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Between winter storm surges – Human occupation on a growing Mid-Holocene transgression maximum (Tapes) beach ridge at Longva, Western Norway

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ABSTRACT

Substantial amounts of archaeological material have been found intermixed with beach pebbles and cobbles on the Tapes beach ridge at Longva on the island Flemsøya/Skuløya in Western Norway. The artefacts show that the beach ridge was settled in the Late Mesolithic. The most significant remains are fireplaces, birch bark from the floor of a tent/hut, fish sinkers and middens containing numerous waste flakes and lithic tools. Radiocarbon dating, mainly of burnt hazelnut shells, shows two periods of occupation. The older and longer period is dated to between 7600 and 6800 cal yr BP, and the younger phase to between 6200 and 5900 cal yr BP. Pollen analysis revealed open vegetation at the beach ridge during the occupation periods. Based on the beach ridge deposits and radiocarbon dates, we reconstructed the Tapes transgression maximum high tide sea level to 8.2–9.0 m between 7600 and 5600 cal yr BP. We conclude that the late Mesolithic inhabitants at Longva occupied the beach ridge while it was growing. During the largest storm surges – most likely to have been in the winter months – the sea would have washed over their settlements and deposited pebbles and cobbles on top of their remains. We suggest that the inhabitants abandoned the settlement before each stormy season, but returned and restored the site the following spring or summer.

1. Introduction

It is well known that Mesolithic people on the coast established their settlements close to the contemporaneous sea level, but how did they cope with winter storm surges? This would depend on how exposed a settlement was to storm waves and wind – and whether people lived at the site during the stormy season of the year. Here we present archaeological material found intermixed with beach pebbles and cobbles on top of the Mid-Holocene transgression maximum beach ridge at Longva on the island Flemsøya, one of the Nordøyane islands off the coast of Western Norway (Fig. 1). The excavations show that storms overtopped the beach ridge and deposited cobbles, gravel and sand on the settlement. It is unlikely that tents, boats, storage and food supplies would have survived such storms undamaged. Nevertheless, the beach ridge was occupied for nearly two thousand years.

The Mid-Holocene transgression maximum beach ridge is a well-defined landform on the Nordøyane islands (Fig. 1B). The ridge runs more or less continuously along the coast of the islands, at an elevation of about 10 m (Larsen et al., 1988). Many of the roads that run along the islands are built on top of this rather broad beach ridge. In many places, the beach ridge dams up a swale – a narrow, shallow, trough-like depression (Otvos, 2000) – on the landward side of the ridge. To drain the swale and surrounding area, farmers have cut trenches through the ridge in recent years. In Norway, the Mid-Holocene transgression is called the ‘Tapes’ transgression, named after the warm-water mollusk *Tapes decussata*. Since the ridge is the result of this transgression, it is called the Tapes beach ridge.

Earlier investigations of the Tapes beach ridge on these islands have focused on the deposits buried by the beach ridge (Fig. 1B).

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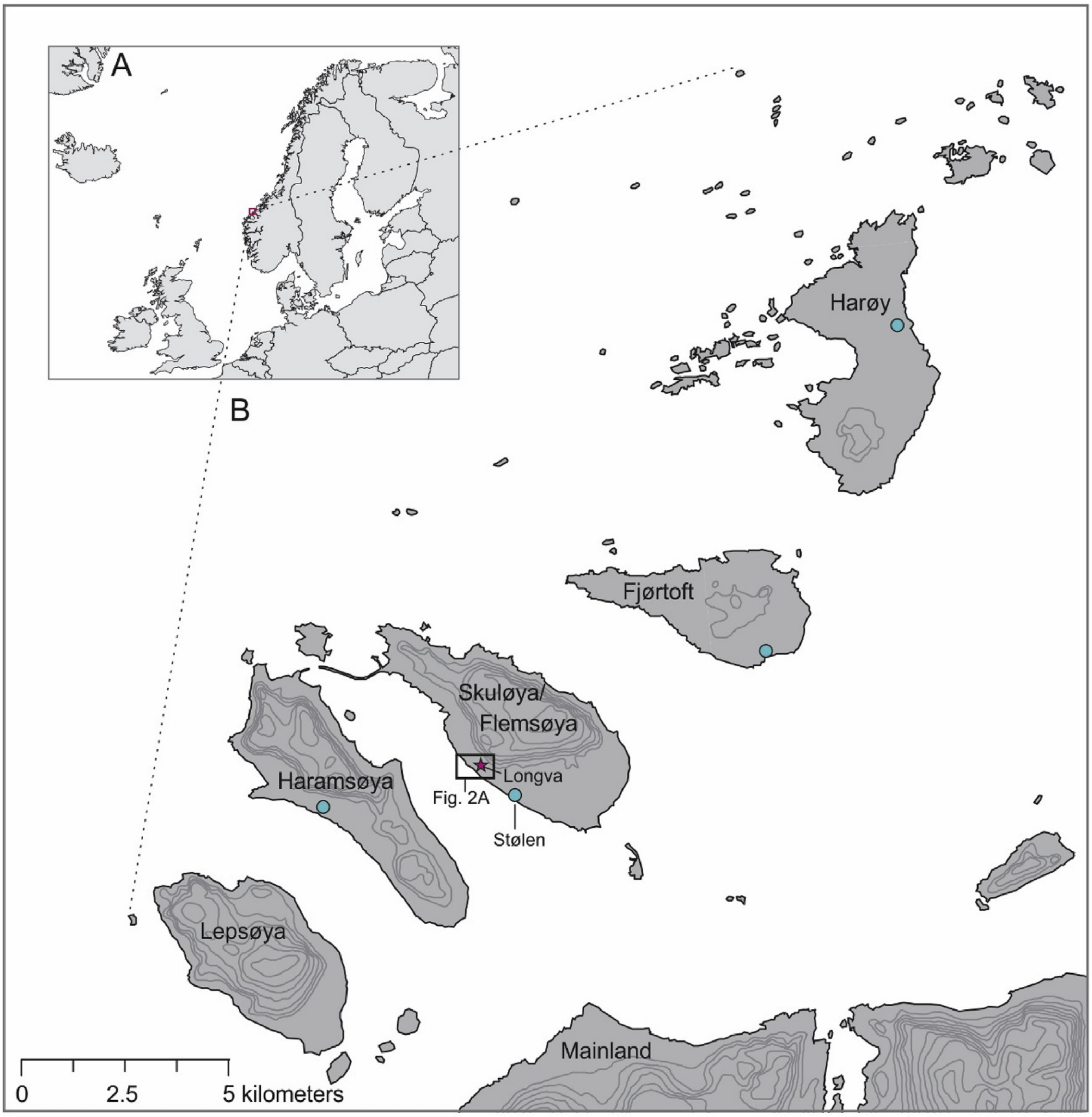

Fig. 1. (A) The Nordøyane islands are situated just off the coast of Western Norway. (B) The excavated area is at Longva (purple star) on Skuløya/Flemsøya. The rectangle indicates the area of the aerial map in Fig. 2A. Locations of earlier relevant investigations are indicated by blue dots: Harøy — Storegga tsunami sand sheet in peat below the Tapes beach ridge (Bondevik, 2003); Fjørtoft — Mesolithic site discovered below the Tapes beach ridge (Indrelid, 1973, 1974); Stølen at Skuløya/Flemsøya — Mesolithic site in the Tapes beach ridge (Bjerck, 1982); Haramsøya — pollen and plant fossils in peat below the Tapes beach ridge (Hafsten and Tallantire, 1978). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Peat below the ridge has been subjected to pollen and macrofossil analysis and radiocarbon dating to date the formation of the ridge (Bondevik, 2003; Hafsten and Tallantire, 1978). In addition, cultural remains found underneath the ridge at Fjørtoft (Fig. 1B) show that settlements were submerged by the transgression (Indrelid, 1973, 1974). It was inferred that an extensive sand sheet in the buried peat at Harøy (Fig. 1) was deposited by the Storegga tsunami 8150 cal yr BP (Bondevik, 2003). About 200 m east of Longva, at Stølen (Fig. 1B), Bjerck (1982) studied a cultural layer he interpreted to be covered by beach sediments from the Tapes transgression maximum.

We use the cultural remains and the deposits to radiocarbon date the former sea level and to shed light on the interaction between human settlements and storm waves. The importance of our discovery is that people lived intermittently on the beach ridge over a period of about 2000 years, during the Holocene transgression maximum sea level, and while the final part of the Tapes beach ridge was formed.

2. Study area

Flemsøya island, also called Skuløya, ('øya' means 'the island') is located just off the coast of Western Norway, at 62°40′N, 6°16′E (Fig. 1). The climate is oceanic, with mild winters and rather cool summers. The average annual temperature is 6.9 °C. Precipitation is 1300 mm a year, with most precipitation in the autumn months. The prevailing wind is southwesterly, and the strongest winds are usually from this direction too. Since 1958, wind strength of storm or more (>24.5 m/s over a period of 10 min) has been recorded along this coastline on 35 occasions, of which 32 were in winter, i.e. December, January or February (data from the weather station on Vigra (Norwegian Meteorological Institute, 2018), the next island south of Lepsøya in Fig. 1B, about 14 km south of Longva). In this region, storm surges occur when a deep low-pressure center moves along the coast and causes strong southwesterly winds to blow towards the coast (Gjevik and Røed, 1976). Such storm surges have occasionally caused extensive damage to coastal constructions and ships.

During the period when the settlement was occupied, between 7600 and 5900 cal yr BP, the sea was warmer and severe storms were less frequent than today. One of the driving mechanisms for storms in the North Atlantic is the thermal gradient between 50° and 65°N (Lamb, 1995). Cooling in the Arctic will strengthen this gradient, resulting in more severe storms and increased storm frequency. The higher sea surface temperature in the Arctic during the Mesolithic (Mangerud and Svendsen, 2018) weakened the gradient and must have resulted in fewer storms in this region. Sedimentological data seem to confirm this hypothesis and show that there was an increase in storm surge elevations in the colder periods of the Holocene, with a maximum during the Little Ice Age (e.g. Jelgersma et al., 1995; Pouzet et al., 2018).

3. Methods

3.1. Archaeological excavations

We excavated five sites along an 800-m stretch of the Tapes beach ridge at Longva. *Locality 65* (Lødøen et al., 2017) was the main site, and is the focus of this paper (Figs. 2A and 3). Locality 65 consists of six excavation areas next to each other: fields 1a, 1b, 2a, 2b, 3 and 4, with trench 1 west of field 1b and trench 3 east of field 3 (Fig. 2B). The excavations covered 622 m^2. We established a local 1 × 1 m grid for location of samples, structures and finds (Fig. 2B). We used a laser-guided total station to locate and measure the elevations of structures, trenches and layers. All elevations relate to the NN2000 datum level, which here is 5 cm above mean sea level.

