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A multiproxy approach to understanding the impact of the Storegga tsunami upon Mesolithic hunter-fisher-gatherers across different regions of western Norway

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ABSTRACT

The Storegga tsunami (c. 8150 cal BP) is geologically well attested from various isolation basins across the west Norwegian coast. Ascertaining the impact it had upon the Mesolithic peoples who lived through it, however, remains a difficult proposition; one further complicated by broadly synchronic processes of climate change and sea-level rise. This paper presents a regional scale approach to addressing this matter through a multiproxy study comprising: 1) the performance of a new numerical tsunami run-up simulation for six different focus areas; 2) characterising the impact of the tsunami upon key resource base ecosystems; 3) characterising the potential for complication arising from contemporaneous processes of environmental change caused by the '8.2 ka BP event', and sea-level rise associated with the early-mid Holocene 'Tapes' transgression, and 4) the reconstruction of temporal traditions in site location relative to the contemporary palaeoshoreline within the six focus areas used for the numerical simulation.

Severity of run-up and inundation is found to be acutely variable according to coastal geomorphology and topography, bathymetry, and proximity to the propagation centre. Although the tsunami may have had a severely negative impact upon some coastal inhabitants and ecosystems, it is not possible from current evidence to reliably infer unequivocal impacts relating to the tsunami through the archaeological record, nor is it clear that impact upon key ecosystem components was necessarily lasting, widespread, or even entirely negative for coastal hunter-fisher-gatherers. Variability in projected run-up and settlement histories highlight the appeal of regionally based approaches to reconstructing impact, at least where data resolution may permit. The tsunami does not appear to have prompted a lasting shift away from coastally oriented ways of life.

1. Introduction

Around 8150 cal BP, during the coldest years of the 8.2 ka BP cooling 'event'[1], a massive submarine landslide, the Storegga Slide, occurred off the west Norwegian continental shelf (Bondevik et al., 2012; Dawson et al., 2011). It caused the largest palaeotsunami on record from these waters, reaching at least as far away as Greenland (Wagner et al., 2007). The tsunami struck during daylight hours, sometime around

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[1] NGRIP Ice Core data suggests a duration of 160 years for the 8.2 ka BP event (Thomas et al., 2007). However, the changes associated with it vary in nature, severity, timing, and duration, depending on the location, spatial resolution of data, and proxies used (see Rohling and Pälike, 2005; Li et al., 2019; Rush et al., 2023; Bondevik et al., 2023). In parts of Norway, the 8.2 ka BP event may have manifested over a greater period of time (e.g. Paus et al., 2019), or as part of an intermittent series of cooling episodes throughout the ninth millennium BP (e.g. Nesje et al., 2006). Consequently, the convention of referring to an 'event' is followed here, but its environmental signature across Western Norway remains unclear; even in the event of a discrete period of rapid-onset change in climate, weather or environment, and with a good awareness of the changing world around them, it is not clear to what extent the people who lived through it, at least in Western Norway, would have conceived of it as such.

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October/November (Bateman et al., 2021; Rydgren and Bondevik, 2015). The impact of the tsunami upon Mesolithic hunter-fisher-gatherers living in northern Britain and northern Norway has been investigated (Waddington and Wicks, 2017; Blankholm, 2020); and the impacts of other, smaller, palaeotsunamis that struck the West Coast of Norway have been explored (Bøe et al., 2007; Nielsen, 2020), but little has been done archaeologically to characterise the potential impact of the Storegga tsunami in Western Norway (Nyland et al., 2021), despite the tsunami being relatively well attested here through run-up deposits documented from various lake basins (Bondevik, 2022).

During the Middle and Late Mesolithic in Western Norway (see Table 1), hunter-fisher-gatherers lived predominantly coastally oriented lifestyles with settlements often on, or adjacent to, contemporary shorelines (Bergsvik, 2001; Bergsvik and Ritchie, 2020). Our hypothesis is that the damage wrought by the tsunami upon key resource bases, ecosystems, or coastal inhabitants and their habitations, could have prompted a temporary but archaeologically visible shift in the preference for coastal living. We also consider whether the regionally variable impact of the tsunami may have resulted in an accordingly varied human response (as seen in settlement patterns) throughout different areas of the West Norwegian coast.

To investigate this possibility, and to demonstrate the localised variability in physical impact, this research presents the results of a numerical simulation of the tsunami and its peak run-up across six different portions (Focus areas 1–6) of the West Norwegian coast (from Møre og Romsdal in the North, to Rogaland in the South) for which we have plotted the elevation of Mesolithic sites relative to contemporary palaeoshoreline reconstructions (Fig. 1). The six focus areas included are, from North to South: 1) Northeastern Aukra (Møre og Romsdal County), 2) Skatestraumen (Bremanger, Vestland County), 3) Fosnstraumen (Vestland County), 4) the central/inner islands of Bømlo and Stord (Vestland County), 5) northern, east Karmøy and Fosenhalvøya (Rogaland County), and 6) Sola, Tananger and Hafrsfjord (Rogaland County). The numerical simulation allows for a regionally specific description of how multiple tsunami waves affected different landforms within the six focus areas, showing variation in wave sequences, peak run-up, and drawdown. The results of the numerical simulation are followed by consideration of the tsunami's impact upon marine and coastal environmental productivity, including key resources for coastal Mesolithic communities. The difficulties of discerning these impacts from those of the broadly convergent effects of the 8.2 ka BP event and early-mid Holocene 'Tapes' transgression are also considered, before temporal variability among site elevations are explored as a potential proxy for disruption to preferences for coastal living.

2. Reconstructing impact utilizing numeric simulation of the tsunami model

The simulation presented here, commissioned by the Life After the Storegga Tsunami (LAST) project (Norwegian Research Council project no. 302858) and developed by the Norwegian Geophysical Institute, is the first to combine an offshore tsunami generation and propagation model with high-resolution run-up simulations across the complex archipelagic and fjord-lined coasts of Western Norway. Results for this initial application are given for the six focus areas that formed the basis for study of temporal variability in site location (see below). Geological evidence of the tsunami run-up is extensively documented, but unevenly distributed across the Norwegian coast (Fig. 2; Bondevik, 2022). Numerical simulation offers a means to model the path of the wave and its run-up more evenly.

Numerical simulations of inundation were carried out in a three-stage workflow: (1) the BingCLAW program is used to simulate the dynamics of the landslide itself; (2) the GloBouss program models the propagation of the wave across the open sea, (3) the ComMIT/MOST model (Community Model Interface for Tsunami/Method of Splitting for Tsunami) models the inundation at the coast on nested (or telescopic) grids at increasingly fine resolution. The landslide and global tsunami models used the palaeo-bathymetry model of Hill et al. (2014) with a resolution of 1 min (1.853 km) interpolated onto a 2 km grid for the landslide simulation and a 1 km grid for the global tsunami simulation. The regional inundation calculations used specially constructed topo-bathymetric models of the Norwegian coast, interpolated onto grids with 160 m, 40 m, and 10 m resolution. The sources of all codes and topo-bathymetric data are provided in Supplementary Material A and B.

BingCLAW is a 2-layer viscoplastic landslide model with several parameters defining the rheology of the sliding material. The parameters used were determined by Kim et al. (2019) to most closely reproduce the relative heights of the observed run-up heights and run-out area. Wave amplitude can show some variation with the choice of rheological parameters in the landslide simulation (Kim et al., 2019). However, for all parameters studied, the spatial form and relative amplitudes of the tsunami at different locations remain unchanged and the images in Figs. 3 and 4 are representative of all simulations. BingCLAW models the evolution of the slide in time and space and records the depth of the sea floor every 120 s to capture temporal and spatial change in bathymetry. GloBouss reads in the output from BingCLAW and propagates the wave generated by the relatively rapid deformation of the sea-floor. ComMIT/MOST reads in the wave heights and horizontal velocities of the wave output from GloBouss to calculate the inundation. A similar coupling of the GloBouss and MOST models was performed by Løvholt et al. (2012) for the 2011 Tohoku earthquake and tsunami.

Fig. 3 displays the height of the water resulting from the simulation of the Storegga slide at three different times throughout the wave's evolution. Fig. 3a displays the water height 10 min following the initiation of the slide. At the highest part of the slide, close to the red line, a large length-scale (many tens of km) decrease in the water level, sometimes exceeding 15 m, results from the rapid lowering of the sea floor. A similar rise in sea level occurs where the displaced material falls, as the sea floor effectively rises.

In Fig. 3b, over an hour after the slide initiation, a long-period positive polarity (upward first) wavefront propagates out in the direction of the slide motion. On the coastline of Northern West Norway closest to the slide scarp, the negatively polarized (downward first) long-period wavefront approaches the coast resulting in a vast withdrawal of water and a decrease of many meters in the sea level. Shorter period waves (period of below 10 km) with relatively high amplitudes appear above the slide region as the long-period wavefronts propagate away. In Fig. 3c, after almost 4 h, the long period wavefront accelerates and decreases in amplitude in regions of deeper water (e.g., down the western coast of Norway) and decelerates and increases in amplitude in shallower water (e.g., to the Southwest towards Shetland). The initial wave travelling down the coast has positive polarity but is followed by a much longer and deeper decrease in water height. Over the slide zone and along the North West coast, the sea level is now highly complicated with waves of many different length scales, amplitudes, and directions as the waves have been reflected from the coastline at multiple angles.

