems likely that a marine environment continued and that the episode was relatively short. Two radiocarbon dates obtained provide an indication of the maximum age of the high-energy episode. Valves of *Cerastoderma edule* recovered from stratum 8 yielded an age of 7820±80 (Table 2), while from stratum 12, a valve of *Arctica islandica* yielded 7620±60 BP. Both of these dates should have 405±40 radiocarbon years deducted to accommodate the marine reservoir effect (Harkness, 1983; Bowman, 1999). Given that the shells were redeposited, it seems likely that the high-energy episode took place after the younger of the two dates ca. 7215 BP.

The top sequence in the section comprises strata 13–15. In terms of structure and composition, these strata are quite distinct from the underlying strata 3–12. In this sequence, a series of bioturbated horizons in strata 13 and 14 is overlain by well-laminated and

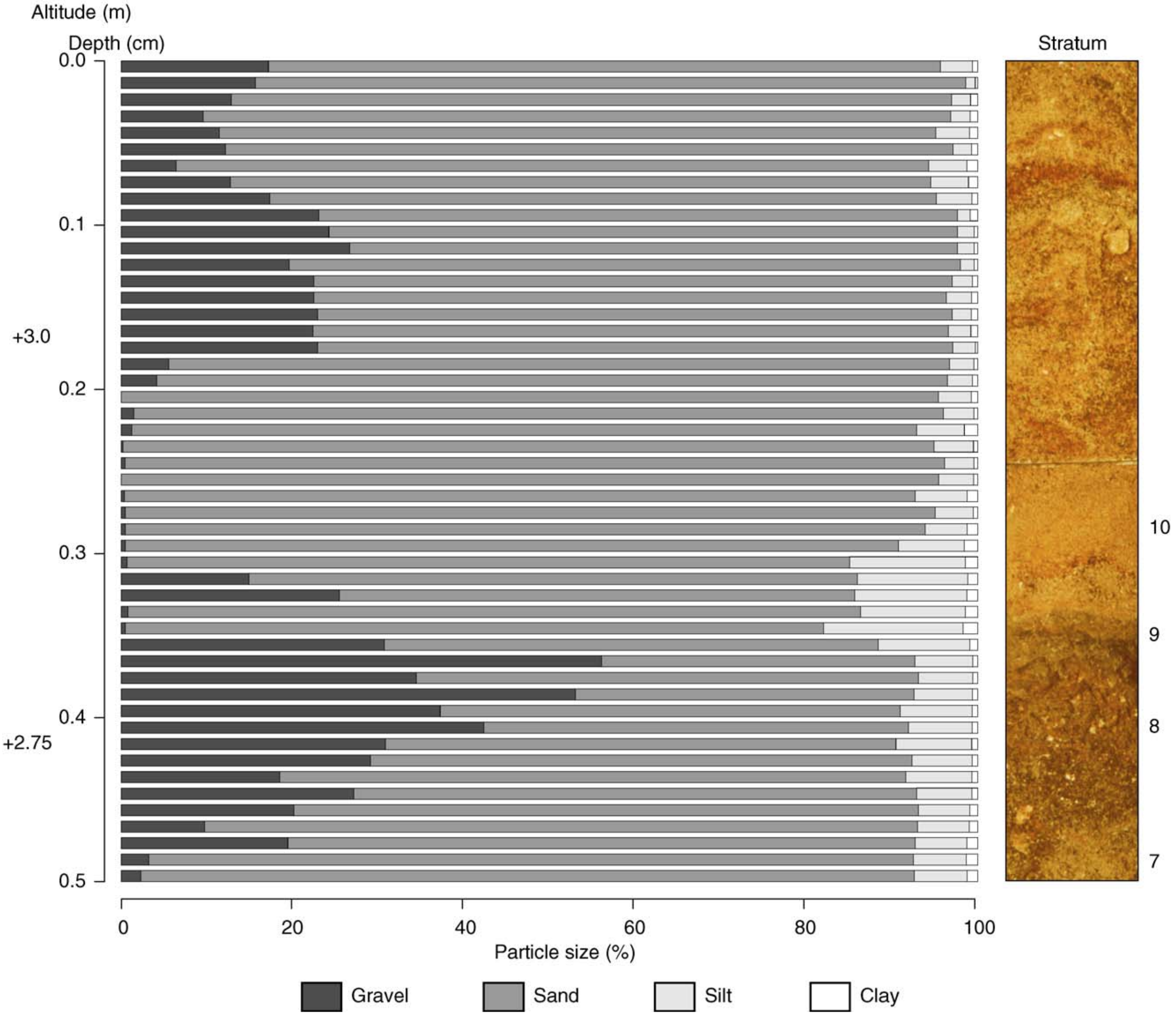

Fig. 4. Monoliths and particle size analyses from strata 7–10, at a site 5 m west of the section described in Table 1 and depicted in Fig. 3.

stratified shelly sand beds in stratum 15. The bioturbated horizons were recorded at 250, 220–235, 190–191, 155–170 and 130–148 cm depth, and comprise many burrows in the sand and gravelly sand. The burrows are infilled with grit, gravel and shell hash. Each bioturbated horizon is overlain by sands in which there is no evidence of disturbance. The burrows may have been made by razorfish (razor shells), which are described by McMillan (1968) as "strong burrowers in sand". Five species of razorfish have been recorded around the British Isles (Tebble, 1966), and of these *Ensis ensis* (Linné) burrows into fine sand and occasionally silty sand; *Ensis arcuatus* (Jeffreys) into fine or coarse sand and into fine or coarse shell gravel, and *Ensis siliqua* (Linne) into fine sands (Tebble, 1966). Although species of *Ensis* are difficult to identify without the soft parts of the animal, shells of *E. arcuatus* have