The topsoil was first removed with a mechanical digger. The cultural and associated natural layers were excavated by hand in 5 and 10 cm thick sections within each of the stratigraphic layers. All excavated soil was sieved with water in a 4 mm mesh. Artefacts were collected and catalogued following standard procedures (Table 1). Charcoal and charred hazelnut samples were collected for radiocarbon dating from profiles and in defined structures, like fireplaces and dwelling depressions.

We also cut out box samples (Fig. 2B) of the deposits from profile walls for other investigations: sedimentology, pollen analysis, radiocarbon dating, chemical analysis and micro-morphology. Additionally, pollen samples were collected in small plastic tubes from selected contexts (Figs. 2B and 4). For more details about the excavations, see Lødøen et al. (2017), and pollen sampling, see Mehl and Hjelle (2018).

3.2. Radiocarbon ages

Most radiocarbon ages were measured on charcoal and charred hazelnut shells (Table 2). All samples were identified to wood species before they were submitted to Beta Analytic for radiocarbon measurements. The results were calibrated using OxCal 4.2.4 (Bronk Ramsey, 2009) with the IntCal13 calibration dataset (Reimer et al., 2013). Calibrated ages were rounded off to the nearest 5 years. Bulk samples of peat buried underneath the beach ridge were also dated (Table 2). The last column of Table 2 gives the coordinates of each radiocarbon-dated sample related to the local grid we established at the site (Fig. 2B).

3.3. Laboratory methods and numerical analysis

Pollen samples of volume 1 cm^3 were processed following standard procedures with acetolysis and HF treatment (Fægri and Iversen, 1989). Identification of pollen grains followed the keys in Fægri and Iversen (1989) together with the reference collection at the University of Bergen. The main gradients in the pollen data are shown using principal component analysis (PCA) in the program Canoco ver. 4.5.6 for Windows (ter Braak and Šmilauer, 2002). Seventy pollen samples with a mean pollen sum of 830 were included in the ordination. Charcoal was treated as a passive variable, and the pollen percentage data were square root-transformed prior to analysis. Samples for loss on ignition were dried for 15 h, followed by burning at 550 °C for 6 h (e.g. Heiri et al., 2001). All pollen diagrams, including loss on ignition at one site, are presented in the supplementary data.

4. Results

4.1. Stratigraphy

The excavations of the beach ridge and swale revealed ten stratigraphic layers, from A (surface) to J (bottom of excavations), in alphabetical order (Fig. 4). Most of the cultural remains were found in layer E, a beach gravel layer that forms the distal and youngest part of the beach ridge. The three uppermost layers, A–C, postdate the beach ridge, are to some extent modified by farming, and are not treated further in this paper. All layers are described and visualized in cross sections (Figs. 4 and 5), and the main pattern in the pollen data from these layers is illustrated in a PCA plot (Fig. 6). Below we present the stratigraphy through the Tapes beach ridge and accompanying swale, from bottom to top.

4.1.1. Layer J: Marine deposits at the base of the excavations (Late Glacial to Early Holocene)

Blue-gray silt and clay were exposed in the lower part of the trenches, followed upwards by scattered cobbles and boulders covered by well sorted brownish-gray sand, with loss on ignition below 2% (Figs. 4 and 5 and S2). The sorted sand has a sharp upper boundary to gravel and coarse sand. We interpret layer J as marine deposits influenced by the shallowing of the sea during the postglacial isostatic uplift. This layer was not studied in detail.

4.1.2. Layer I: Dark brown peat underneath the beach ridge (Early Holocene to 8150 cal yr BP)

The peat is compact, 10–30 cm thick, and rests on gravel and coarse sand (Figs. 4 and 5). Both the upper and lower boundaries are sharp. Loss on ignition is high, reaching its highest values, just over 80%, in the middle part of the peat (Fig. S2). The peat splits easily into layers and is well humified. Plant fragments include numerous *Phragmites* (common reed) rhizomes, found parallel to the layering in the peat. Tree roots (probably *Betula* (birch)) or *Alnus* (alder) were also found in the upper part of the peat. Radiocarbon ages of bulk samples are 10,500–10,275 cal yr BP at the base and 7685–7595 cal yr BP at the top (Table 2).

We interpret the peat as formed from the accumulation of plants in a wet, fresh-water environment. The pollen diagrams show that Poaceae (grasses, including *Phragmites*), Cyperaceae (sedges), *Sphagnum* (peat moss), *Calluna* (heather) and other dwarf shrubs grew in/by the wet swale on the inland side of a beach ridge (Figs. S1 and S2). Few diatoms were found, but provide further evidence that the peat accumulated in a wet fresh-water environment without influence of sea spray (Liisa Puusepp, pers. comm.). Only one occurrence of a marine dinoflagellate cyst (*Operculodinium centrocarpum*) were found (Fig. S2). Pebbles and cobbles

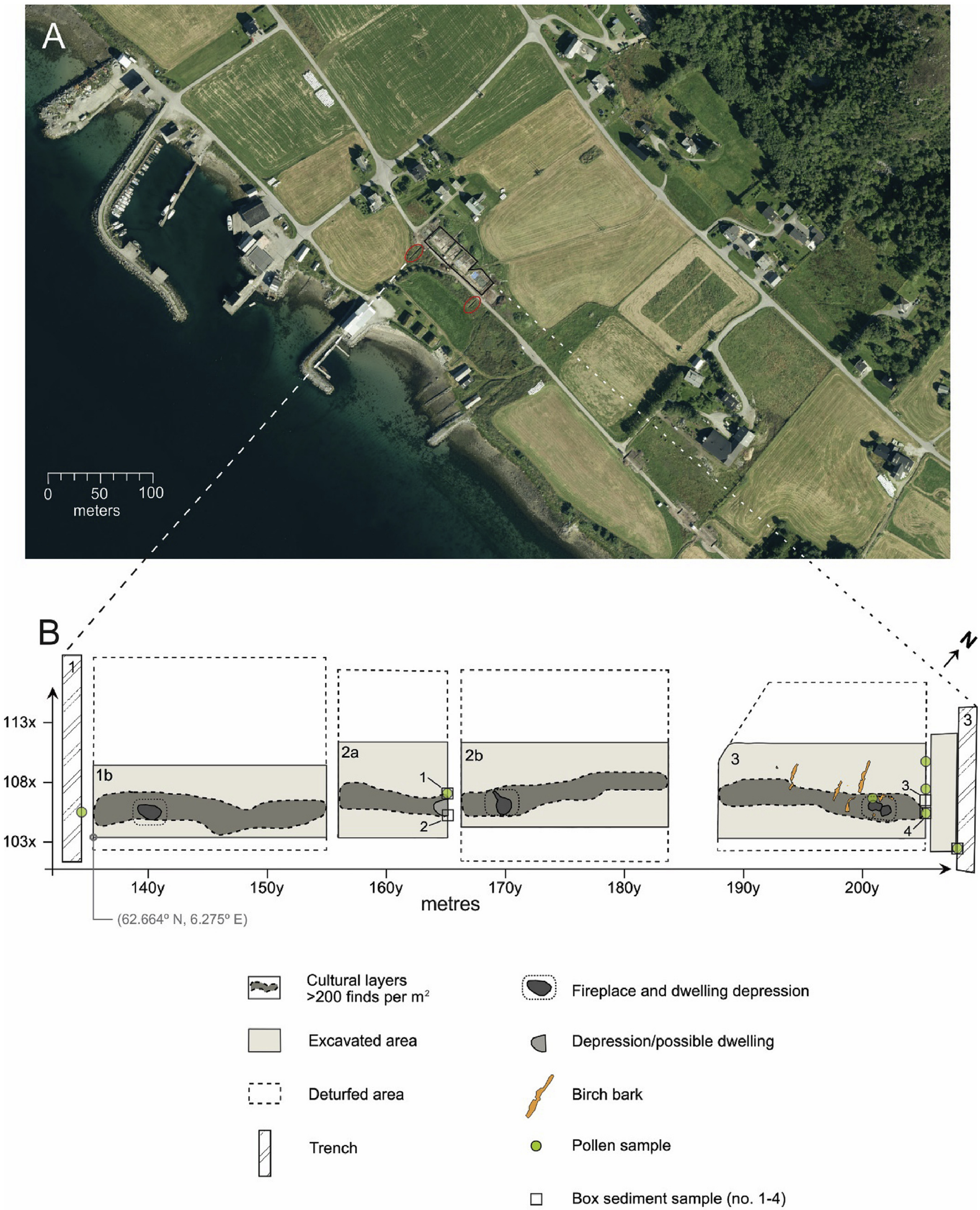

Fig. 2. (A) Aerial photograph showing the excavation area of locality 65 at Longva. Trench 1 and 3 were also extended south of the beach ridge, as indicated by red circles. Photo taken 20 August 2015. (B) Map of the excavated area with samples and finds. Field 1a, not shown on this map, is west of trench 1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 3. Overview of the excavations on the Tapes beach ridge, looking westwards. The cultural layer (E) is between the stippled lines. The well-developed strandflat can be seen in the distance above the three red boathouses. Drone photo, Trond Klungseth Lødøen. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

buried the peat as the beach ridge moved inland during the transgression.

Samples of bulk peat at the upper boundary was radiocarbon dated to be about 200–300 years younger than samples of birch bark and charcoal from layers F and E above (Table 2; Fig. 10). Such a young age for the bulk peat (between 7510 and 7830 cal yr BP, Table 2) is in conflict with the interpretation of the above sand sheet, layer H (see below) as deposited by the Storegga tsunami, dated elsewhere to 8150 cal yr BP (Bondevik et al., 2012). We thus believe that the bulk peat may be contaminated by younger carbon from roots growing into the peat. A similar contamination problem was encountered in the peat underneath the Tapes beach ridge on Harøy (Fig. 1B) (Bondevik, 2003).

4.1.3. *Layer H: Storegga sand layer (8150 cal yr BP)*

Across most of the excavated areas, there is an extensive sheet of sorted sand on top of the peat (I) (Figs. 4, 5 and 7). The layer thins inland, from >10 cm underneath the beach ridge to 1–2 cm at the end of the trenches (Fig. 5). The sand is mainly fine-grained, between 0.125 and 0.250 mm, but in some places we found individual clasts of gravel in the sand, ranging in size from 10 to 20 mm in diameter. According to grain size analysis of the sand layer along trench 1 and 3 (Figs. S3A and B), the sand becomes finer grained inland.