It is instructive to examine the evolution with time of the wave at single offshore locations close to our focus areas (see Fig. 3d). Near focus area 1 (Northeastern Aukra) the initial decrease in water level exceeding 15 m is followed by rapidly changing water level and significant rises. Close to the shore, shoaling results in water heights exceeding 15 m although the maximum height obtained varies significantly depending upon the local topo-bathymetry and the form of the incoming wave. Further down the coast, an observer would see an initial rise in water level followed by a long-period withdrawal. Further to the south, the amplitudes are lower and the periods longer.

Fig. 4 shows the maximum water height obtained throughout the entire simulation (as opposed to snapshots showing both rises and falls). The top-left panel displays the maximum water height from the global calculation. This exceeds 15 m both directly above the area of the slide and at locations along several hundred kilometres of coastline. The

Table 1

Current chronology in both Cal BC and uncal BP of the West Norwegian Mesolithic, including approximate timings for the tsunami, 8.2 ka BP event, and Holocene Climatic Optimum. The column 'Abbreviated Chronozone' refers to cultural subdivisions of periodic stages (Column: Period Name) as used within the early Holocene archaeology of Western Norway: EM = Early Mesolithic/'Fosna'; MM = Middle Mesolithic; LM = Late Mesolithic; EN = Early Neolithic.

Climate events	Abbreviated 'Chronozone'	BC	Uncal. BP	Period name (western Norway)	BC	Uncal. BP
Holocene Climatic	EM1	9500–9000	10,200-9590	Early Mesolithic ("Fosna")	9200–8200	10,000-9000
Storegga Tsunami	EM2	9000–8500	9590–9270			
	EM3	8500–8000	9270–8900			
	MM1	8000–7500	8900–8400	Middle Mesolithic (Early microblade tradition)	8200–6400	9000–7500
	MM2	7500–7000	8400–7970			
8.2 Event	MM3	7000–6500	7970–7690			
	LM1	6500–6000	7690–7110	Late Mesolithic (Late microblade tradition)	6400–4000	7500–5200
	LM2	6000–5500	7110–6560			
	LM3	5500–5000	6560–6090			
	LM4	5000–4500	6090–5680			
	LM5	4500–4000	5680–5230			
	EN	4000–3300	5230–4700	Early Neolithic	4000–3300	5200–4700

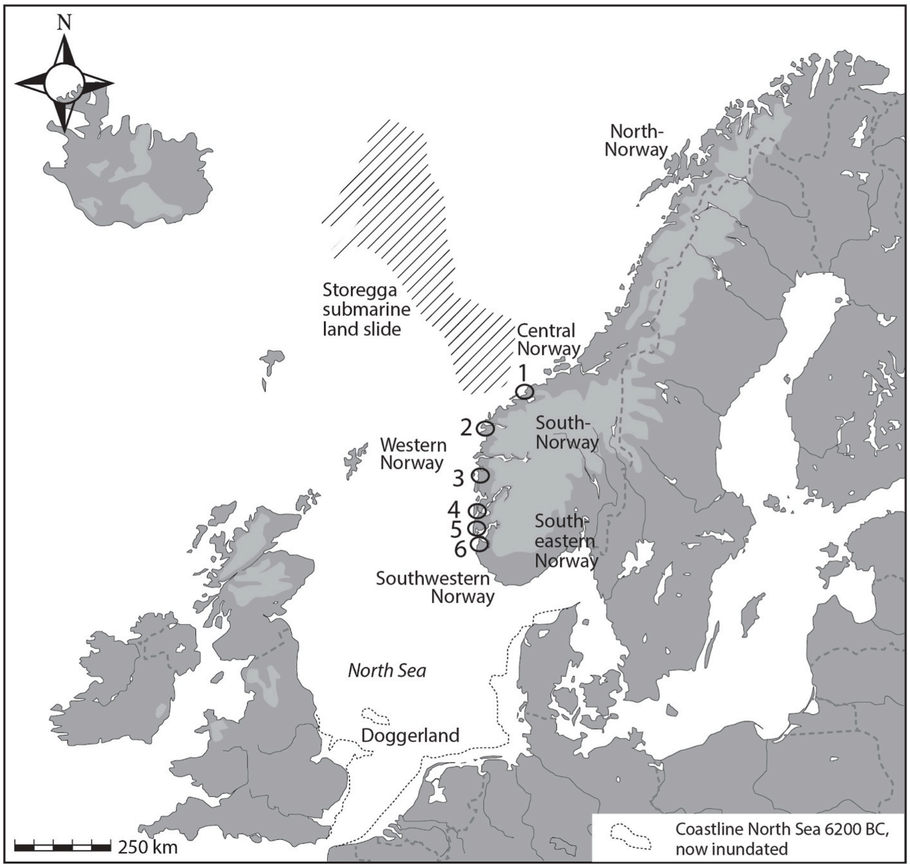

Fig. 1. Map showing the west Norwegian coast and the area of the Storegga Slide, with the six focus areas highlighted. The approximate coastline of the southern North Sea around 8200 cal BP is also highlighted. The numbers mark the six focus areas presented in Supplementary Material Appendix A: 1: Northeastern Aukra (Møre og Romsdal County); 2: Skatestraumen (Vestland County); 3: Fosnstraumen (Vestland County); 4: Central/inner islands of Bømlo and Stord (Vestland County); 5: Northern, east Karmøy and Fosenhalvøya (Rogaland County); 6: Sola, Tananger and Hafrsfjord (Rogaland County) (Image by A.J. Nyland).

remaining six panels show the maximum heights calculated for the regional simulations for each of the zones of interest. The panels generally confirm the following features.

(1) the greatest water heights were experienced at the more northerly focus areas (1 and 2).

(2) The maximum water height close to the shoreline varies greatly locally. The significance of high water will, of course, vary considerably depending upon the topographic relief of the afflicted coastline. Places with low lying coastal landscapes likely suffered significant inundation despite the relatively lower offshore amplitudes. Wave period is a significant factor in this, as a long period wave will have many tens of kilometers of water to press onshore.

(3) We note that the greatest inundation often occurs many hours after the first wave arrival. This is clearly seen in Fig. 3d.

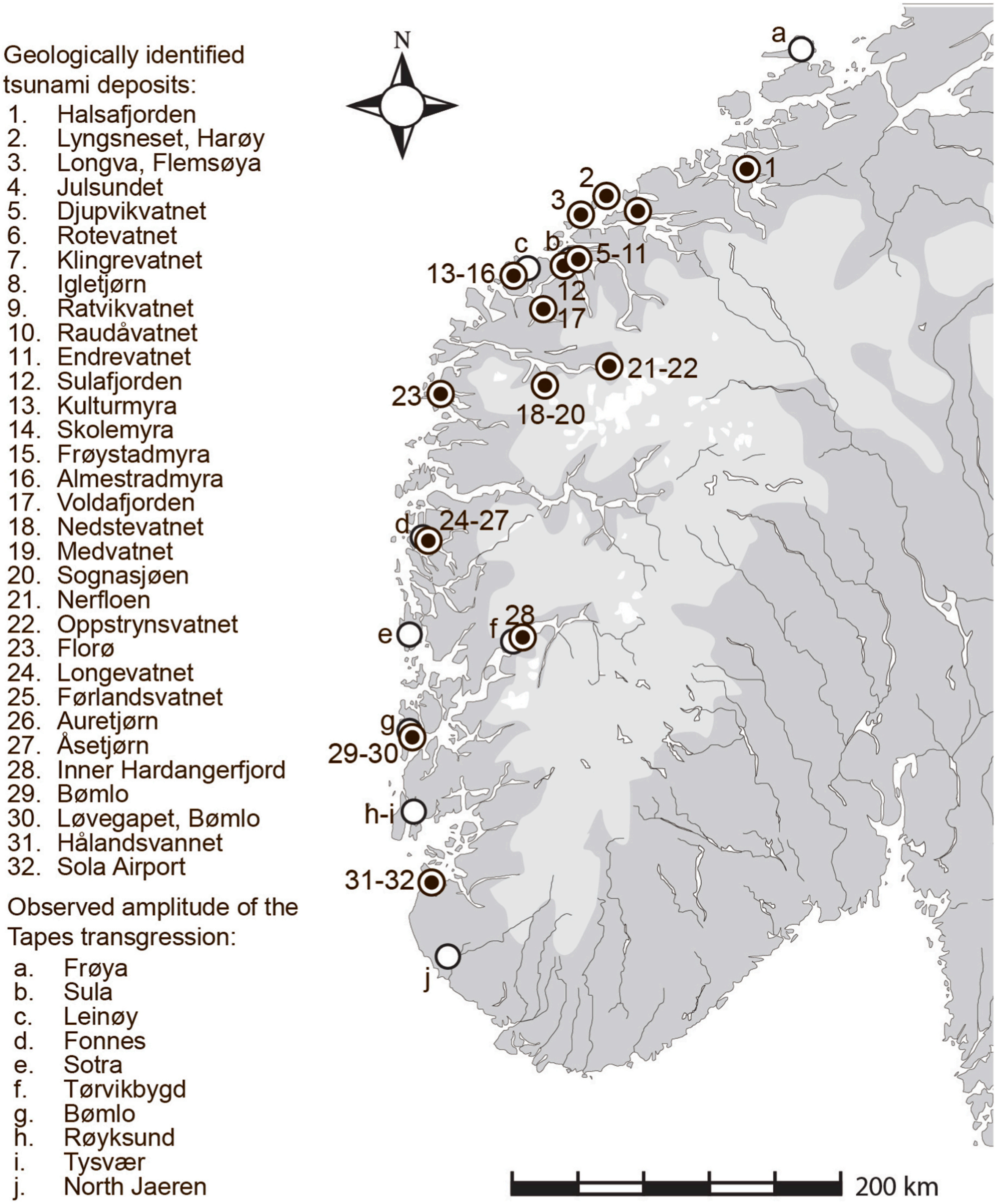

Fig. 2. Location of Storegga tsunami deposits and sites where the tapes amplitude has been recorded from within western Norway (Image by A.J. Nyland).