been identified from 60 cm in stratum 15 (Tooley et al., 2003; see also Appendix A, Table 3). This species lives today from low in the intertidal zone to depths of 36 m or so (Tebble, 1966) at sites around the British Isles. According to Keen (Appendix A, Table 3) the shell assemblages are made up of species that live in littoral or shallow water, in summer sea temperatures not below 10 °C. The death assemblages comprise individuals that come from sandy tidal flats or shallow subtidal waters or from rocky intertidal habitats: conditions that obtain today in the local area, notably in Largo Bay, Shell Bay, Ruddons Point and Kincraig Point. The final stratum (15) contains very conspicuous laminated beds of shells and shell hash with peat intraclasts and other organic detritus including seaweed and rare rounded pebbles. From the base of this stratum, a valve of *Cerastoderma edule* gave a radiocarbon age of 5090 ± 80, which taking account of the marine reservoir effect yields ca. 4700 BP. The shell assemblages are dominated by gastropods such as *Cingula cingillus* (Montagu), *Onoba semicostata* (Montagu), *Littorina obtusata* (Linné) and *Littorina littorea* (Linné), with bivalves such as *Spisula elliptica* and *Cerastoderma edule* (Linné) (see Appendix A) and are indicative of a provenance from sandy tidal flats and rocky intertidal situations. The stratigraphy of stratum 15 is similar to that which might be expected to develop from conditions presently existing in Largo Bay, at the mouth of the Cocklemill Burn, while the nature, structure and composition of the molluscan death assemblage is similar to that found at present at high water mark in the area. The sequence in strata 13–15 may be taken to indicate a change in the pattern of sediment accumulation, in which the intertidal surfaces reached in strata 13 and 14 were subsequently covered around ca. 4700 radiocarbon years BP by more rapidly accumulating sediments of later intertidal sandflats in stratum 15.