We also found a few fragments of wood and clasts of peat in the sand layer. The pollen composition (Fig. 6) is mainly similar to layer I, reflecting the source of the peat clasts. In some places the sand sheet is bedded, consisting of two beds (Fig. 7), a lower coarser grained bed and an upper finer grained bed. Towards the beach ridge, the sand sheet fingers into the beach ridge deposits (layer G), and we were not able to separate it from the beach ridge deposits (Figs. 4 and 5). Both the upper and lower boundaries of the bed are sharp.

We interpret the sand sheet as deposited by the Storegga tsunami. From the thinning of the bed and the finer grain size inland, it is obvious that the sand was deposited from the sea side. Its uniform character and widespread occurrence points to a single event. As mentioned above, the oldest radiocarbon age of birch bark in layer F just above the sand sheet is 7935–7790 cal yr BP, indicating that the sand sheet could very well have been deposited at 8150 cal years BP. Tsunami sand layers deposited and preserved in swales are well known, e.g. in Thailand (Jankaew et al., 2008) and northern Sumatra (Monecke et al., 2008), and are commonly 5–10 cm thick layers of fine sand, similar to layer H.

4.1.4. *Layer G: Beach pebbles and cobbles – proximal part of the Tapes beach ridge (8150–7800 cal yr BP)*

Layer G forms the lower and proximal part of the Tapes beach ridge and consists of sand, pebbles and cobbles. The cobbles are generally sub-rounded. The cobbles and pebbles are mainly supported in a matrix of coarse sand and fine gravel. Layer G rests sharply on peat (I) or sand (H). The layer is light gray in color and forms the proximal part of the beach ridge (Figs. 3–5). Its upper boundary is against either layer F (Fig. 4), a 2–3 cm thick layer of peat, or layer E (Figs. 5 and 8A). Its upper boundary is sharp.

4.1.5. *Layer F: Thin layer of peat with cultural remains of birch bark (7800–7600 cal yr BP)*

This thin discontinuous layer of peat is found between beach deposits of layer G and beach deposits with cultural remains (E), or, closer to the swale, between Storegga sand (H) and layer E (Figs. 4 and 5). It is about 2–3 cm thick. Organic remains of charcoal and birch bark in this peat are the oldest archaeological remains at the site.

The sheets of birch bark (Fig. 2B) could be remnants of the floors in dwelling depressions. In all we extracted nine sheets of birch bark, in total 4.53 m^2 (Table 1), dated to between 7800 and 7300 cal yr BP (Table 2). The age span indicates a long tradition in the use of birch bark at the site. Pollen samples from just above and below a sheet of birch bark in one of the dwelling depressions

Table 1
Artefacts typical of the late Mesolithic from layer E and F, locality 65 at Longva, Flemsøya.

Artefacts	Material	Number
Transverse arrowheads	Flint	7
Transverse arrowheads	Quartzite	1
Polished arrowheads[a]	Slate	6
Bifacial arrowheads	Flint	1
Adzes	Diabase	4
Adzes	Greenstone	2
Adzes	Undefined	7
Fish sinkers	Eclogite	9
Blade knives	Flint	1
Scrapers	Flint	48
Scrapers	Quartz	5
Scrapers	Quartzite	1
Drillbits	Flint	11
Drillbits	Quartz	1
Burins	Flint	9
Burins	Quartz	6
Retouched tools	Flint	79
Retouched tools	Quartz	6
Retouched tools	Quartzite	1
Retouched tools	Rock crystal	2
Retouched blades	Flint	54
Retouched blades	Quartz	1
Retouched blades	Quartzite	2
Retouched blades	Rock crystal	7
Retouched flakes	Flint	600
Retouched flakes	Quartz	51
Retouched flakes	Quartzite	9
Retouched flakes	Rock crystal	39
Retouched flakes	Mylonite	1
Micro blades (<8 mm)	Flint	520
Micro blades (<8 mm)	Quartz	3
Micro blades (<8 mm)	Quartzite	15
Micro blades (<8 mm)	Rock crystal	21
Blades (8–12 mm)	Flint	84
Blades (8–12 mm)	Quartz	1
Blades (8–12 mm)	Quartzite	1
Blades (8–12 mm)	Rock crystal	2
Blades (8–12 mm)	Mylonite	1
Macro blades (>12 mm)	Flint	11
Macro blades (>12 mm)	Quartzite	1
Bladelike flakes	Flint	188
Bladelike flakes	Quartz	10
Bladelike flakes	Quartzite	8
Bladelike flakes	Rock crystal	9
Micro blade cores	Flint	8
Micro blade cores	Quartz	2
Bipolar cores	Flint	2023
Bipolar cores	Quartz	126
Bipolar cores	Quartzite	13
Bipolar cores	Rock crystal	38
Cores (undefined)	Flint	245
Cores (undefined)	Quartz	85
Cores (undefined)	Quartzite	14
Cores (undefined)	Rock crystal	15
Cores (undefined)	Mylonite	1
Hammerstones	Quartzite	3
Hammerstones	Undefined	2
Grinding slabs	Quartzite	9
Grinding slabs	Sandstone	151
Grinding slabs	Slate	2
Pumice with usewear	Pumice	24
Flakes and debris	Flint	59018
Flakes and debris	Quartz	4172
Flakes and debris	Quartzite	877
Flakes and debris	Rock crystal	679
Flakes and debris	Sandstone	5
Flakes and debris	Mylonite	32
Flakes and debris	Slate	5
Flakes and debris	Undetermined	7
Charred nutshells[b]	Hazel (*Corylus avellana*)	40
Charcoal[b]	Birch (*Betula* sp.)	12
Charcoal[b]	Willow (*Salix* sp.)	1
Charcoal[b]	Undetermined	40
Bark sheets[c]	Birch (*Betula* sp.)	9 pieces (4.53 m^2[b])
Total	Flint	62907
Total	Quartz	4469
Total	Quartzite	955
Total	Rock crystal	812
Total	Sandstone	156
Total	Mylonite	35
Total	Pumice	24
Total	Slate	13
Total	Eclogite	9
Total	Diabase	4
Total	Greenstone	2
Total	Undefined	17

[a] Early Neolithic feature.
[b] Collected for radiocarbon dating from defined structures (fireplaces, dwelling depressions) and profiles. Many of the charcoal pieces were identified as pine, but these were not selected for dating. One sample would normally consist of many fragments.
[c] Probably remains of a floor – see Fig. 2B for location. All nine bark sheets were radiocarbon dated, see Table 2.

(Fig. 2B and S4) were analyzed and show that birch grew in the vicinity at the time. The peat layer must have developed before the site was occupied, and the birch bark might have been utilized to protect the dwelling huts against underground moisture. This interpretation is supported by the large amounts of Cyperaceae in the pollen record (Fig. S4), which indicate humid conditions.

The thin layer of peat between the beach ridge (G) and the cultural deposits (E) indicates a period of some years without material being thrown over the crest of the beach ridge. It also suggests that the highest sea level during the transgression, when storms would most easily throw beach material over the top of the ridge, was reached later. The peat layer F may be seen as a continuation of peat layer I, as is also indicated by the high degree of similarity in pollen composition between the top of layer I and one sample from the bottom of layer F, from below the birch bark (on the right side of the diagram in Fig. 6A, and Fig. S4).

4.1.6. *Layer E: Beach pebbles and cobbles with cultural remains (7600–5600 cal yr BP)*

Layer E is a cultural layer built up of waste from the Mesolithic occupation intermixed with beach pebbles and cobbles. The layer is found inland and above the crest of the beach ridge (G) (Figs. 3–5). It is 10–40 cm thick, occasionally resting on a thin layer of peat (F) (Fig. 5). Where peat (F) is missing, it has a sharp boundary to beach layer G (Figs. 5 and 8A). The layer is about 3–5 m wide and tapers off inland, into the swale (Figs. 4 and 5). Inspection in the field and examination of detailed photos of the trenches indicate that the layer coarsens upwards and is slightly layered, with a gentle dip towards the swale (Fig. 5). This shows that the layer was deposited from the sea side towards the swale.

The layer has a black and fatty appearance, quite different from the clean beach gravel below (G). This is due to the decomposed organic material between the cobbles and pebbles. Typical archaeological remains include waste flakes, stone tools (Fig. 9A), charcoal, burnt hazelnut shells, fire-cracked rocks and fish sinkers of eclogite (Figs. 8C and 9B). In total we collected 69,403 lithic artefacts, mainly of flint (Table 1). Pollen analysis of samples from the layer (Fig. 6 and S1, S5–S7) shows microscopic charcoal and species found in open vegetation, including several nutrient-demanding species, e.g. *Urtica* (nettle) and *Galeopsis* (hemp-nettle). These indicate the production and deposition of organic waste from human occupation. Nettle, in particular, is commonly found in Mesolithic settlement sites (Hjelle et al., 2012). The PCA plot shows that the pollen composition in most of the samples from layer E

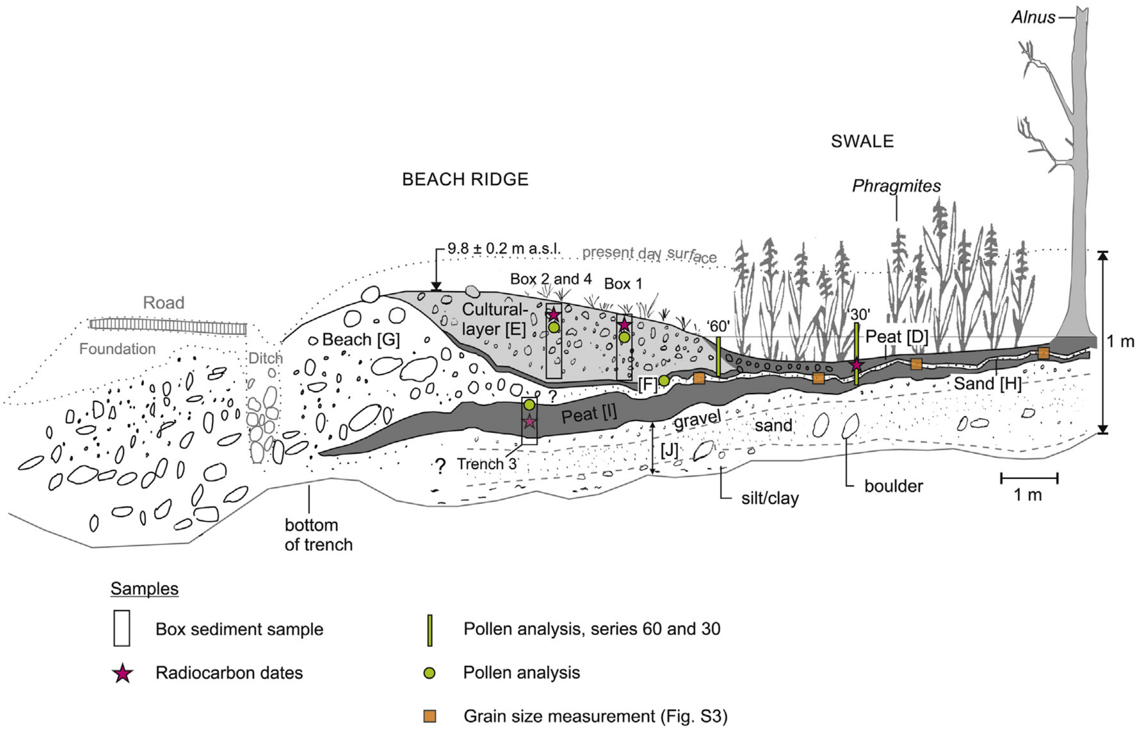

Fig. 4. A cross section through the Tapes beach ridge based on mapping and photos of the stratigraphy in the excavated trenches, trench 1 and 3 (see Fig. 2B for location). Approximate positions of sediment samples collected for pollen analysis, grain size analysis and radiocarbon dating are projected on to this profile (see Fig. 2B for location). Sand sheet (H), between peat layers, is inferred to have been deposited by the Storegga tsunami. The peat contains stems/roots of *Phragmites* (common reed), showing that reeds must have grown in the swale, drawn in gray for illustration. Stippled features in pale gray show modern topography or structures. Vertical scale is nearly three times the horizontal scale. View looking westwards.

differs from that in all other analyzed layers.