3. Impact of the tsunami upon marine and coastal environments

Since coastal settlements were, at the time of the tsunami, commonly situated adjacent to or directly upon the contemporary shoreline, the most significant risk, aside from loss of life, would have been to human-constructed habitats through the destruction or outright loss of homes, boats, toolkits, any potential food reserves and any articles of importance for day-to-day life that were difficult or time-consuming to replace or repair. This type of damage or loss may have been compounded by the disarray brought by loss of life, and the late autumnal timing of the tsunami, just before the winter months. However, in addition to the risks associated with the immediate impact of the event, tsunamis may also act as potent forces of environmental change, with the potential to cause lasting disruption to ecosystems of key importance to subsistence routines.

Recent tsunamis have provided the opportunity to examine evidence of lasting ecological impact and recovery rates across a variety of different species and settings (e.g. Urabe and Nakashizuka, 2016; Hayasaka et al., 2012). Although the ecological impacts of recently observed tsunamis are not necessarily ideal analogues for an early Holocene tsunami affecting the Norwegian coastline, and not least because of the variable ecological effects of different human lifeways in the aftermath of extreme wave phenomena, assessments of recent tsunami impact upon terrestrial and marine/littoral ecosystems nevertheless provide a

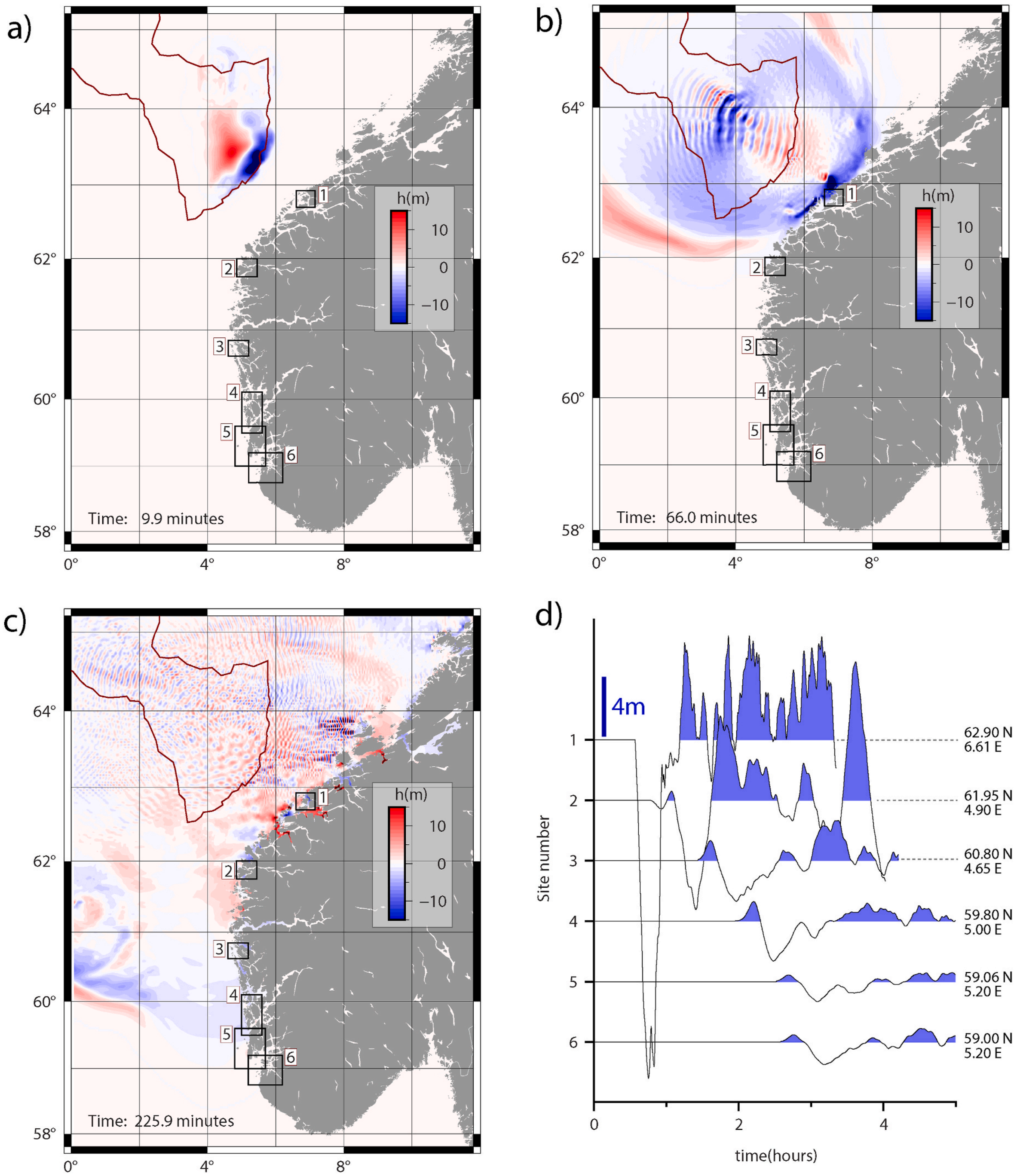

Fig. 3. Evolution of the Storegga tsunami from initiation to inundation computed in a numerical tsunami simulation coupled to viscoplastic landslide model. Panels (a), (b), and (c) show water height modelled at the times indicated together with the outline of the slide runout extent from Haflidason et al. (2005). Regions 1 to 6 were selected for high-resolution inundation calculations for reference to the focus areas used for site distribution analysis. The waveforms in panel (d) show the water height as a function of time at a selected offshore location within each of the respective regions. The exact time-evolution of the wave varies greatly from location to location and far higher wave amplitudes than those displayed can occur as the wave approaches the shoreline. (Image by S. Gibbons).

useful point of departure for discussion. Understanding these changes is an important factor when considering the longer-term effects of palaeotsunamis upon prehistoric communities (Losey, 2005; McFadgen, 2007; Fitzhugh, 2012), with the loss of key resource bases having the potential to disrupt the subsistence routines of coastal hunter-fisher-gatherers, leaving them in a precarious state for some time after the tsunami. As relatively short-lived but potentially violent agents of environmental change, it is conceivable that tsunamis may prompt the crossing of ecological thresholds. While many tsunami impact studies rely, necessarily, upon comparison of ecosystems before and after the event, it is possible that a return to a pre-perturbation state should not necessarily be expected (Newbold et al., 2020: 7). Consequently, discussion focusses on elements thought to have been important to Mesolithic hunter-fisher-gatherer subsistence, and the extent to which they may have been severely, lastingly, or irreversibly impacted.

The coastal orientation of Mesolithic sites in Western Norway implies a strong maritime oriented subsistence economy (e.g. Bjerck, 2007, 2008a, 2008b; Breivik, 2014; Åstveit and Tøssebro, 2023). Osteological data from various faunal assemblages indicate that aquatic fauna were important resources. Fish predominate, including Gadids (cod, saithe,