6. Interpretation of the environmental changes recorded at the site

At the base of the sequence, strata 1 and 2 probably record the gradual replacement of accumulating sand sometime after ca. 8800 radiocarbon years BP by a *limus*, which then continued to develop until ca. 8000 radiocarbon years BP. An early–mid Holocene peat beneath later marine sediments is widely recorded at coastal sites in this area of Fife, notably beneath the raised Holocene mudflats ("carselands") north–west of St. Andrews, with radiocarbon dates ranging between ca. 9900 and ca. 5800 years BP (Chisholm, 1971; Morrison et al., 1981), and given the stratigraphical and environmental context of the peat at Cocklemill Burn it seems likely that it equates to an episode in the accumulation of the widespread coastal organic deposits in the area.

The high-energy environment indicated by strata 8–11 in the middle sequence, and dated at later than ca. 7215 BP is a unique and distinctive feature of the stratigraphy. On the basis of its stratigraphical context, sedimentology and age, it is correlated with the Holocene Storegga Slide tsunami, first recognised by Dawson et al. (1988) and now identified at a growing number of sites in eastern Scotland (e.g. Dawson and Smith, 1997, 2000; Smith et al., 1999, 2000; Bondevik et al., 2003; Smith et al., in press) and at several sites in Norway (Bondevik, 1996, Bondevik et al., 1997), Iceland (Hansom and Briggs, 1991) and the Faroes (Grauert et al., 2001). The possibility that the deposit may have been laid down during a storm surge is considered less likely because of the uniqueness of the sequence of strata involved and because storm surge deposits are generally of limited geographical extent and of a finer nature (Tooley, 1985). The deposit seen in the section at Cocklemill Burn is 1.77 m thick (strata 8–11), thicker than the maximum thickness previously recorded for the tsunami (1.59 m in borehole HB11 of Smith et al., 1992), and much thicker than commonly recorded for storm surge deposits (e.g. Shi, 1995). The stratigraphical context of the deposit at Cocklemill Burn is quite unlike that of deposits of the Holocene Storegga Slide tsunami so far found elsewhere in Scotland, which consist of a distinctive sand horizon occurring within peat or silt. The grain size of the deposit at Cocklemill Burn, with two episodes of coarser sediment within an overall fining-upwards profile, is similar to that of the tsunami deposit at several locations in eastern Scotland, where, whilst a broadly fining-upwards particle size trend is observed (e.g. in the Dornoch Firth, see Firth et al., 1996), two or more episodes of coarser sedimentation may occur (e.g. Dawson et al., 1991; Shi, 1995). The maximum age for the deposit at Cocklemill Burn lies within the envelope of ages for the tsunami in eastern Scotland, of ca. 6600–7500 BP, being slightly older than the statistically derived age of ca. 7100 given by Smith et al. (in press) but close to the age of ca. 7200 radiocarbon years BP preferred for the event by Bondevik (1996) and Bondevik et al. (1997) from Norwegian evidence. The nearest sites of the tsunami deposit in eastern Scotland to Cocklemill Burn are at Silver Moss, near St. Andrews, to the north, where a date of sometime between 7050 ± 100 and 7555 ± 110 radiocarbon years BP has been obtained (Morrison et al., 1981) and at Lochhouses, on the south side of the mouth of the Firth of Forth, where a date of between 7490 ± 70 and 7450 ± 60 radiocarbon years BP was obtained by Robinson (1982). Both sites were interpreted by Dawson et al. (1988) as disclosing evidence for the tsunami. Taken together, the evidence of stratigraphy, sedimentology and age supports the likelihood that the Holocene Storegga Slide tsunami is recorded at the Cocklemill Burn.

The altitude of the shoreline at Cocklemill Burn at the time of the tsunami is unknown. In their isobase model for uplift since the tsunami, Smith et al. (2000) estimate MHWS at the time of the event in the area to have been +6.5 m OD. The base of the sequence of deposits interpreted above as due to the tsunami (the base of stratum 8), lies at +2.26 m OD (Table 1), but this sequence of deposits lies in all probability some distance to seaward of contemporary MHWS, and thus provides only a minimum estimate for this site. In addition, the model of Smith et al. (2000) is based upon relatively few data points, the nearest being from Silver Moss, some 22 km to the north.