We radiocarbon dated 61 samples of burnt hazelnut shells and charcoal from this layer (Table 2, Fig. 10). The dates clearly show two periods of occupation: the older and longer between 7600 and 6800 cal yr BP (middle and late part of the Late Mesolithic), and the younger between 6200 and 5900 cal yr BP (end of the Mesolithic/early Neolithic). The dates seem to indicate that there was no or very limited and infrequent occupation for a period of 600 years between 6800 and 6200 cal yr BP.

The Tapes beach ridge may have continued to accumulate into the Early Neolithic. We found six fragments of Neolithic polished slate points at the very top of the layer (Table 1). Three of the radiocarbon dates from the top of the layer are 5400–5600 cal yr BP (Fig. 10), in agreement with the Neolithic slate points. Unfortunately, we were not able to document whether these Neolithic fragments really were buried in beach sediments, or whether they were found just above layer E, and would date from after the formation of the beach ridge. The pollen diagram from layer E in box 1 (Fig. S7) – dated on hazelnut shells (Fig. 12) – shows deposition of *Urtica* pollen and charcoal to at least 6000 cal yr BP. We suggest that the Early Neolithic fragments and samples dated to 5400 and 5600 cal yr BP belong to the top of layer E, and that the Tapes beach ridge continued to accumulate until around 5600 cal yr BP.

4.1.7. Layer D: Peat, with scattered beach pebbles in the lower part, accumulated in the swale (from minimum 6400 cal yr BP)

Layer D is brown peat, but in several places, especially at field site 1b, we found many pebbles and small cobbles within the peat (Figs. 3 and 7). In these places the layer has a large contrast in grain size, from the *in situ* organic material that forms the peat, to the rounded pebbles and cobbles supported by the peat (Fig. 7). The pebbles and cobbles occur in the lower part of layer D (Figs. 4 and 5). We only found a few archaeological remains in this peat, although we searched quite extensively for them.

We interpret layer D as a combination of peat formed in the swale from accumulation of organic material in a wet environment and pebbles and cobbles from the beach thrown over the beach ridge and into the swale during severe storms. Like peat (F), peat (D) can be viewed as a continuation of peat (I). The dispersed clasts of pebbles and cobbles in the lower part of the peat are a continuation of the beach ridge deposits (layers G, E) into the swale. Pollen analysis indicates that alder (*Alnus*) swamp developed in the swale with Poaceae (probably *Phragmites*), *Filipendula* and *Caltha* (marsh marigold) reflecting the humid conditions. Microscopic charcoal is only recorded in the lower pollen samples from layer D (Fig. 6 and Fig. S7).

4.2. Archaeological remains

The majority of the finds in layer E are of Mesolithic origin. Flint is by far the most common raw material (90%), but quartz, quartzite and rock crystal are also represented (Table 1). Most of the archaeological remains are waste flakes (93%) from tool production. The tools include transverse arrowheads and polished rock adzes (axe with cutting edge perpendicular to the handle; Fig. 9A), blade knives, scrapers, flakes and blades with secondary retouch and use-wear, and regular blades, mainly microblades, as well as associated cores and nine large, possibly, fish sinkers.

The fish sinkers are well-rounded rocks of eclogite. They have a furrow cut lengthwise on both sides (Figs. 8C and 9B) and weigh from 328 to 834 g. The broad-cut furrow indicates that they were tied to a rope and possibly used for nets or fish traps (Åstveit, 2008),

Table 2
Radiocarbon ages from locality 65 at Longva, Flemsøya. All samples were measured at Beta Analytic Inc., Miami, USA.

Beta lab no.	Sample	Material[a]	Layer[b]	^{14}C age BP	Cal yr BP[c]	Location; Context
415029	LO-34	Hazelnut shell	E	6570 ± 30	7555–7430	Site 1b (104.5 x | 151 y)
415028	LO-33	Hazelnut shell	E	6140 ± 30	7160–6945	Site 1b (104.5 x | 166 y)
458883	LO-74	Hazelnut shell	E	6440 ± 30	7425–7310	Site 1b (104.5 x | 151 y)
458884	LO-75	Charcoal (*Betula* sp.)	E	6400 ± 30	7420–7265	Site 1b (104.5 x | 151 y)
458885	LO-76	Charcoal (*Betula* sp.)	E	6740 ± 30	7660–7570	Site 1b (104.5 x | 151 y)
458886	LO-77	Charcoal (*Betula* sp.)	E/G	6880 ± 30	7785–7665	Site 1b (104.5 x | 151 y)
458882	LO-73	Charcoal (*Betula* sp.)	E (top)	6220 ± 30	7245–7015	Site 1b (104.5 x | 151 y)
415030	LO-35	Hazelnut shell	E	6520 ± 30	7470–7420	Site 1b (105 x | 141 y); Fireplace
415031	LO-36	Hazelnut shell	E	6480 ± 30	7435–7325	Site 1b (105 x | 141 y); Below fireplace
389722	LO-20	Hazelnut shell	E (base)	6680 ± 30	7590–7505	Site 1b (107 x | 143 y)
389720	LO-18	Hazelnut shell	E (top)	6160 ± 30	7165–6955	Site 1b (107 x | 143 y)
389721	LO-19	Charcoal (*Betula* sp.)	E (middle)	6070 ± 30	7000–6805	Site 1b (107 x | 143 y)
458888	LO-79	Hazelnut shell	D	6310 ± 30	7275–7170	Site 1b (108 x | 155 y)
428849	LO-50	Hazelnut shell	E (top)	5150 ± 30	5980–5895	Site 2a (105 x | 166 y)
428850	LO-51	Hazelnut shell	E	6020 ± 30	6945–6785	Site 2a (105 x | 166 y)
458899	LO-90	Hazelnut shell	E	5830 ± 30	6720–6560	Site 2a (105 x | 166 y)
458900	LO-91	Charcoal (*Betula* sp.)	E (base)	6500 ± 30	7440–7335	Site 2a (105 x | 166 y)
472532	LO-104	Hazelnut shell	E (base)	6050 ± 30	6975–6800	Site 2a (105 x | 166 y); Box sample 2: 0–5 cm
472533	LO-105	Hazelnut shell	E	6270 ± 30	7260–7160	Site 2a (105 x | 166 y); Box sample 2: 5–10 cm
472534	LO-106	Hazelnut shell	E	6180 ± 30	7165–6990	Site 2a (105 x | 166 y); Box sample 2: 10–15 cm
472535	LO-107	Hazelnut shell	E	6140 ± 30	7160–6945	Site 2a (105 x | 166 y); Box sample 2: 15–20 cm
472536	LO-108	Hazelnut shell	E (top)	6160 ± 30	7165–6955	Site 2a (105 x | 166 y); Box sample 2: 20–25 cm
472527	LO-99	Hazelnut shell	E (base)	6100 ± 30	7150–6980	Site 2a (106 x | 166 y); Box sample 1: 5–10 cm
472528	LO-100	Hazelnut shell	E	6080 ± 30	7005–6880	Site 2a (106 x | 166 y); Box sample 1: 10–15 cm
472529	LO-101	Hazelnut shell	E	5420 ± 30	6290–6185	Site 2a (106 x | 166 y); Box sample 1: 15–20 cm
472530	LO-102	Hazelnut shell	E	5250 ± 30	6175–5930	Site 2a (106 x | 166 y); Box sample 1: 20–25 cm
472531	LO-103	Hazelnut shell	E (top)	5460 ± 30	6275–5930	Site 2a (106 x | 166 y); Box sample 1: 25–30 cm
428843	LO-44	Hazelnut shell	E/F	6230 ± 40	7255–7010	Site 2a (107 x | 162 y)
389708	LO-6	Charcoal (*Betula* sp.)	D/E (top)	4730 ± 30	5585–5325	Site 2a (107 x | 163 y)
389704	LO-2	Hazelnut shell	E (top)	5230 ± 30	6095–5920	Site 2a (107 x | 159 y)
389705	LO-3	Hazelnut shell	E (middle)	5220 ± 30	6000–5915	Site 2a (107 x | 159 y)
428841	LO-42	Hazelnut shell	D	5250 ± 30	6175–5930	Site 2a (107 x | 162 y)
428842	LO-43	Hazelnut shell	E	5250 ± 30	6175–5930	Site 2a (107 x | 162 y)
389706	LO-4	Hazelnut shell	E (base)/F	5800 ± 30	6670–6500	Site 2a (107 x | 159 y)
389709	LO-7	Charcoal (*Betula* sp.)	D/E (middle)	6140 ± 30	7160–6945	Site 2a (107 x | 163 y)
428853	LO-54	Hazelnut shell	E	5330 ± 30	6210–5995	Site 2b (105 x | 170 y); Fireplace
431633	LO-55	Hazelnut shell	E	6440 ± 30	7425–7310	Site 2b (105 x | 170 y); Fireplace
389711	LO-9	Charcoal (*Salix* sp.)	E (top)	4830 ± 30	5605–5485	Site 2b (107 x | 172 y)
389712	LO-10	Charcoal (*Betula* sp.)	E (base)	6110 ± 30	7155–6895	Site 2b (107 x |172 y);
428846	LO-47	Charcoal (*Betula* sp.)	E	6560 ± 40	7560–7425	Site 3 (105 x | 200 y); Fireplace
428844	LO-45	Birchbark	F	7010 ± 30	7935–7790	Site 3 (105 x | 201 y)
428847	LO-48	Charcoal (*Betula* sp.)	E	5980 ± 30	6890–6740	Site 3 (105 x | 201 y); Possible fireplace
468567	LO-93	Birchbark	F	6500 ± 30	7474–7225	Site 3 (106 x | 199 y)
428845	LO-46	Birchbark	F	6870 ± 40	7790–7620	Site 3 (106 x | 203 y)
428851	LO-52	Hazelnut shell	D/E	6130 ± 30	7160–6940	Site 3 (106 x | 205 y)
428852	LO-53	Hazelnut shell	E	6100 ± 30	7150–6890	Site 3 (106 x | 205 y)
458901	LO-92	Hazelnut shell	E (middle)	6070 ± 30	7000–6805	Site 3 (106 x | 205 y)
458894	LO-85	Charcoal (*Betula* sp.)	E (top)	6120 ± 30	7165–6800	Site 3 (107 x | 188 y)
458895	LO-86	Hazelnut shell	E	6360 ± 30	7410–7250	Site 3 (107 x | 188 y)
458896	LO-87	Hazelnut shell	E	6320 ± 30	7310–7175	Site 3 (107 x | 188 y)
458897	LO-88	Hazelnut shell	E	6450 ± 30	7430–7315	Site 3 (107 x | 188 y)
458898	LO-89	Charcoal (*Betula* sp.)	E (base)	6480 ± 30	7435–7325	Site 3 (107 x | 188 y)
389714	LO-12	Hazelnut shell	E (base)	6560 ± 30	7505–7425	Site 3 (107 x | 190 y)
389713	LO-11	Hazelnut shell	E (top)	6210 ± 30	7240–7010	Site 3 (107 x | 190 y)
468571	LO-97	Birchbark	F/E (base)	6630 ± 30	7574–7460	Site 3 (107 x | 194 y)
389715	LO-13	Hazelnut shell	E (top)	4020 ± 30	4565–4420	Site 3 (107 x | 196 y)
389716	LO-14	Hazelnut shell	E (base)	6570 ± 30	7555–7430	Site 3 (107 x | 196 y)
389717	LO-15	Charcoal (*Betula* sp.)	E	6540 ± 30	7485–7425	Site 3 (107 x | 196 y)