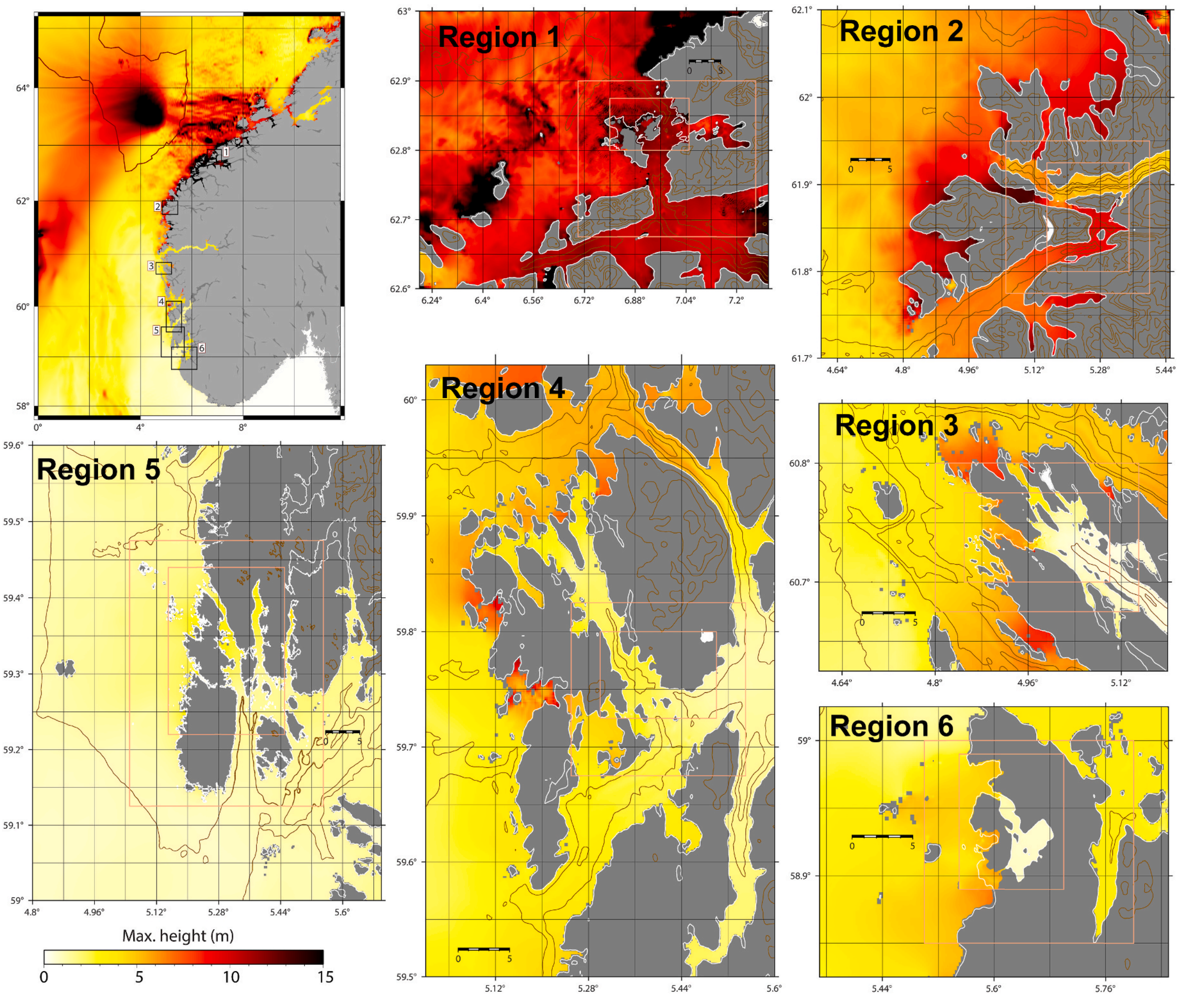

Fig. 4. Maximum height of water attained during the entire simulation globally (top left) and for each of the selected regions as numbered. The A-, B-, and C nested grids have cell-dimension 160 m, 40 m, and 10 m respectively. The outlines of the higher resolution grids are shown and the maximum height colour is always calculated for the grid of highest resolution. The continuity of the colour over the grid boundary is an indication of convergence. The white line is a contour of the original shoreline such that regions of colour trapped between the grey dry land and the white shoreline indicate regions of inundation. These are clearest for Aukra (Focus Area 1) and Sola-Tananger, Hafrsfjord (Focus area 6). (Image by S. Gibbons).

pollack), Salmonids (salmon, trout), Clupeids (herring), Scombrids (mackrel) and Labrids (wrasses) (Ritchie et al., 2016). Additionally, marine mammals, including otters and seals—notably grey seals—were hunted along with terrestrial prey including ungulates and fur bearing taxa (Bjerck, 2008a; Breivik, 2014; Skar et al., 2016). Although shell middens comparable to those found elsewhere across Atlantic Europe are lacking, marine molluscs may also have played some importance (Åstveit et al., 2016; Bjerck, 2007). The collapse or failure of some of these resources, or abrupt changes in their predictability, could, assuming there was little in the way of an accessible alternative, have had severe consequences for coastal groups.

3.1. *Impact upon terrestrial resource bases*

Shore-bound flora within the run-up zone, with low salt tolerance or shallow roots, may have been more severely affected than more tolerant or deeply rooted taxa (Paterson et al., 2012). Deforestation within the path of run-up may have been extensive if also locally variable depending upon coastal morphology. Herbaceous taxa, which can play an important role in dune stabilisation, may have been more vulnerable than arboreal or woodier species (Hayasaka et al., 2012). Recovery after a tsunami can begin very quickly, however (e.g. Goff et al., 2012), with some propagules able to survive extensive tsunami induced beach erosion (Hayasaka et al., 2012). Full succession recovery may have taken several years or more and may not have begun until well into the following year given the late autumnal timing of the tsunami. At the site Vika 3/Løvegapet, on the island of Bømlo, temporary deforestation by the tsunami was followed by rapid re-establishment of local vegetation (Svendsen, 2016). Impacts upon terrestrial fauna (including ungulates) are difficult to speculate (Losey, 2005). It may be assumed that they were less severe, except for species restricted to, or dependent upon environments caught within the run-up.

Marine mammals (of which only some venture temporarily on land) present a difficult resource to assess. In the water, pinnipeds may generally be considered strong swimmers, and potentially resilient even to unusually large waves (Losey, 2005). However, stories of phocid and even cetacean strandings are associated with some extreme tsunamis (McFadgen, 2007: 33). Grey seal (*Halichoerus grypus*), which would have been hunted on rocky shores during the autumn (Breivik, 2014), may have been badly affected. For this species, pupping, which favours rocky haul-outs and islets, begins in October (Nilssen and Haug 2007), meaning many individuals (and particularly pups) may have been vulnerable. As eutherian mammals bearing a single pup per annum, it may have taken years for their populations to recover if mortality was sustained in any high numbers, but actual impact remains impossible to ascertain, and their importance to Mesolithic peoples appears to have been more secondary to that of fish during the period in question (Boethius et al., 2020).

3.2. Impact upon aquatic resource bases

With regards to resources from the marine and littoral environment, tsunamis may pose a threat to key species through the direct impact of the wave, but also through damage or disruption to ecosystems, even conceivably inducing bottom-up trophic cascade. Sudden and violent suspension of the seabed can cause substantial defaunation, particularly to sessile macrobenthic fauna, with mollusca and crustacea among the more vulnerable types (Khan et al., 2018). Observations of these macrobenthic communities in the aftermath of a tsunami show that while some communities may recover within a matter of days (Paterson et al., 2012), it may take 2–3 years or more for a return to pre-tsunami states among other species (Chunga-Llauce and Pacheco, 2021; Abe et al., 2016). Community imbalance is, in many cases, more likely than pan-species wipeout or permanent damage, with opportunistic re-colonisers quick to take advantage of any potential for reduced competition in affected areas (Sato and Chiba, 2016; Sanpanich et al., 2006). As the Storegga tsunami was not caused by an earthquake, the effects of seismic subsidence or uplift, which have been identified as having significantly deleterious impacts upon benthic and littoral fauna and flora distributions, and with potential to have knock-on effects for some fish (Losey, 2005; Chunga-Llauce and Pacheco, 2021; Ito et al., 2016), may have been avoided—such changes have perhaps a higher potential to force the crossing of ecological thresholds within the affected littoral zone.

Planktonic communities tend to fare better than benthic communities, with several studies indicating either minimal disruption or a very quick recovery among some taxa (Tachibana et al., 2017; Nishibe et al., 2016). Disruption may cause significant chlorophyll-*a* blooms (Haldar et al., 2013), capable of disrupting marine biome productivity. While this can have a negative impact upon vegetation, fish and other fauna dependent upon these ecosystems, they can also provide an excess of nutrients, that may have enabled a particularly fruitful fish harvest for the following months (e.g. Sachoemar et al., 2012) so long as patch distribution was not also substantially altered.

Extensive perennial kelp forests along shallow rocky coasts, dominated by *Laminaria hyperborea*, and coral reefs from greater depths, both support the observation that the archipelagic coasts of Western Norway were probably attractive for the island wake preferences of phytoplankton blooms (Breivik, 2014). Research into the impact of tsunamis upon kelp beds has been limited, but a study of two differently affected littoral zones following the 2011 Tōhoku tsunami found that beds of the perennial *E. bicyclis* and *S. japonica* var. *religiosa* suffered only minor physical destruction, and in the area exposed to heavier disturbance, mortality among the sea urchins that fed extensively upon the kelp actually allowed for an expansion in depth range owing to reduced grazing pressure (Muraoka et al., 2017).

Perhaps the most severe impact upon aquatic resources as far as coastal Mesolithic communities were concerned would have been upon fish. Extreme tsunamis have been known to wash quantities of fish ashore (Lander et al., 2003). Remains of saithe (*Pollachius virens*), indicative of an autumnal mortality, have been recovered from Storegga run-up deposits within two cores from lake Gorrtjønna I, in Bjugn, to the north of focus area 1 (Northeastern Aukra), seemingly transported ashore and into the lake (Bondevik et al., 1997a: 51). The age-profile (between 0.5 and 1 years) accords with the preference of saithe for coastal waters as nursery grounds, leaving the fjords once mature (Heino et al., 2012). Run-up around the island coasts and fjord mouths was high in places, and seemingly penetrated deep within some fjords (Figs. 3 and 4), and geological evidence of tsunami run-up in various lake basins attests to various freshwater systems having been breached (Bondevik et al., 1997a, 1998). Some cod (*Gadus morhua*) are resident within the fjords, and may have also been vulnerable, while pollack (*Pollachius*) would probably have been away at sea in the autumn (Heino et al., 2012). It is not clear to what extent demersal species such as wrasses would have been vulnerable (Okazaki et al., 2017; Shoji and Morimoto, 2016).