The fluctuations in relative sea level implied by the sequence of deposits at the top of the section may well reflect broader trends. In this sequence, the surface of the bioturbated strata (13 and 14), at +6.29 m, and the surface of the uppermost stratum, 15, at +7.29 m, may mark different Holocene shorelines. In the Forth valley, to the west of the Cocklemill Burn and ca. 60 km nearer the probable centre of glacio-isostatic uplift in Scotland, four visible Holocene shorelines are recognised (e.g. Smith, 1968), the highest of which, the Main Postglacial Shoreline, has been dated as having been abandoned at ca. 6850 radiocarbon years BP (Robinson, 1993). However, away from the centre of uplift, lower shorelines have been shown to overlap the Main Postglacial Shoreline, as envisaged by Smith et al. (2000). The shoreline which was reached after the Main Postglacial Shoreline, the Blairdrummond Shoreline, was originally dated at between ca. 2000 and 4000 radiocarbon years BP (Smith et al., 2000), but more recently additional dates place that shoreline as having been reached between ca. 3500 and 5000 radiocarbon years BP (Smith et al., 2003). At the Cocklemill Burn, the covering of the intertidal, bioturbated strata by a deposit dated at ca. 4700 radiocarbon years BP may indicate that the surface of stratum 15 (and thus of the marine deposits in the section) is that of the Blairdrummond Shoreline overlapping the Main Postglacial Shoreline in this area away from the centre of isostatic uplift. In their isobase models for the Main Postglacial and Blairdrummond shorelines (Fig. 5), Smith et al. (2000) estimate that in the Cocklemill Burn area the Main Postglacial Shoreline lies at ca. +8.0 m OD (ca. 5.5 m MHWS) compared with a sandflat surface of +6.29 m OD in the present study, whereas the Blairdrummond Shoreline lies at ca. +8.5 m OD (ca. 6.0 m MHWS) compared with +7.29 m OD for the sandflat here.

7. Discussion

The Cocklemill Burn site provides information on the rate of relative sea-level rise during the early–mid Holocene. *Limus* accumulating towards the base of the section (stratum 2) from 8750 ± 40 to 7970 ± 40 BP, and certainly before ca. 7420 BP (the date on shells within the tsunami sediment layer—stratum 8), was overwhelmed as relative sea level rose up to +5.39 m OD to reach the Main Postglacial Shoreline sandflat (stratum 14). The Main Postglacial Shoreline in the area was probably reached later than at the head of the Forth valley, given the effect of shoreline diachroneity, and possibly around 6000 radiocarbon years BP according to Smith et al. (2002). Assuming that the date at which the *limus* was covered was after 8000 radiocarbon years BP, a minimum rate of rise of around 3 mm a^{-1} is indicated using calibrated dates for the sediments accumulated from the top of the *limus* to the top of the highest bioturbated stratum.

The sediments at Cocklemill Burn, however, would have accumulated during a more variable relative sea-level rise than the rate of around 3 mm a^{-1} and a rate of 10 mm a^{-1} occurred whilst the sediments in strata 8–12 accumulated. Prior to the estimated age of the Main Postglacial Shoreline at Cocklemill Burn, episodes of particularly rapid rates of relative sea-level rise for areas around NW Europe are believed to have occurred according to a number of studies (e.g. Tooley, 1974, 1978, 1989, 1993; Petersen, 1981; Streif, 1989; see also summaries in Smith et al., 2002). These rapid rise episodes are all registered before the Holocene Storegga Slide tsunami, and Smith et al. (2002) have commented for a site in the Tay valley, Scotland, that a noticeable slowing in the rate of relative sea-level rise took place directly after the tsunami occurred. If the age of the tsunami is compared with the culmination of the Main Postglacial Transgression (and formation of the Main Postglacial Shoreline) in Scotland, it will be noted that the tsunami always occurs before the culmination, but occurs closer to the culmination nearer the centre of uplift (Smith et al., 2002).