(*continued on next page*)

Table 2 (*continued*)

Beta lab no.	Sample	Material[a]	Layer[b]	^{14}C age BP	Cal yr BP[c]	Location; Context
415035	LO-37	Birchbark	E	6550 ± 30	7495–7425	Site 3 (107 x | 198 y)
468568	LO-94	Birchbark	F	6570 ± 30	7555–7430	Site 3 (107 x | 199 y)
389718	LO-16	Hazelnut shell	E (top)	6330 ± 30	7315–7180	Site 3 (107 x | 201 y)
389719	LO-17	Hazelnut shell	E (base)	6340 ± 30	7320–7245	Site 3 (107 x | 201 y)
468572	LO-98	Birchbark	F/E (base)	6530 ± 30	7507–7340	Site 3 (108 x | 192 y)
468570	LO-96	Birchbark	F/E (base)	6650 ± 30	7580–7475	Site 3 (108 x | 194 y)
468569	LO-95	Birchbark	F	6740 ± 30	7662–7569	Site 3 (108 x | 203 y)
415036	LO-38	Hazelnut shell	E	6450 ± 30	7430–7315	Trench 1 (101 x | 134 y)
415037	LO-39	Hazelnut shell	E (base)	6360 ± 30	7410–7250	Trench 1 (101 x | 134 y)
458891	LO-82	Hazelnut shell	E (top)	4840 ± 30	5605–5485	Trench 1 (101 x | 134 y)
458892	LO-83	Hazelnut shell	E	6360 ± 30	7410–7250	Trench 1 (101 x | 134 y)
458887	LO-78	Charcoal (*Betula* sp.)	F	6130 ± 30	7160–6940	Trench 1 (105 x | 135 y)
428840	LO-41	Hazelnut shell	E (base)	6730 ± 30	7620–7570	Trench 1 (105 x | 135 y)
428839	LO-40	Charcoal (*Betula* sp.)	E (top)	5680 ± 30	6500–6405	Trench 1 (105 x | 135 y)
427476	K-56588	Bulk peat	F (top)	5520 ± 30	6400–6290	Trench 1 (pollen)
427479	K-56592	Bulk peat	I (top)	6710 ± 30	7650–7510	Trench 1 (pollen)
446626	K-56595	Bulk peat	I (middle)	7430 ± 30	8330–8190	Trench 1 (pollen)
427478	K-56598	Bulk peat	I (base)	8290 ± 30	9425–9140	Trench 1 (pollen)
482271	K-57238	Bulk peat[d]	D (lower)	5620 ± 30	6465–6315	Site 3 (pollen series 30)
482272	K-57339	Bulk peat	I	6210 ± 30	7240–7010	Site 3 (pollen series 30)
427477	K-16148	Bulk peat[e]	I (top)	6810 ± 30	7685–7595	Trench 3 (pollen)
428312	K-16148	Bulk peat[d]	I (top)	6930 ± 30	7830–7690	Trench 3 (pollen)
446625	K-16158	Bulk peat[d]	I (middle)	7720 ± 30	8580–8430	Trench 3 (pollen)
446624	K-16166	Bulk peat[d]	I (lower)	8430 ± 30	9520–9425	Trench 3 (pollen)
428313	K-16170	Bulk peat[d]	I (base)	8460 ± 30	9530–9445	Trench 3 (pollen)
427480	K-16170	Bulk peat[e]	I (base)	9230 ± 30	10,500–10,280	Trench 3 (pollen)

[a] The hazelnut shells (*Corylus avellana*) were all charred.
[b] Where possible we indicate the level within the layer (top, middle, lower and base). Where there is a slash (/) between two layers, we did not/could not decide which layer the sample was from.
[c] 2σ range interval.
[d] Insoluble fraction.
[e] Soluble fraction.

or as sinkers for a fishing line with hooks used in deeper water (Bergsvik, 2017). The bedrock at Longva is migmatite gneiss, but there is a small outcrop of eclogite on the northern side of the island (Norwegian Geological Survey), and eclogite is also known to occur as individual rocks at Longva (pers. com. Oddvar Longva). It could be that rocks of this type were selected as fish sinkers because eclogite has a higher density (3.5 g/cm^3) than most other rock types (2.6–2.8 g/cm^3), or because the red garnet in a grass-green matrix of pyroxene (omphacite) has such a striking appearance (Fig. 8C).

The excavations documented three dwelling depressions with associated fireplaces, but it seems reasonable to assume that there could have been many more, obliterated by later cultural activity and/or wave action. One of the dwelling depressions revealed pieces of birch bark, which are likely to derive from the floor construction (see above and Figs. 2B and 8B). Similar but slightly older sheets of birch bark were also recovered in a cultural layer at Dysvikja, on the neighboring island of Fjørtoft (Fig. 1B), and were interpreted as the remains of a floor (Indrelid, 1973). Floors of bark are well known from Mesolithic sites in Germany (e.g. Duvensee Wohnplätze) and Denmark (e.g. Barmosen 1 or Ulkestrup Lyng I og II) (Andersen, 1982; Sørensen et al., 2018).

However, several of the birch bark sheets were found outside the dwelling depressions (Fig. 2B), and may have had a different function. Birch bark found at other prehistoric sites elsewhere in Scandinavia has been used for other purposes, such as containers (Fletcher et al., 2018) and canoes (Westerdahl, 1985a, b). The elongated sheets of birch bark perpendicular to the shoreline outside the dwelling depression (Fig. 2B) might be the remains of canoes. We searched for evidence of stitch holes or cut edges of bark, but found none. The sheets could also have been collected for use at a later date.

5. Discussion

5.1. How was the cultural layer deposited?

The geological process that leads to the formation of a beach ridge is a key to understanding the archaeological setting. A beach ridge – called a berm when actively formed (Otvos, 2000) – is related to the storm water level and to the exposure of the beach to waves (e.g. (Bendixen et al., 2013; Clemmensen et al., 2016)). The berm is formed by wave run-up during extreme sea levels in a storm surge (Fig. 11). The waves throw cobbles, pebbles and sand on top of the berm and landward of the berm crest. Layer E consists mainly of rounded pebbles and cobbles, in addition to the remains of human activities. Plenty of pebbles were also found supported by peat in layer D, documenting that waves threw pebbles as far as the swale (Figs. 4, 5 and 7). Layer E is a result of a combination of storm waves overtopping the beach ridge with sediments, and human occupation.

Human activities modified layer E. There are traces of fireplaces with a collection of larger cobbles, many fire-cracked rocks and possible foundations dug into the layer (Fig. 2B). The blackish color and fat-like texture of the layer are due to charcoal and decomposed organic material (Fig. 8A). The archaeological material must have accumulated at different rates and at different places on the beach ridge depending on human activities and the duration of the different occupation periods.

The same factors must have affected the degree of compaction of the layer. Fig. 2B shows that the archaeological material has a relatively even distribution with few clear concentration areas. This suggests that layer E to some extent has been affected by the added beach sediments and sea splash during storm surges, which could have disturbed and evened out the archaeological material. However, the small amount of water-rolled lithic archaeological

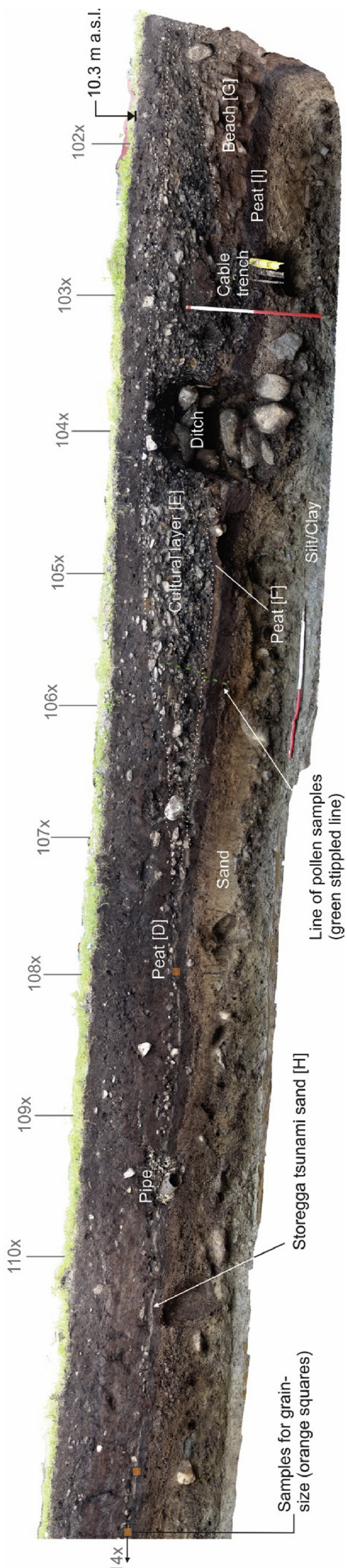

Fig. 5. Composite image (photogrammetry) of the stratigraphy of trench 1, eastern wall (looking eastwards). The white and red rod is 1 m long. The beach pebbles and cobbles of layer E, inside the white stippled line, contains the cultural remains. The black appearance of this layer is due to charcoal and burnt stones. X-coordinates show 1 m intervals based on the local grid (see Fig. 2B). Green stippled line between 105x and 106x shows the location of the pollen profile (Fig. S1). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

material (0.2%) shows very little, if any, influence of wave abrasion. The pollen composition reflects terrestrial plants typical of areas where organic material accumulates and trampling causes disturbance.