The penetration of the wave up fjords and into freshwater systems may have damaged spawning grounds for key species (Losey, 2005). Anadromous species, such as salmon (*Salmo salmar*) and herring (*Clupea harengus* L.) spawn between October and January (Heggberget, 1988), and the tsunami may have caught individuals, or destroyed spawning grounds or food supply where such areas where penetrated by the wave. Ultimately, variable coastal geomorphology would have offered (at least relative) shelter to seaweed and seagrass in some areas (e.g. Komatsu et al., 2015; Muraoka et al., 2017), and disrupted ecosystems may have even resulted in a surfeit of food for some species. Recent studies suggest that even in the face of unusually large tsunamis capable of altering food-web structure, pelagic fish may recover rapidly (Ito et al., 2016), and even seemingly large numbers of fatalities may not necessarily adversely affect populations in the long term (Losey, 2005). Assuming population-wide devastation was avoided, and underlying food chains were disrupted rather than destroyed, impacts upon fish ecology may have been regionally varied and potentially relatively short-lived.

3.3. Summary of ecological impacts

It is not clear to what extent terrestrial environment damage from the wave would have had a lastingly negative impact upon human groups, outside perhaps the salination of coastal freshwater sources and aquifers. Terrestrial resources were, on the whole, probably much less at risk of damage than aquatic resources (see Losey, 2005). As with wave run-up and inundation, damage or loss sustained to aquatic resources and ecosystems was likely to be highly geographically variable, and not necessarily long-lasting. However, even with limited evidence, it is observed that at least some populations of economically important fish species (saithe), sustained losses (Bondevik et al., 1997a: 50–51). If bottom-up trophic cascade did occur, it was probably spatially restricted to the worst affected areas—a general relationship between wave height and damage sustained to benthic communities has been noted in one recent study (Urabe et al., 2013). Comparatively sheltered areas of the coastline or stretches exposed to lower wave-heights may have weathered the impact of the tsunami better. Consequently, mortality among sessile marine molluscs, crustaceans, and some fish, as well as habitat damage, would have been highly spatially variable. However, the mixed faunal economies associated with Mesolithic coastal hunter-fisher-gatherers from Western Norway may reflect a subsistence routine that was adapted to uncertainty, or at least variety, rather than predication on a narrow range of species. In summary, the impact of the tsunami upon some aquatic resources was almost certainly pronounced, but regionally variable, and not necessarily long-lived. If even a few key species avoided major depopulation, subsistence routines may have been able to carry on with modest adjustment, or at least resume quite rapidly.

4. Complicating factors: the impact of the 8.2 ka BP cold event and the tapes transgression

Attempts at understanding the impact of the Storegga tsunami upon coastal Mesolithic hunter-fisher-gatherers are complicated by convergent impacts of the 8.2 ka BP event and the Tapes transgression. The 8.2 ka BP event, the most notable climatic downturn of the Holocene, may have been a major contributing factor towards any changes in Mesolithic lifestyles. The Tapes transgression may not have caused rapid onset change to important ecosystems, but would have changed the relative elevation and positioning of sites and respective environments over millennia, if not centuries. Peaking just after the 8.2 ka BP event and the Storegga tsunami, the sea-level rise is likely to have taphonomically obscured archaeological data pertaining to the period of key interest.

4.1. The 8.2 ka BP event

Caused by the multistage release of glacially dammed waters into the Atlantic Ocean following the retreat of the Laurentide Ice Sheet from Lakes Agassiz and Ojibway, the 8.2 ka BP event interrupted the Holocene Thermal Maximum (HTM) in Norway and caused significant disruption to oceanic circulation currents in the North Seas (Kleiven et al., 2008; Eldevik et al., 2014). Although centred around 8200 cal BP, the timing appears variable globally, with some proxies indicating multi-centennial scales of cooling beginning several centuries earlier (Rohling and Pälike, 2005), as has been suggested by some Norwegian palaeoclimate proxies (Balascio and Bradley, 2012; Paus et al., 2019; Nesje et al., 2006). As a decadal or centennial-scale cooling episode, it perhaps held greater potential for effecting regime shift through sustained impact than the more punctuated but short-lived effects of the tsunami. Striking during the coldest years of the 8.2 ka BP event (Bondevik et al., 2012; Rydgren and Bondevik, 2015), the convergent timing of the tsunami with this cooling episode may have exacerbated or compounded their associated ecological impacts.

Evidence of a response to the 8.2 ka BP cold event from archaeological and demographic studies in Scandinavia have so far been mixed (Manninen et al. 2018, 2023; Fossum, 2020; Jørgensen, 2020a, 2020b; Jørgensen et al., 2022; Solheim et al., 2020; Breivik et al., 2018; Solheim and Persson, 2018; Persson, 2018; Manninen, 2014; Tallavaara et al., 2010). Changes in material culture of Western Norway are not apparent from this period (Bergsvik, 2002; Bjerck, 2008a; Nyland et al., 2021). Palaeodemographic reconstruction for this region with a focus on the Storegga tsunami and 8.2 ka BP cold event is currently being developed (Kilhavn and Megarry forthcoming; see also Lundström, 2023), as is a more detailed approach to variation in lithic assemblages (Nyland and Damlien forthcoming).

Early attainment of the HTM in Scandinavia meant that prior to the onset of the 8.2 ka BP event, the climate for Western Norway (as well as the North and South) was comparable to, if not warmer than that of today, with relatively low January and high July temperatures (Nesje et al., 2005, 2006; Hald, 2009). A series of short-lived cooling events between 8550 and 7900 cal BP may have seen temporary re-glaciation of central montane areas (well east of the coast and focus areas) reflected in the reduced range of pine (Dahl and Nesje, 1996; Nesje et al., 2005). From this sequence, it appears that a period of notably dry winters between 8300 and 8200 cal BP was followed by a reduction in peak July temperatures, and relatively high January temperatures and precipitation (Nesje et al., 2001, 2006, 2005). REVEALS (Regional Estimates of Vegetation Abundance from Large Sites) analysis of long-term changes in forest cover at Kalandsvatnet, near Bergen, suggest a decline in *Quercus* and increase in herbaceous taxa (Mehl and Hjelle, 2015). More generally, however, multiple datasets indicate that temperature change effected by the 8.2 ka BP event across Western Norway was potentially relatively modest (Bjune et al., 2005; Seppä et al., 2009; Eldevik et al., 2014; Bondevik et al., 2023). Perhaps the biggest impacts upon coastal ecosystems would have been increased storminess during this period (Clarke and Rendell, 2009) although recent research suggests storminess may have peaked later, in the early eighth millennium BP (Goslin et al., 2018), broadly matching coeval site and beach ridge formation at the Mesolithic site of Longva (Bondevik et al., 2019).

Evidence of an abrupt but short-lived fluctuation in key indicator species of planktonic foraminifera in marine cores from the Norwegian Sea and North Sea was initially suggested as reflective of a punctuated reduction in SST (Sea Surface Temperature), and presumably also salinity, associated with the release of glacial meltwaters into the North Atlantic (Risebrobakken et al., 2003; Klitgaard-Kristensen et al., 1998, 2001). The coldest conditions seemingly lasting for 70 years (Risebrobakken et al., 2003), which does not accord well with the terrestrial proxies indicative of a longer (or multi-episodic) phase of cooling (e.g. Paus et al., 2019; Nesje et al., 2006). Recent reassessment of marine sediments from marine core MD95-2011 near the Vøring Plateau has, however, suggested that these fluctuations may actually pertain to older sediments reworked by the Storegga tsunami, meaning that the severity and extent of the cooling may have been overestimated (Bondevik et al., 2023).

With regards to the impact of the 8.2 ka BP event upon foundational floral and faunal communities described earlier, coral growth is noted as having slowed but continued throughout this period (López Correa et al., 2012). The broad optimum temperature range (10–15 °C) of Laminaria (Bolton and Lüning, 1982) suggests that, even without disregarding foraminifera based estimates of earlier studies (e.g. Hald et al., 2007), changes in SST's would not have been significantly detrimental to *Laminaria hyperborea* growth (Birks and Koç, 2002). As migratory species affected by seasonal variability (Heino et al., 2012), cod, saithe and pollack catchability may have changed with a shift in sea temperatures. Fish assemblages from three sites in the Hardangerfjord show a shift in the dominant catch from cod at Kotedalen (8600-8000 cal BP) and Sævarhelleren (9000-8000 cal BP) to saithe at Olsteinhelleren (7600-6800 cal BP) (Ritchie et al., 2016), but it is not clear that this seemingly localised shift (see Boethius et al., 2020) was influenced by the 8.2 ka BP event.

Even if resource scheduling was affected, Mesolithic hunter-fisher-gatherers were taking a variety of species, and presumably had knowledge of multiple local resource catchments and prey movements, as seen during the more pronounced Preboreal Oscillation (Breivik, 2014). From these various indicators, and particularly in light of new data (Bondevik et al., 2023), it is currently difficult to reliably infer the severity and duration of the 8.2 ka BP event as felt across Western Norway, much less how it impacted Mesolithic populations who may have had multiple means of living within the landscape at their disposal.

4.2. Early-mid Holocene marine transgression

The most notable stage of Holocene sea-level change documented from the Norwegian coast is the early-mid Holocene (or 'Tapes') transgression, broadly constrained between 10 and 7 thousand years ago. The extent and timing of the transgression varies considerably around different parts of the Norwegian coast, with amplitudes of as little as 2–3 m in some areas, and 20 m or more in others (Table 2; Creel et al., 2021). Various coastal basin deposits from western Norway, previously interpreted as pertaining to the Tapes maximum, have been re-assessed as Storegga run-up deposits, with the tsunami potentially having also destroyed interfaces delimiting the preceding regression minima in areas (Bondevik et al., 1998). The distribution and density of datapoints across the coasts of Western Norway, and particularly SLIP data, give this region (with the exception of some areas, such as Sogn and

Table 2
Observed amplitude of the Tapes transgression from sites within the study area. Ranges span from the regression minimum to transgression maximum. Post-glacial sea level rise is recorded in all areas apart from Tørvikygd, in the Hardangerfjord, where there was localised emergence. Data points taken from Fjeldskaar and Bondevik (2020, Table 1; Fig. 1). Location lettering refers to those shown in Fig. 2.