It is speculated here that the rapid and variable rate of relative sea-level rise during the early and mid Holocene could have a bearing on the cause of the Holocene Storegga Slide tsunami. Solheim et al. (in press) have observed that the Holocene Storegga Slide of Bugge et al. (1987) is only one of a series of submarine slides in that area which during the last 500,000 years appear to have occurred at lateglacial to interglacial times with a periodicity of ca. 100,000 years. Bryn et al. (2003) have maintained that loading of the continental shelf with unstable glacial and fluvioglacial sediments created the potential for failure and that movement was later initiated by an earthquake or earthquakes triggered by spatially variable glacio-isostatic rebound.

The cause of the Holocene Storegga Slide may, however, have been rather more complex than simply the effect of glacio-isostatic rebound. It is particularly interesting to note that in the general area of the slides, the Holocene Storegga Slide tsunami appears to occur very close to the peak of the main Holocene transgression if relative sea-level graphs for the area (e.g. Hafsten, 1983) are compared with the likely age range of the tsunami between ca. 7100 BP; (Smith et al., in press) and up to ca. 7300 BP (Bondevik et al., 1997). Prior to the Holocene Storegga Slide tsunami, the early–mid Holocene sea surface had been rising at an accelerated, though variable, rate as discussed by Tooley (1993), first recorded in Sweden by Mörner (1969) and later in NW England by Tooley (1974). The rates quoted of between 20 and 75 mm a^{-1} were probably associated with the disintegration of the Laurentide Ice Sheet and the catastrophic discharge of sub-glacial and pro-glacial meltwater about 7600 BP (CRE-III of Blanchon and Shaw, 1995) as maintained by Tooley et al. (2000). This