The sequences of radiocarbon ages show little sign of vertical mixing of the layer. To test the degree of reworking, we radiocarbon-dated hazelnut shells at 5 cm intervals from the bottom to the top of layer E in two box samples, box 1 and box 2 (Figs. 2B and 4, Table 2). With one exception – the deepest sample in box 2 – the samples fitted a sequence from older to younger upwards through the layer (Fig. 12). The dates also show that the accumulation rate is about three times higher in box 2 than in box 1, and that the dates are older in box 2 than in box 1. This is because layer E grew from the beach ridge into the swale. Box 1 is about 2 m closer to the swale than box 2 (Figs. 2B and 4). At the location of box 1, pebbles would accumulate more slowly and later than in box 2, which is located closer to the crest of the beach ridge and the source of the pebbles. We also plotted all the dates that can be attributed to either the top, middle or base of layer E (not shown here), and the same picture arose showing more recent dates towards the top of the layer.

Bjerck (1982) studied cultural remains of the same age in the same beach ridge at Stølen (Fig. 1B), but reached a different conclusion. He interpreted the cultural layer (his bed 10) as being deposited before the Tapes transgression maximum, but the deposits above the cultural layer (his bed 11) as a result of the Tapes transgression. He suggested that when the waves washed over the site, the occupants would abandon it. However, his layer 10, according to his own descriptions, is clearly a mixture of beach gravel and cultural remains. According to our interpretation, his layers 10 and 11 both correspond to our layer E, and show occupation through the sea-level high stand following the transgression maximum.

5.2. Settlement and subsistence on a growing beach ridge in the Late Mesolithic

It is quite surprising to find evidence that people settled on an actively growing beach ridge. At Longva, storm waves have thrown beach sediments – cobbles, pebbles and sand – on to, and over the settlement, and obviously, this must have been difficult to cope with. During a big storm at such an exposed location, it is fair to assume that tents, building structures, boats, storage and food supplies would be unlikely to survive undisturbed. This suggests that the beach ridge would mainly be occupied during fair weather conditions, e.g. McFadgen (1987).

The location on the beach ridge and the presence of artefacts such as fish sinkers and arrowheads indicate that the settlement mainly subsisted on fishing, and hunting of sea mammals and sea birds. Unfortunately, no osteological material was found and all the bones, which we assume would have been plentiful, are likely to have decomposed, so we cannot say what species were fished or hunted. However, the heavy line or net fish sinkers suggest that fishing was important and took place in deeper water and with the use of boats. At Stølen, Bjerck (1982) collected about 30 fragments of burnt bones. Some of the fragments were identified as trout and some unspecified to medium sized mammals – that likely could be seal bones. On the other hand, the many hazelnut shells show that people also exploited the inland area of the island, because hazel grows in more sheltered areas at some distance from the sea.

The size of the settlement and the character of the archaeological material suggest long-term occupation. The deposits of organic waste are thick and embed a huge variety of flakes and other remains from past activities. Further evidence is provided by the presence of dwelling depressions, associated with a possible

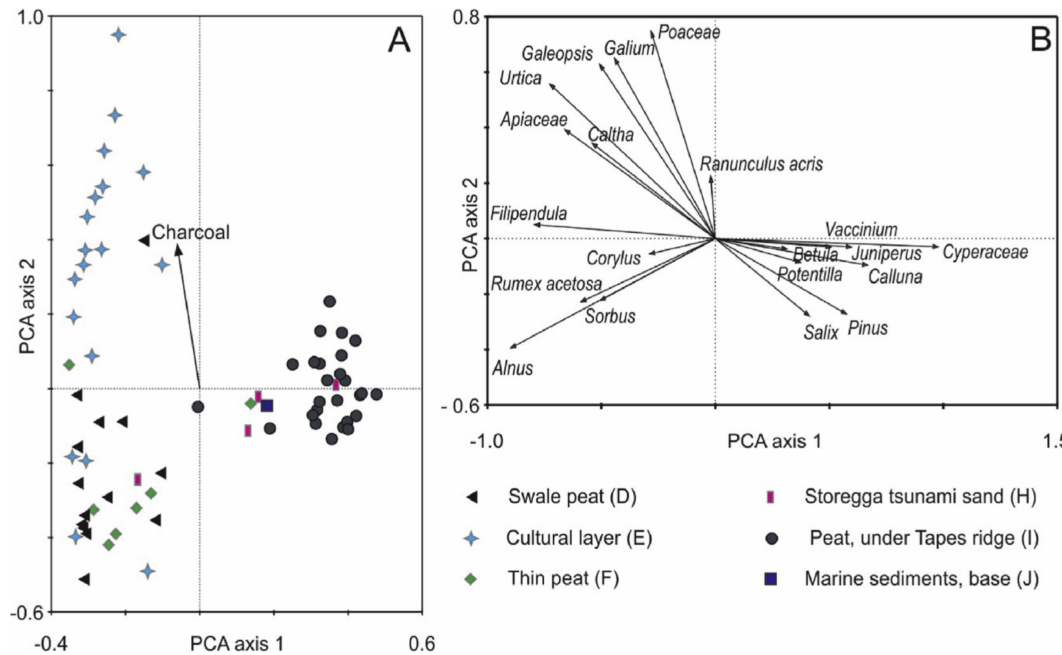

Fig. 6. Principal component analysis (PCA) plots of all pollen samples from seven different locations (see Fig. 2B). Axis 1 explains 59.8% of the variation and axis 2 explains 9.8%. (A) Plot of all pollen samples from the different layers, J to D. (B) Species (only selected species shown). The first axis shows the importance of Cyperaceae (sedges) and dwarf shrubs (*Calluna* and *Vaccinium*) in peat layer I. Samples from the Storegga tsunami sand layer H are similar to layer I, as is one sample from the bottom of the peat (F). Samples from layers D, E and F plot on the negative side of the first axis because of the high values of *Filipendula* (meadowsweet). The second axis separates samples from (F) and (D), characterized by *Alnus*, from the cultural layer (E). The cultural layer is associated with *Urtica* (nettle), *Galeopsis* (hemp-nettle) and Poaceae (grasses), as well as microscopic charcoal. See Fig. S9 for additional information.

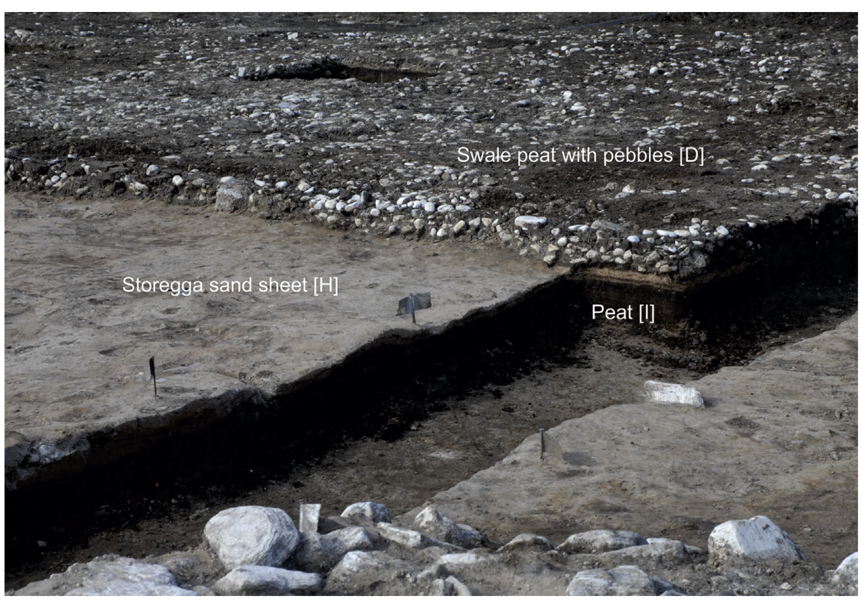

Fig. 7. Photo of Storegga tsunami sand sheet (H) and wave-thrown beach pebbles supported by peat (D) from excavation field 1b (Fig. 2B). Photo Stein Bondevik.

birch bark floor, fireplaces and the variety of artefacts, such as fish sinkers, adzes, chisels, knives, scrapers, arrow points and polishing plates, clearly indicating that a number of different activities took place at the site. Moreover, development of nutrient demanding vegetation communities support deposition of organic waste. Altogether, this indicates that people must have lived here for a longer time, and not only for short visits. However, the location of the settlement, on top of the actively growing beach ridge, suggests occupation during favorable weather conditions.