Site No	Location	Tapes Transgression	References
a.	Frøya	3–5 m	Kjemperud (1986)
b.	Sula	12–13 m	Svendsen and Mangerud (1987)
c.	Leinøy	18–22 m	Bondevik et al. (1998); Svendsen and Mangerud (1987)
d.	Fonnes	7–8 m	Kaland (1984)
e.	Sotra	9–10 m	Lohne et al. (2007)
f.	Tørvikbygd	−14 to −12 m	Romundset et al. (1987)
g.	Bømlo	7–9 m	Kaland (1984)
h.	Røyksund	3–8 m	Midtbø (2011)
i.	Tysvær	4–9 m	Prøsch-Danielsen (2006)
j.	North Jaeren	>10 m	Prøsch-Danielsen (2006)

Fjordane) the greatest degree of control (Creel et al., 2021: Fig. 2A), with generally good agreement between observed and modelled Tapes amplitude intervals, although with higher discrepancies to the north (Fjeldskaar and Bondevik, 2020: Fig. 10).

Coastal elevations—including Mesolithic settlements and archaeological deposits among the most vulnerable to the Storegga tsunami—lower than the subsequent Tapes maximum will have been outstripped by the transgression, leaving them buried within or beneath (and potentially eroded away or redeposited by) the transgression (Prøsch-Danielsen, 2006: 85). Storm waves peaking above the mean-sea level of the actual transgression maximum may result in beach ridges (Rasmussen et al., 2018). Such an example is exemplified by recent investigations at Longva on the island of Skuløya/Flemsøya, which have revealed a deposit formed by the Storegga tsunami (which predates attainment of the Tapes maximum in this region) underlying a sequence of cultural remains deposited within what was an actively forming beach ridge (Bondevik et al., 2019). While the case at Longva shows that it is possible to find tsunami run-up and archaeological deposits within and beneath beach ridges, occupied areas of the coast located beneath the peak elevation of the Tapes will have higher susceptibility to taphonomic disturbance or erasure due to exposure to wave action during submergance and re-exposure (Bang-Andersen, 1995).

Lastly, it is worth noting that while the influx of waters into the North Atlantic associated with the causation of the 8.2 ka BP cold event has been associated with a pre-8.2 ka BP cold event sea-level jump in some areas (e.g. Hijma and Cohen, 2019), the signature of this is either muted or lost against the backdrop of broader early-mid Holocene sea-level change in Norway. Numerically modelled predictions of sea-level rise project an RSL rise of between 0.6 and 0.8 m for much of northwest Europe, including Norway, but glacio-isostatic readjustment may have diminished the effects of this sea-level change here (Kendall et al., 2008: Fig. 2).

5. Mapping Mesolithic site elevation relative to contemporary palaeoshorelines

Evidence (direct and indirect) of the tsunami from archaeological sequences has been postulated at various sites along the West Norwegian coast (e.g. Prøsch-Danielsen, 2006; Åstveit, 2008a, 2008b) but remains rare and difficult to confirm. Beyond showing that preferred site locations were among those affected (e.g. Bondevik et al., 1998, 2019; Bondevik, 2003; Svendsen, 2016: 8; Åstveit et al., 2016; Nyland et al., 2021) it is of limited value for inferring broader cultural impact among coastal communities. Settlements may have been washed away by the tsunami or cleared and restored upon return if not completely abandoned or destroyed. Furthermore, the majority of confirmed Storegga deposits in Norway are subaquatic (Table 3), or at least, located within lake basins and fjords (Bondevik et al., 1997b; Bøe et al., 2004), further hinting at why direct archaeological site-based evidence of the tsunami is rare. Tsunami waves are not always hugely destructive (see for example McFadgen, 2007: 26), but waves of even 1 m may be sufficient to cause devastation, inundating large stretches of flat, low-lying land, and with energetic potential able to cause structural damage and loss of life. In many settings, however, a run-up of lower than 5 m may prove difficult to detect geologically many years after the event (Lowe and de Lange, 2000), with even extreme run-up elevations requiring a sediment trap to form deposits (Dawson et al., 2020). Hence, habitation areas within the run-up zone may have been destroyed by the tsunami, and surviving examples may not necessarily align with locations conducive to the preservation of run-up deposits.

Going beyond site-specific datasets, the hunter-fisher-gatherers of the earlier Mesolithic in this region have been characterised as well-capable of dealing with early Holocene climatic fluctuations (Breivik, 2014). Short of a population replacement scenario, changes in material culture in the face of a severe hazard may reflect dramatic population change resulting in the loss of particular subsets of specialised cultural knowledge (e.g. McFadgen, 2007: 231), but traditions of technology and material culture in Western Norway do not, on the basis of current evidence, reflect major change concordant with this period (Nyland et al., 2021; Bjerck, 2008a; Olsen, 1992). It has been suggested that people may have become more sedentary during this period (Olsen, 1992; Bergsvik, 1995, 2001, 2002; Bjerck et al., 2008; Åstveit, 2008c, 2008d; Boethius et al., 2020; Bergsvik and Ritchie, 2020), but this view, along with what it would have meant to have been sedentary in Western Norway during the Mesolithic, has recently been challenged (see Åstveit and Tøssebro, 2023), and in any case it is not clear that such changes would necessarily be linked to the tsunami. Site location is therefore assumed to provide a potential proxy for environmental change, varying partly in accordance with resource distribution and ecological productivity (cf. Breivik, 2014; Breivik et al., 2018), as well as landscape associated risks (e.g. Fitzhugh, 2012).

Table 3
Tsunami deposits from the north to south within the study area (Nordmøre to Rogaland). For Geomorphology, MB = Marine Basin, OC = Outcrop, and LB = Lake Basin. Location numbers refer to those shown in Fig. 2. The majority of these sites are located within Sunnmøre, where run-up appears to have been highest along the Norwegian coast. While many of these sites have been confidently related to the tsunami, several are postulated rather than confidently ascertained (see respective references for details). Outside of Lyngneset, Løvegapet, Longva, and Sola, all deposits are located within lake or marine basins (subaquatic, or water margin locations).

Location	Run-Up	Geomorphology	References
1. Halsafjorden	–	MB	Bøe et al. (2004)
2. Lyngneset	–	OC	Bondevik (2003)
3. Longva	–	OC	Bondevik et al. (2019)
4. Julsundet	–	MB	Bøe et al. (2004)
5. Djupvikvatnet	10–12 m	LB	Bondevik et al., 1997a
6. Rotevatnet		LB	Bondevik et al., 1997b
7. Klingrevatnet		MB	Bondevik et al., 1997a
8. Igletjørn		LB	Bondevik et al., 1997b
9. Ratvikvatnet		LB	Bondevik et al., 1997a
10. Raudåvatnet		LB	Bondevik et al., 1997b
11. Endrevatnet		LB	Bondevik et al., 1997a
12. Sulafjorden	–	MB	Bøe et al. (2004)
13. Kulturmyra	9–13 m	MB	Bondevik et al., 1997b
14. Skolemyra		LB	Bondevik et al., 1997a
15. Frøystadmyra		LB	Bondevik et al., 1997b
16. Almestradmyra		LB	Bondevik et al., 1997a
17. Voldafjorden	–	MB	Sejrup et al. (2001)
18. Nedstevatnet	–	LB	Bøe et al. (2004)
19. Medvatnet	–	LB	Bøe et al. (2004)
20. Nerfloen	1–7.5 m	LB	Vasskog et al. (2013)
21. Oppstrynsvatnet		LB	Vasskog et al. (2013)
22. Fløro	–	LB	Bondevik et al., 1997b
23. Sognasjøen	–	MB	Bøe et al. (2004)
24. Longevatnet	3–5 m	LB	Bondevik et al., 1997a
25. Førlandsvatnet		LB	Bondevik et al., 1997b
26. Auretjørn		LB	Bondevik et al., 1997a
27. Asetjørn		LB	Bondevik et al., 1997b
28. Inner Hardangerfjord	–	MB	Bellwald et al. (2016)
29. Bømlo	3–5 m	LB	Bondevik et al., 1997b
30. Vika 1&3 Løvegapet, Bømlo	–	OC	Svendsen (2016)
31. Hålandsvannet	<3 m	LB	Prøsch-Danielsen (2006)
32. Stavanger Sola Airport		OC	Prøsch-Danielsen (2006)

5.1. Relationship to the shorelines in six focus areas

Assessment of settlement patterning is based upon data from excavated and test-pit surveyed sites compared across six focus areas along the West Norwegian coast (Fig. 1). References to survey and excavation reports undertaken during the last 30 years by archaeologists at the University museums in Trondheim, Bergen and Stavanger and the County archaeologists of Møre og Romsdal, Vestland and Rogaland are presented together with further details of geographical location, topography, and more (e.g. C14 dates, site names, m.a.s.l.) in Supplementary Material: Appendix A with Tables A1-A6 and Figures A1-A12. The six focus areas listed in the introduction, used in both the numerical simulation and the palaeoshoreline relative distribution plots, were selected based on availability of published data, sizes of the surveyed areas, availability of relevant dates, and relative proximity to the propagation center of the tsunami. Within these focus areas, 173 sites are dated. Although most are typologically dated, approximately a third have one or more radiocarbon dates. Some of the sites also demonstrate multiple settlement phases.