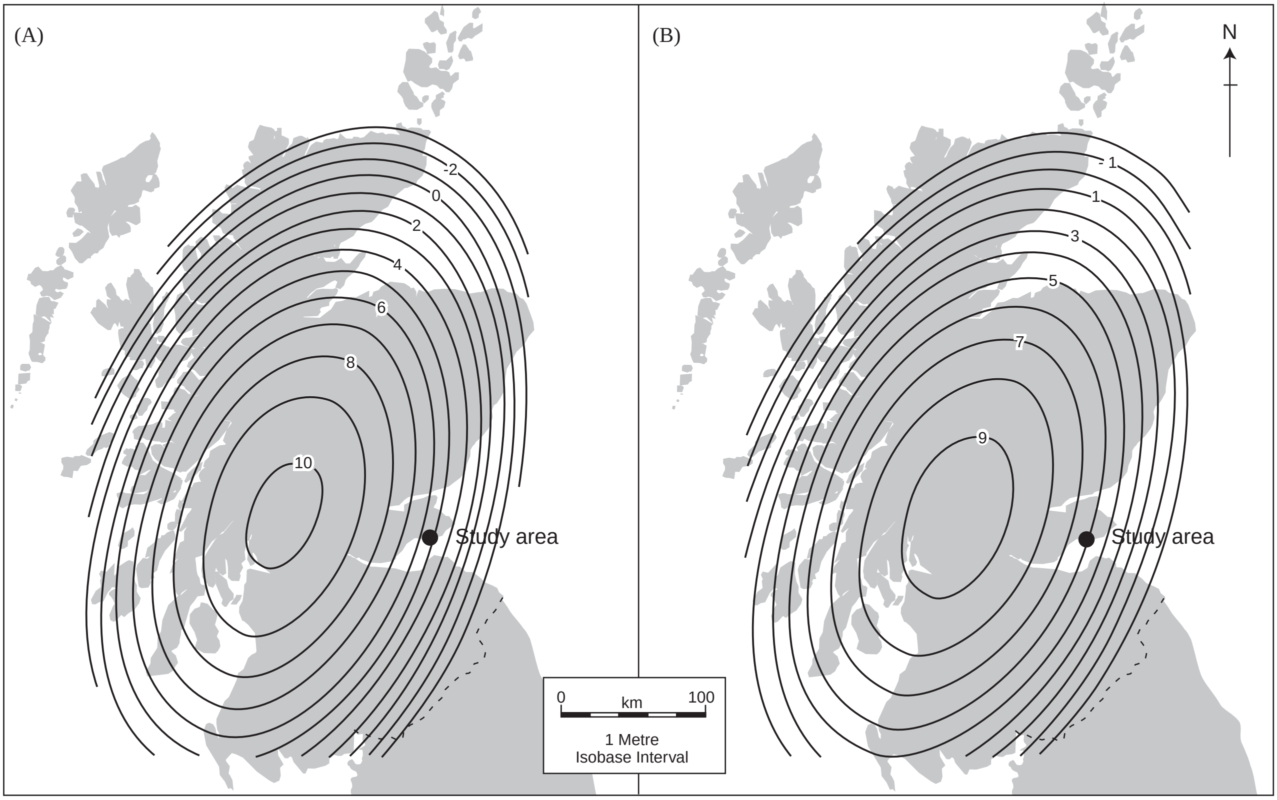

Fig. 5. Isobases in metres above mean high water mark of spring tides for the main postglacial shoreline (A) and the Blairdrummond shoreline (B) in mainland Scotland (after Smith et al., 2000), with the location of the study area indicated.

sea-surface rise becomes manifest as a relative sea-level rise along the Norwegian coastline adjacent to the Storegga Slides during the early Holocene. However, after the Holocene Storegga Slide tsunami, the sea surface rise diminishes and along the coastline adjacent to the slide a relative sea-level fall takes place (because of continuing glacio-isostatic uplift). It may therefore be that changes in water loading offshore in this area, combined with isostatic uplift, reflected in a rapid and considerable rise in relative sea level followed by a fall, could have played a part in earthquake generation with the resultant submarine sliding.

8. Conclusion

The deposits exposed along the banks of the Cocklemill Burn disclose detailed information on relative sea-level change in the area. Notwithstanding the relatively exposed coastal environment in which the deposits accumulated, a picture of relative sea-level change, consistent with evidence in the surrounding area, emerges. Of particular note is the unique sequence of deposits which record the Holocene Storegga Slide tsunami and the evidence of overlapping shorelines. The evidence described here demonstrates that valuable detail on relative sea-level change can be determined from exposed coastal locations comprising relatively coarse sediment laid down under high-energy conditions in the outer limits of the Firth of Forth, eastern Scotland.

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Appendix A. Cocklemill Burn Mollusca (David Keen, University of Birmingham)

Samples were received as individual shells except the sample from 60 cm which contained the shells in the original sediment. All samples were washed through sieves to 500 μm and dried at 40 °C, prior to counting under a ×10 to ×60 binocular microscope. The taxonomic nomenclature follows (Seaward, 1982).

A.1. Faunal description (Table 3)

A total of 29 taxa (12 gastropods, 1 scaphopod and 16 bivalves) were identified. Overwhelmingly these are inhabitants of Sea Area 7 (Firth of Forth) today (Seaward, 1982).