We therefore conclude that the site at Longva was mainly occupied outside the stormy season. Today, most of the storms in this area occur between November and February. At that time of the year, the settlement was probably abandoned and people moved to a place with more shelter. During a storm surge, the sea would wash over the ridge and deposit pebbles and cobbles on top of the settlement (Fig. 11). The deposition of beach material is probably also what protected the artefacts – the cultural remains were regularly covered by beach material. However, the next spring or

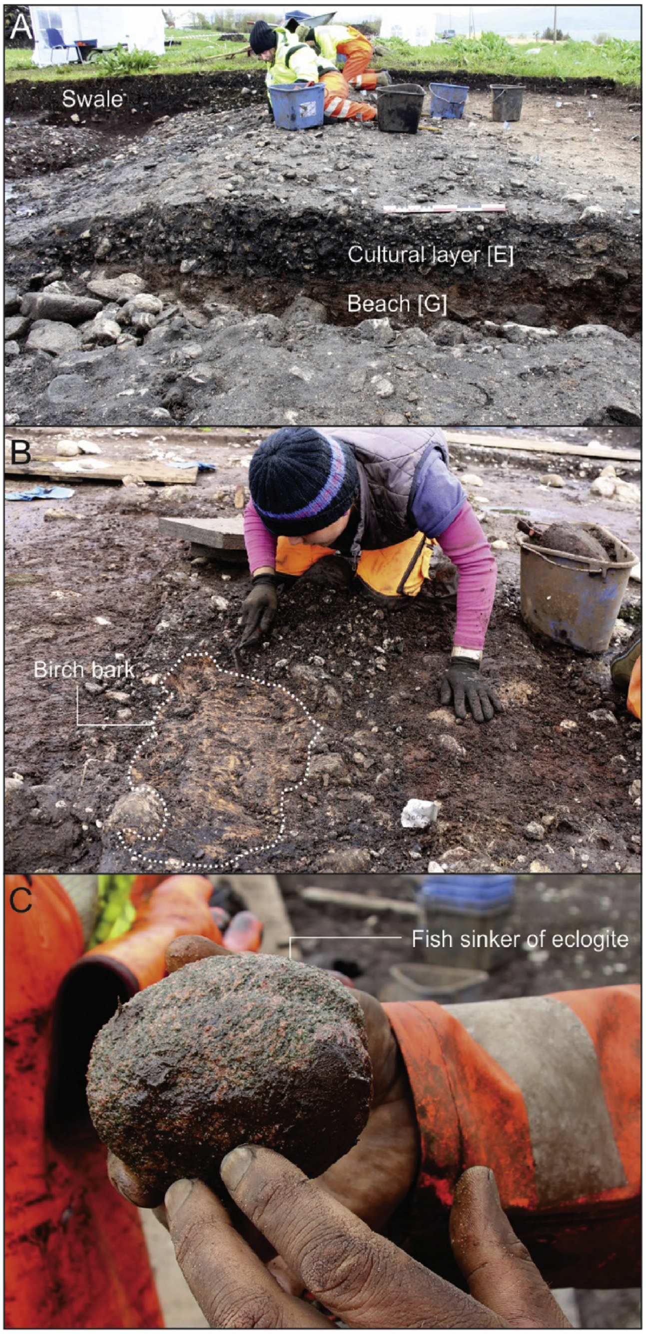

Fig. 8. Photos from the excavations. (A) Sharp boundary between the cultural layer E and beach G. (B) Birch bark at the base of layer F. (C) Fish (line or net) sinker of eclogite, photo Hanne Årskog. Other photos, Trond Klungseth Lødøen.

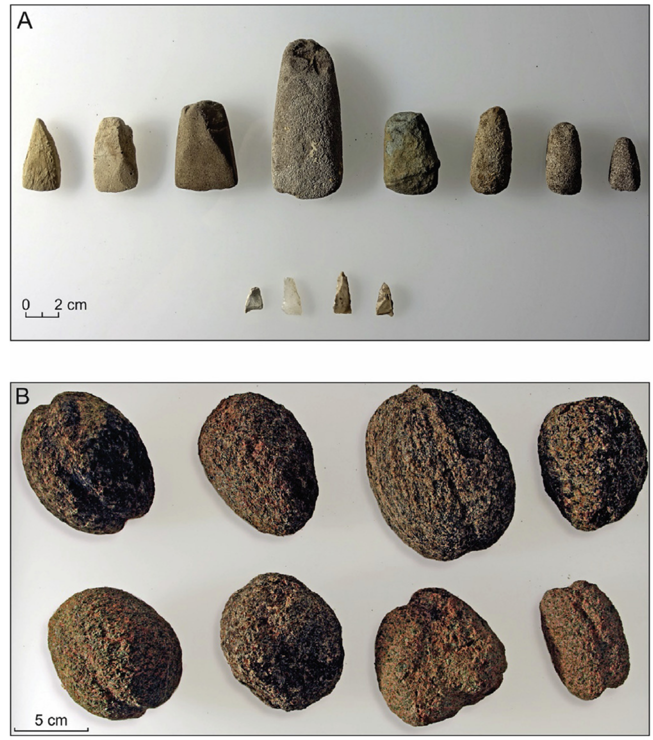

Fig. 9. Some of the lithic archaeological material. (A) Polished rock adzes (top) and transverse arrowheads (bottom). (B) Fish sinkers of eclogite. Photo, Nikolai Rypdal Tallaksen.

summer people would return and restore the site.

If Longva was not their permanent base, where did they spend the rest of the year? People must have arrived on the island by boats, and boats must also have been vital for fishing and hunting (Bjerck, 2017). The shortest distance to the mainland is only 6 km (Fig. 1B), a distance that could easily be travelled by canoe/umiak in a day (Rowley-Conwy and Piper, 2017). The people could have spent the winter months, or a longer period, somewhere on the mainland or elsewhere on the island or neighboring islands where there was shelter from the winter storms. The important point is that they returned regularly to Longva, probably as part of a regional mobile settlement pattern (Bergsvik, 2001; Rowley-Conwy and Piper, 2017).

The Tapes beach ridge must have been an attractive place to settle. Stølen (Fig. 1B) was occupied at the same time as Longva, according to the overlapping radiocarbon dates (Bjerck, 1982) (Fig. 10, Table 2). There may thus have been several families on the beach ridge at the same time, all participating in fishing and hunting. The beach ridge would have provided a site where it was easy to launch boats and equipment used for fishing and hunting and where catches could readily be landed. There would also have been some shelter from wind and waves on the distal side of the exceptionally broad beach ridge. Moreover, there would have been a strategic good view of the “shipping lane” between the mainland and the Nordøyane islands from the crest of the beach ridge (Fig. 1B).

Few of the samples from the cultural layer (E) that were radiocarbon dated are from the period 6200–6800 cal yr BP (Fig. 10, Table 2), suggesting that the site was abandoned or only used to a limited extent during these 600 years. This gap may coincide with the maximum sea level following the Tapes transgression (Fig. 13), and could indicate that the slightly higher sea level and higher reach of the storms was unfavorable for the settlement and caused people to move or only occupy the site for short periods. The large quantities of pebbles in the swale peat at site 1b (Fig. 7) show that material has been thrown over the beach ridge and into the swale. One possibility is that the layer of pebbles in the swale peat was deposited during this period. Unfortunately, we do not have any radiocarbon ages to confirm this hypothesis. However, the absence of radiocarbon dates between 6200 and 6800 cal yr BP could also have other explanations, such as a decline in the population, poor preservation of samples etc.

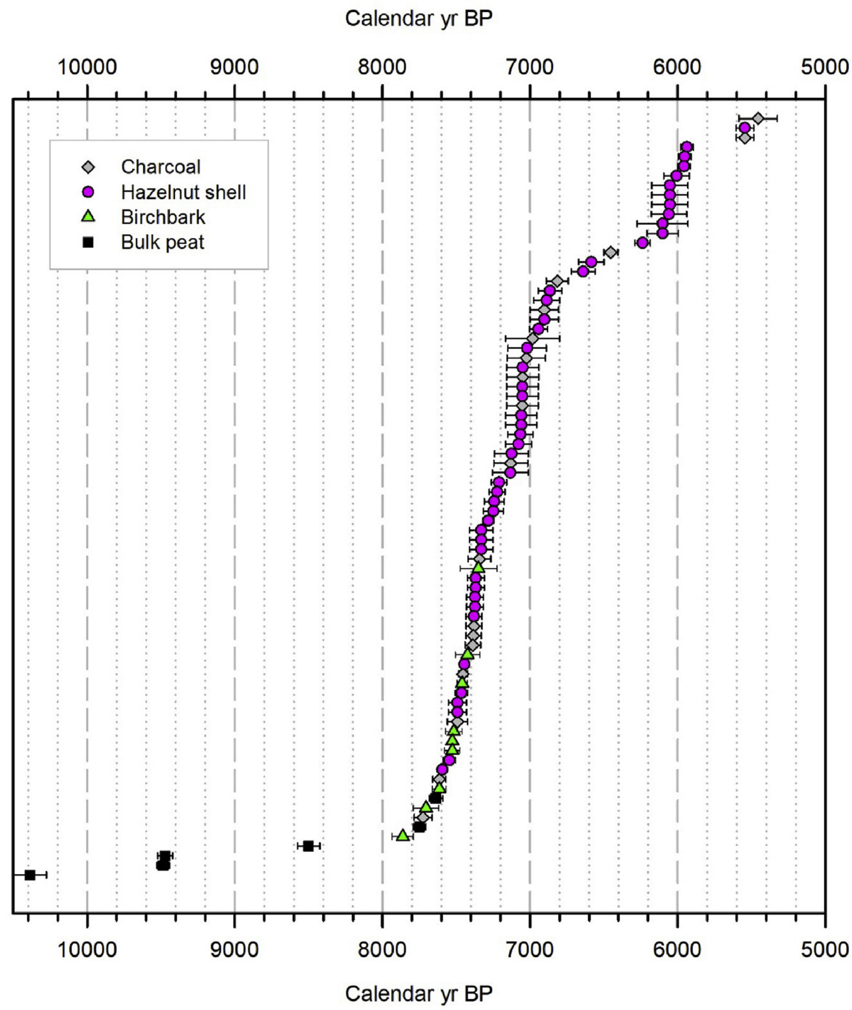

Fig. 10. All radiocarbon dates plotted in descending order towards the right. Peat bulk dates are from layer I in trench 3, below the Storegga sand sheet, all the other dates are from layer F and layer E. From the distribution of dates we see two late Mesolithic occupations, the first between 7800 and 6800 cal yr BP, and a younger occupation between 6200 and 5900 cal yr BP. The two youngest peat dates in layer I were rejected – dates of birch bark and charcoal from layer F above were slightly older.

5.3. Sea level and the duration of the Tapes transgression maximum

We use the archaeological radiocarbon ages to date the duration of the Tapes transgression maximum phase. Layer E, the top and distal layer of the beach ridge containing cultural remains, was deposited during the high-stand sea level following the Tapes transgression. The lower boundary of layer E is well constrained and dated to 7600 cal yr BP, but the upper boundary is somewhat uncertain. The youngest radiocarbon ages (two samples of charcoal and one of hazelnut shell, Fig. 10), from the upper part of the layer, are 5400–5600 cal yr BP, and several artefacts from the top of the layer were also ascribed to the Early Neolithic (6 polished arrowheads, Table 1), in agreement with these radiocarbon ages. Bjerck (1982) also found a tanged point of Early Neolithic age in the Tapes beach ridge deposits at Stølen (Fig. 1B). We conclude that the maximum sea level of the Tapes transgression lasted 2000 years from 7600 cal yr BP and extended into the Early Neolithic, to about 5600 cal yr BP (Fig. 13), with an uncertainty of about 100 years.