To facilitate regional comparison, radiocarbon dates from sites within each focus area are plotted against local sea-level curves (the sea-level curves used have been made and presented by Prøsch-Danielsen, 2006; Bjerck et al., 2008b: 550[2]; Simpson, 2009; Midtbø, 2011; Kaland, 1984; Bergsvik, 2002; Svendsen and Warren, 2001) (Fig. 5). These sea-level reconstructions vary in age (one being already 40 years old) but are all still used for reference in their respective areas. To match the mentioned sea-level reconstruction curves (which are given as uncalibrated), we have also plotted the radiocarbon dates from the sites as uncalibrated. This consistency allows us to illustrate long-term regional tendencies; potential disturbances to these (along with calibrated values wherever provided by sources) are given in Supplementary Material Tables A1-A6. All C14 dates from each site are plotted in Fig. 5. Our objective is to investigate potential disturbances related to the environmental change in the late ninth millennium BP, and specifically the Storegga tsunami, so dates younger than the end of the Late Mesolithic (i.e. younger than c. 4500–4000 BCE) are omitted. In instances where estimations of elevation from the archaeological source data were wide-ranging, a median value was assumed. Where many dates overlap, some data plots may overlap and visually obscure others. Nevertheless, they serve to illustrate the general tendency of known archaeological site locations relative to the contemporary shoreline, as well as continuity or change in traditions of site placement. We recognize that patterns apparent in site elevation data may artificially reflect sampling biases where, for example, there may be a preponderance of dates from a single site locality or cultural horizon. Sites with multiple (and in some cases many) C14 dates are detailed in the Supplementary Material (Tables A1-A6).

Column diagrams were also used to present site elevation data (Fig. 6) using coarser resolution period estimations of Early Mesolithic, Middle Mesolithic and Late Mesolithic (EM, MM and LM) to additionally accommodate typologically dated sites and findspots. Although less precise than absolute dating methods, this allows for a broader database of represented sites and activity phases to be included for consideration. The typology in question pertains to the Mesolithic chronology for West Norway (Table 1). Full details may be found in Supplementary Material Appendix 1. The coarser chronological resolution is why broad time categories (EM, MM and LM) are used in the format of a column diagram, and means that Kotedalen (for example), which is represented by a wealth of radiocarbon dates across multiple phases in Fig. 5, is represented by a single data point each to denote EM and LM associations in Fig. 6, illustrating how this coarser resolution of data presentation helps mitigate against the sampling bias effect of multiple C14 dates included from a single site. Unlike Fig. 5, m.a.s.l. estimates use the lowest value where a range is given, and range values were rounded up or down to the nearest metre for plotting to prevent over-splitting of categories. Sites/artefacts assessed as younger than the Late Mesolithic were omitted.

5.1.1. *Focus area 1: Northeastern Aukra, Møre og Romsdal County*

The island of Aukra is located directly east of the Storegga submarine slide (see Fig. 1, Supplementary Material: Figures A1 and A2). It has a predominantly low topographical relief with much of the island below 25 m above sea level. The Tapes transgression reached its highest level (approx. 12 m.a.s.l.) around 6500–6100 (uncal) BP (5400–5000 cal BC) (Fig. 5.1; Bjerck et al., 2008b). Both geologically observed run-up from near this area (Bondevik et al., 1997a) and the numerical simulation model indicate that this focus area was among the most severely affected by the tsunami (Figs. 3 and 4).

The plotted dates from 21 sites, showing repeated visitations if not duration of stays, indicate broadly continuous settlement throughout the Mesolithic in this region (Supplementary Material Table A1; Fig. 5.1). There is a noticeable disturbance in settlement pattern around the time of the tsunami, and a transitory reduction in recorded activity just afterwards (Fig. 5.1). Prior to, and around the same time as the tsunami, activity seems to have been focused slightly higher up in the terrain (2–3 m), but this was not a long-lasting tradition. The Late Mesolithic sites demonstrate a continuous and strong tradition of living 1–3 m above sea level (Fig. 5.1).

5.1.2. *Focus area 2: Skatestraumen, Bremanger, Vestland County*

Skatestraumen is a strong tidal current channel situated at the coast between the islands Bremangerlandet and Rugsundøy, just to the south of the outlet of Nordfjord slide (Fig. 1, Supplementary Material Figures A3 and A4). The terrain drops from altitudes of several hundred meters to narrow strips of land along the tidal current—the only area of the landscape that would have been inhabitable (see Supplementary material). The shoreline was below present sea level until c. 7500 (uncal) BP (6500-6000 cal BC) (Fig. 5.2), implying that shore-bound sites predating this would be submerged, and shore-bound sites spanning 7500–6500 (uncal) BP (c. 6400-5500 cal BC) would have been affected by the Tapes transgression, which reached a maximum at 6–6.5 m.a.s.l. around 6000 (uncal) BP (Bergsvik, 2002).

As the model shows (Fig. 4), the wave energy and run-up of the tsunami would have been high, if perhaps less severe than at Aukra. The plot of C14 dates from 13 sites (Supplementary Material Table A2) shows that immediately prior to the tsunami, sites were situated 8–12 m above the contemporary shoreline. This position did not change after the tsunami, even as the sea-level rose. Lower-lying sites from this period might have been destroyed by the Tapes transgression, but this is not possible to ascertain. Nevertheless, the positioning of sites at some elevation above the sea during the Early and Middle Mesolithic periods seems to have been a strong and continuous tradition. In contrast to this, sites spanning 6500–5000 (uncal) BP (5500-3900 cal BC) are located even closer to the sea, with elevations between 3 and 5 m above the contemporary shoreline (Fig. 5.2). The latter pattern is confirmed by the sites without C14 dates, which are also mainly situated at these elevations (Supplementary Material Table A2; Fig. 6.2).

5.1.3. *Focus area 3: Fosnstraumen, Vestland County*

Fosnstraumen is a strong tidal current channel situated at the inner part of the coast between the islands Radøy and Fosnøy (Fig. 1, Supplementary Material Figures A5 and A6). The landscape is relatively flat, with altitudes up to 30–40 m. The shoreline displacement curve displays a marked regression during the early postglacial resulting in a minimum of c. 4 m.a.s.l. around 8800 (uncal) BP (c. 9000 cal BC), followed by a transgression stabilizing at 11.5 m.a.s.l. between 7000 and 6000 (uncal) BP (6000–5000 cal BC), before a new regression (Kaland, 1984) (Fig. 5.3). This means that sites located immediately at the shores and dated to the Early Mesolithic (>9500 uncal BP) are undisturbed, whereas sites dated to 9500–7500 uncal BP (9000-8400 cal BC) were submerged and potentially destroyed by the Tapes transgression. An exception is the site Snekkevik 23, dated typologically to the Middle Mesolithic and situated 5–7 m.a.s.l. (Olsen, 1992; Bergsvik, 1995) (Supplementary Material Table A3).

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[2] The sea level curve used for northeastern Aukra is that presented by Bjerck et al., (2008b), page 550 Fig. 5.3 - where all the C14 dates for that project were plotted. Aukra is located on isobase 30. The sea level curve generated for isobase 29 and 30 are also shown as a demonstration of how the curve changes. These sea level curves are made using the model developed by David Simpson (2009).