Table 3
List of Mollusca from the Coklemill Burn sectiom

Sample code	CB[DK]-5	CB[DK]-4	CB[DK]-3	CB[DK]-2	CB[DK]-1	CB[DK]-6
Sample depth (cm)	313–315	400	465–470	470–480	480–485	60
Gastropoda						
Patella aspera (Roding 1798)						1
Gibbula umbilicalis (da Costa, 1778)						1
Littorina littorea (Linné, 1758)		2	1		1	37
Littorina saxatilis agg			3			21
Littorina obtusata (Linné, 1758)		2	1		1	37
Cingula cingillus (Montagu, 1803)						59
Onoba semicostata (Montagu, 1803)						59
Rissoacea undetermined	2	1	2			25
Turritella communis (Risso, 1826)						1
Nucella lapillus (Linné, 1758)				1		5
Nassarius reticulatus (Linné, 1758)						2
Chrysallida spiralis (Montagu, 1803)						1
Turbonilla sp.						2
Scaphopoda						
Dentalium entalis (Linné, 1758)					1	
Bivalvia						
Nucula spp.			1			
Anomia ephippium (Linné, 1758)	1					6
Mytilus edulis (Linné, 1758)			1	1		
Mytilus/Modiolus spp.	2	1			1	3
Ostrea edulis (Linné, 1758)						1
Pectinacea undetermined						2
Astarte elliptica (Brown, 1827)						3
Mysella bidentata (Montagu, 1803)						2
Arctica islandica (Linné, 1758)	1					
Parvicardium ovale (Sowerby, 1840)		1				
Cerastoderma edule (Linné,1758)		1	2	1	2	16
Spisula elliptica (Brown, 1827)						22
Lutraria lutraria (Linné, 1758)						1
Donax vittatus (da Costa, 1778)						8
Macoma balthica (Linné, 1758)				1	1	
Scrobicularia plana (da Costa, 1778)		1		1		1
Ensis arcuatus (Jeffreys, 1865)						1
Pholas dactylus (Linné, 1758)		1				
Total (27 species, 1 genus, 2 families)	6	9	12	5	7	317
Other sub-fossils						
Balanus fragments	Present	Present				Present
Echinoderma fragments						Present
Foraminifera						
Cibicides lobatulus						Present
Ammonia beccarii						Present
Quinqueloculina spp.						Present

Some taxa such as *Gibbula umbilicalis* do not currently occur in this area, but are known from pre-1950 records. *Littorina obtusata*, *Nassarius reticulatus* and *Anomia ephippium* are not recorded in the Firth of Forth today, but are noted from Sea Area 9 (Northumberland) to the south which has its northern boundary near Dunbar.

The majority of the species present lives in littoral or shallow water conditions (Peacock, 1993). Although some taxa have a maximum depth tolerance as deep as 440 m (such as *Astarte elliptica*) these extreme values do not mask the essentially shallow water nature of the fauna. Within the maximum depth ranges there is a number of sub-environments which can be identified. Most of the gastropods (such as *Patella aspera* and *Littorina* spp) are true littoral species, but some of the infaunal bivalves (such as *Astarte elliptica*, *Parvicardium ovale* and *Spisula elliptica*) have minimum water depths of 4–5 m, suggesting that the whole assemblage was washed together from a variety of ecological niches. This suggestion of an amalgam of faunas is also hinted at by the salinity tolerances of the mollusca and the substrates they inhabit. Most of the 29 taxa typically inhabit marine waters of "average" salinity (35‰), but *Scrobicularia plana* is more typical of estuaries where the reduced salinities to about 17‰ prevail. Most of the littoral gastropod species live on rocky shores, but a number of bivalves are infaunal species of sandy-bottomed conditions.

The temperature of the sea at the time of deposition cannot be lower than that tolerated by the most fastidious member of the fauna. While Peacock (1993) notes that *Mytilus edulis* can tolerate summer sea temperatures as low as 4 °C, most of the fauna cannot live in water temperatures below 10 °C, so it is likely that summer sea temperatures at the time of deposition were not lower than this figure.

Several of the samples (see Table 3) contained plates of *Balanus* species, fully in keeping with the shallow water character suggested by the mollusca. Sample CB[DK]-6 at 60 cm also had echinoderm fragments and three species of near shore foraminifera.

A.2. Environmental summary

The assemblage from the Cocklemill Burn is indicative of an open coastline of normal marine salinity for the North Sea and with summer seawater temperatures not below 10 °C. The presence together of species which inhabit slightly different water depths, substrate conditions and salinities indicates that the whole fauna was emplaced by wave action, although whether this was from normal storm action or from the Storegga Slide tsunami is impossible to determine from the molluscan evidence.

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