We estimate that the highest spring tide during the Tapes transgression maximum phase was between 8.2 and 9.0 m above the present mean sea level. The lowest possible frequency of storm waves overtopping the beach ridge would probably be about once every 10 years. The 10-year-recurrence interval for the storm flood ‘still’ water level, caused by low atmospheric pressure that elevated the sea level and strong winds that push sea water up against the coast, is today 0.45 m above the highest astronomical tide (Norwegian Mapping Authority, 2018). In studies of gravel storm berms formed during recent storms in Denmark, the wave run-up was estimated at 0.6–0.75 m (Clemmensen et al., 2016), and 0.75 m is also in agreement with calculations for wave run-up during energetic wave conditions (Masselink and van Heteren, 2014). Using these figures, the highest astronomical tide would have been 9.8 ± 0.2 m (altitude of the crest of the Tapes beach ridge) minus 0.75 m (wave run-up) minus 0.45 m (storm flood), giving 8.6 m (Fig. 11). To account for additional uncertainties, we suggest that the spring tide sea level at Longva would have been 8.6 ± 0.4 m above present day mean sea level during the Tapes transgression maximum.

Our new sea level curve for the period 5000–8000 cal yr BP closely resembles the sea level curve derived from the constructed shoreline diagram (Bondevik et al., 1998; Svendsen and Mangerud, 1987). However, the 7000 ^{14}C year shoreline (about 7900 cal yr BP) and the 5000 ^{14}C yr shoreline (about 5700 cal yr BP) are about 1 m and 2 m too low, respectively, relative to our curve (Fig. 13). The

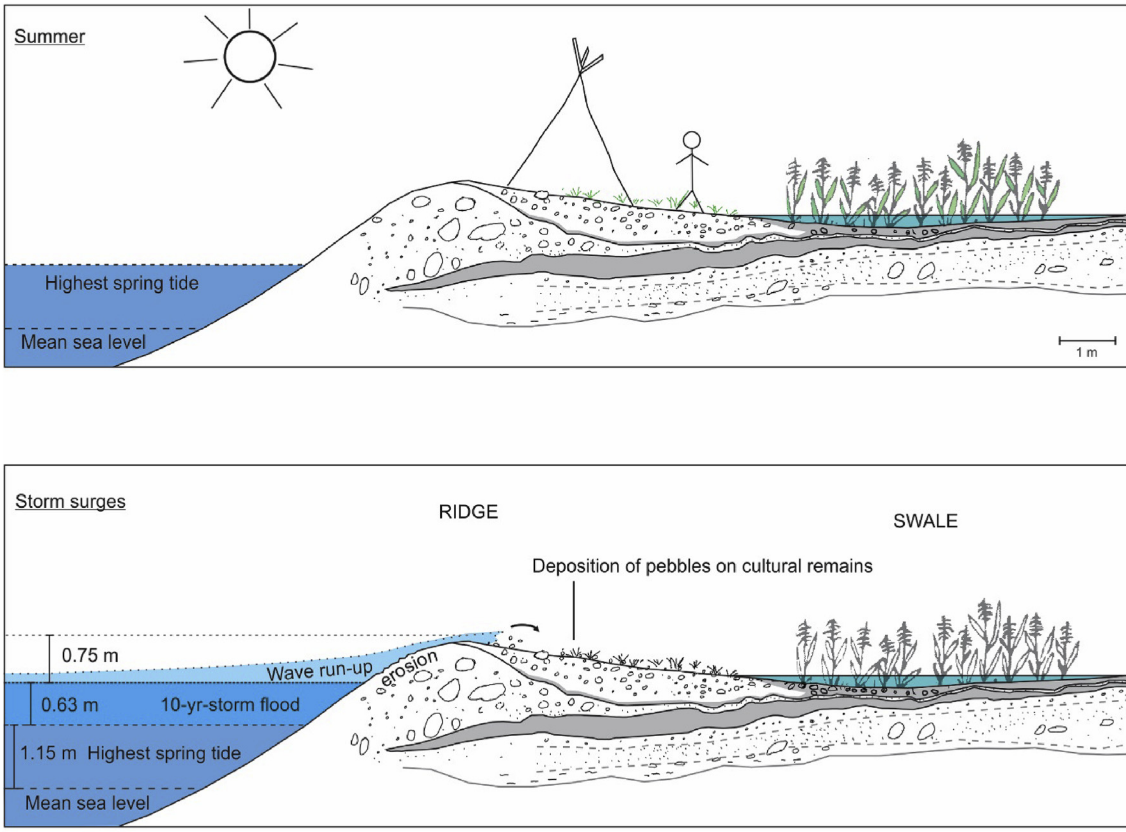

Fig. 11. Depositional model of layer E on the Tapes beach ridge. (A) Fair weather situation – occupation on the distal side of the beach ridge. (B) In the fall or winter, storm surges would occasionally wash over the beach ridge and throw sand, pebbles and small cobbles over the cultural layers and into the swale. The present day 10-year storm flood level at Longva is calculated to be 0.63 m above the highest astronomical tide (Norwegian Mapping Authority, 2018). Wave run-up is estimated at 0.75 m, e.g. Clemmensen et al. (2016).

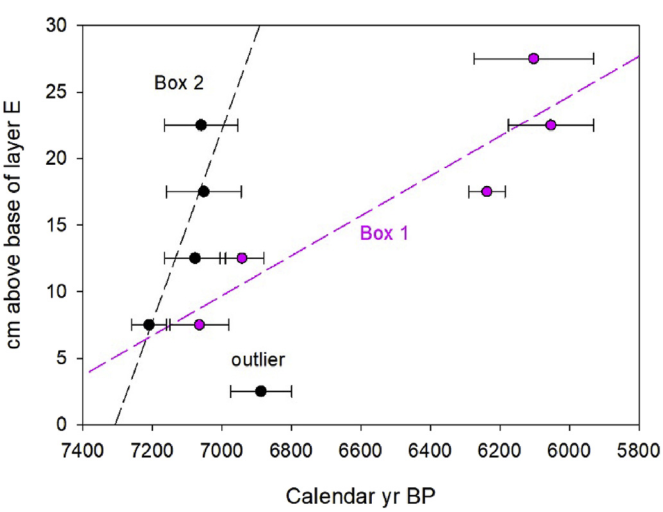

Fig. 12. Plot of radiocarbon dates from box samples 1 and 2. The y-axis shows cm above the lower boundary of layer E. There is a clear relationship; older dates are found at lower depths, except the sample at the base of layer E in box 2, which is marked as an outlier.

new sea level curve for Longva is nearly flat for 2000 years, which would mean that the 7000, 6000, and 5000 ^{14}C yr BP high tide shorelines would cross each other at Longva, at an elevation of about 8.5 m above mean sea level.

6. Conclusions

We draw three conclusions from this study:

- Late Mesolithic people lived on the Tapes beach ridge while it was growing. The archaeological material is part of the beach ridge itself. The biggest winter storms deposited sand, pebbles and cobbles over the cultural remains on the beach ridge and protected the material from reworking. Belongings and structures left behind would rarely survive undisturbed beyond the next big storm. Nevertheless, Late Mesolithic groups occupied the location intermittently for a period of 2000 years. After the stormy season, people would return and reoccupy the site.
- Radiocarbon dating of hazelnut shells and charcoal shows that the Tapes transgression maximum was between 7600 and 5600 cal yr BP at Longva. From the beach ridge deposits and altitude, we reconstructed the Tapes transgression maximum high tide sea level to between 8.2 and 9.0 m above present day mean sea level. Thus, our new sea level curve for the area is nearly flat for 2000 years.
- The settlement at Longva must have been part of a mobile settlement pattern. Families or groups moved to the Tapes beach ridge in the spring/summer to take part in fishing and hunt marine mammals and seabirds. As late autumn and winter approached, they returned to their winter quarters. It is not yet known where these people spent the winter.

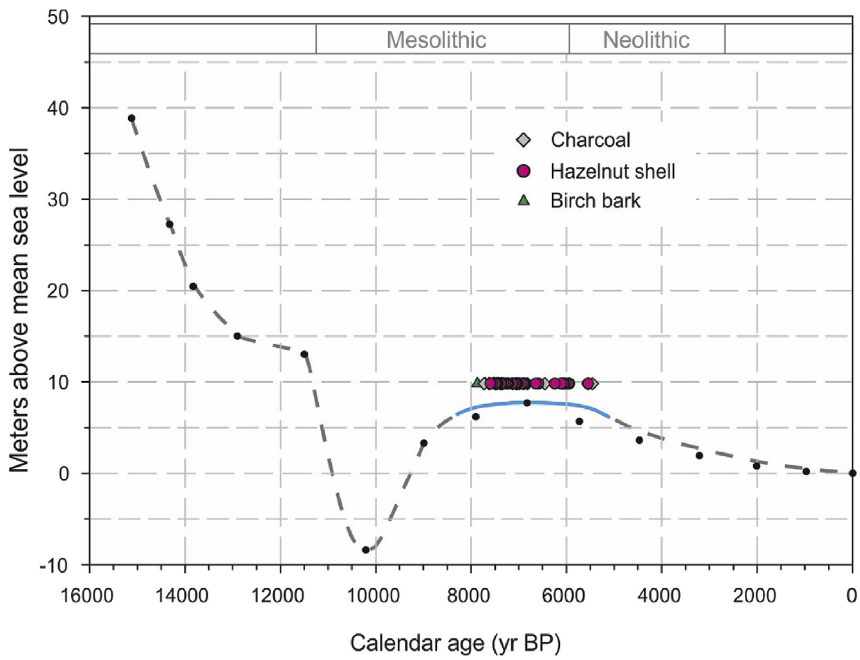

Fig. 13. Mean sea level curve for Longva at Flemsøya. Black dots are readings off the shoreline diagram (Bondevik et al., 1998; Svendsen and Mangerud, 1987) for the location of Longva, minus 1 m to adjust the readings to mean sea level. A stippled line connects these points to a sea level curve. Our revised part of the curve, between 5000 and 8000 year BP, is in blue. Radiocarbon dates in layer E are plotted at the height of the Tapes beach ridge, at 9.8 m above mean sea level. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Author contributions

S.B. had the idea for the manuscript and prepared the first draft. T.K.L led the project with assistance from H.Å. C.T. was one of the two field leaders for the excavations and catalogued most of the lithic material. K.L.H. led the pollen analytical work and I.K.M. analyzed pollen samples. All authors contributed to the final version of the paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2019.05.006.

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