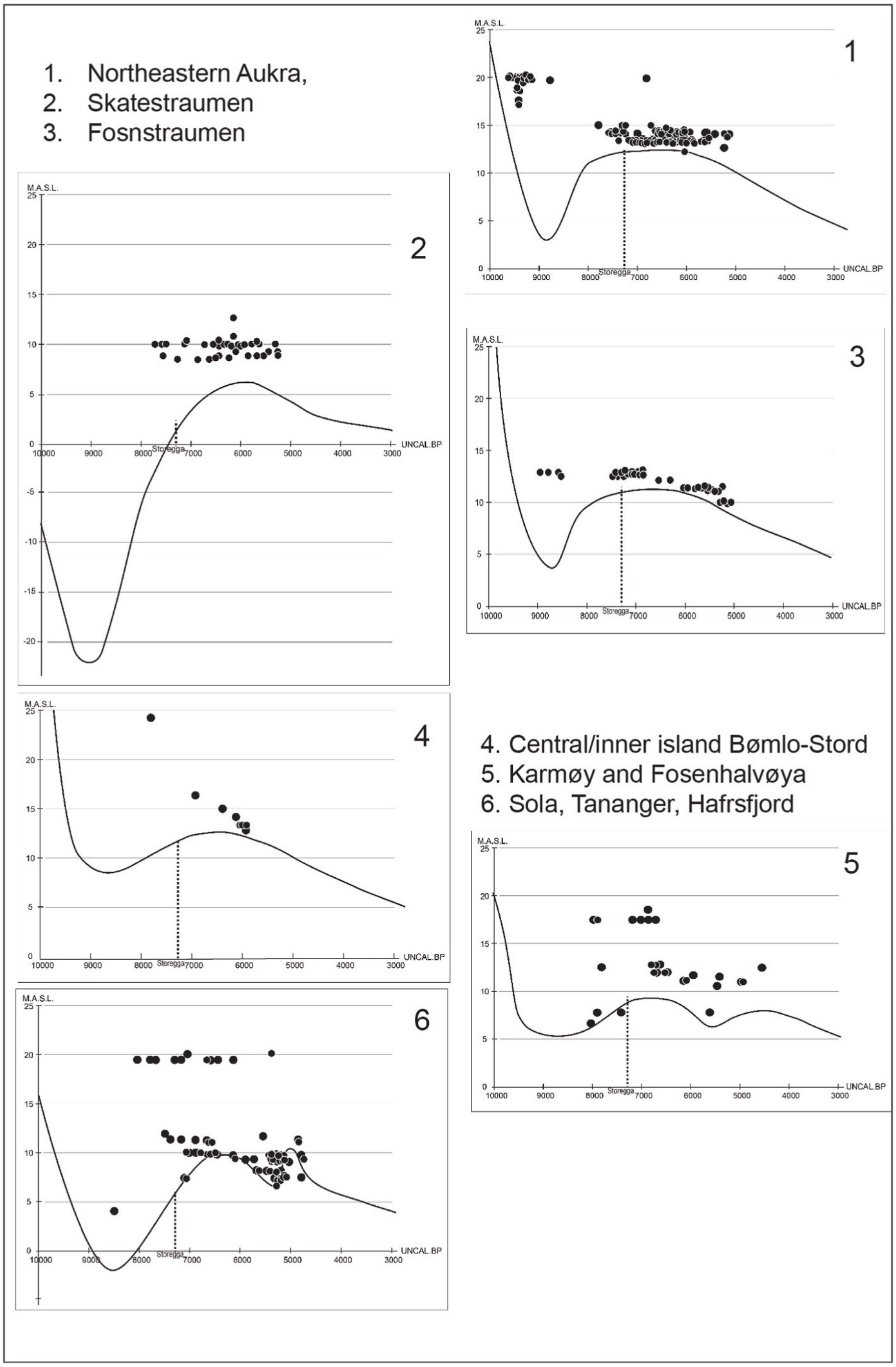

Fig. 5. Illustration of the overall tendencies of site location pattern in six focus areas. C14 dates (uncal BP date used) are plotted in relation to local sea level curves. Focus areas are presented (top to bottom) North to South. Where a range for m.a.s.l is given in the supplementary material, the median was used (Illustration made by plotting each date for each site by hand using Illustrator by A.J. Nyland and K.A. Bergsvik).

The C14-plot from the Early and Middle Mesolithic pertains to just three sites, but one of these sites has 11 occupation phases. It warrants caution in interpretation, but it is still a demonstration of similarities in spatial distribution to the plot from Skatestraumen (described in Focus area 2). Early and Middle Mesolithic sites were placed somewhat higher than the contemporary shoreline, while most Late Mesolithic sites in this focus area, continuing from just before the tsunami, were located between 1 and 3 m above contemporary sea level (Figs. 5.3 and 6.3). Although most of the dates are from the same site, Kotedalen, the same pattern is also found at Ramsvikneset and at Snekkevik 1, including surveyed sites, which strengthen this impression.

5.1.4. Focus area 4: the central/inner islands of Bømlo and Stord, Vestland County

The focus area comprising the 'central/inner islands of Bømlo-Stord' consists primarily of the small islands Spissøy, Nautøy and Føyno, with parts of the larger islands of Bømlo and Stord to the west and east respectively (Fig. 1, Supplementary Material Figures A7 and A8). The terrain is characterized by low ridges and hills reaching altitudes of c. 50 m.a.s.l. The shoreline displacement curve resembles that for Fosnstraumen however, with a regression minimum and a tapes maximum estimated to c. 7–12.5 m.a.s.l. (Kristoffersen and Warren, 2001).

The low number of C14 dates from only six sites in Fig. 5.4 warrants

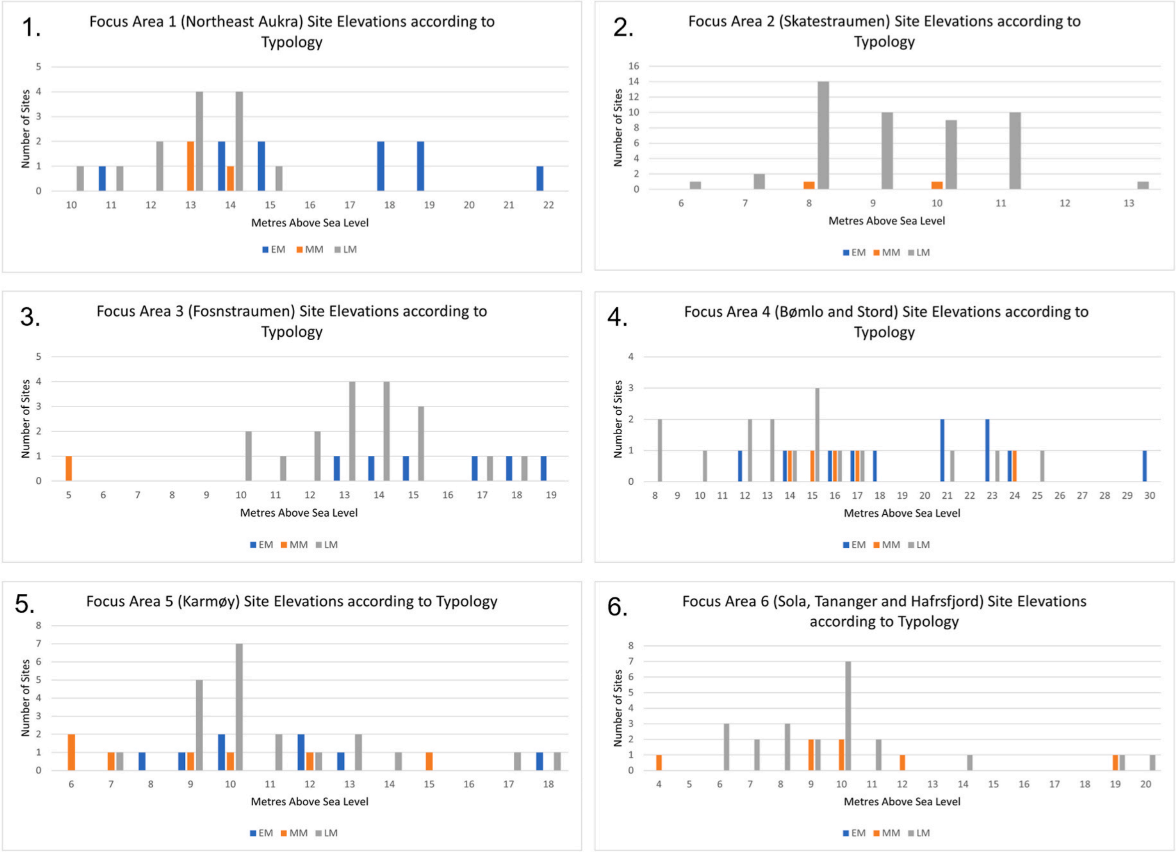

Fig. 6. Overview of site elevation above sea level divided into Early, Middle, and Late Mesolithic subdivisions (see Table 1), indicating varying degrees of flexibility throughout the Mesolithic. Where a range for m.a.s.l. is given in the supplementary material, the lowest level was chosen as a conservative estimation (Image by A.J. Nyland and K.A. Bergsvik).

caution in interpretation here as well (Supplementary Material Table A4). Nevertheless, the high elevation of the two earliest dates aligns with comparable dates from Skatestraumen and Fosnstraumen (Focus Areas 2 and 3), while later Mesolithic dates show a similar close connection to the contemporary shorelines. For sites dated typologically/technologically, the Early Mesolithic shows great variation in elevation (Fig. 6.4; Supplementary Material Table A4). However, the lack of precision available through this form of dating combined with the rapidity and severity of the regression at this time means that interpretations of site elevation have greatly reduced certainty for this period. In the Middle Mesolithic, sites are clustered within a relatively tight range between 5 and 10 m above the contemporary shoreline, while the elevations of Late Mesolithic sites are more flexible, within a range of 2–15 m (Fig. 6.4).

5.1.5. *Focus area 5: the northern east part of the island Karmøy and Fosen peninsula (Fosenhalvøya), Rogaland County*

This focus area comprises the northern, east part of the island Karmøy and the Fosen peninsula East of the narrow North-South oriented deep sound 'Karmøysundet' (Fig. 1, Supplementary Material Figures A9 and A10). The landscape on both Karmøy and Fosen is characterised by gently sloping hills no higher than 82 m.a.s.l. The Tapes transgression is interpreted as having two peaks in this focus area (Fig. 5.5), with the first, about 8–9 m.a.s.l., between approximately 7100–6800 (uncal) BP (around 6000 cal BC) (Skjelstad, 2011; Midtbø, 2011).

The plotted location of 15 C^{14} dated sites (Supplementary Material Table A5) in this focus area, as well as the 14 typologically dated ones, shows a different pattern to the investigated focus areas further north. Whereas the Middle Mesolithic sites show more flexibility than sites in the Early Mesolithic (Fig. 6.5), Late Mesolithic sites are also flexible with regards to distance from the shore, but still exhibit a preference for localities 2–4 m above the contemporary sea-level (Fig. 5.5). In the Middle Mesolithic, people began making use of rock shelters at higher elevations (Fiskåvatnet and Helleren lok.2, 17–20 m.a.s.l. see Supplementary Material Table A5). If it were not for these sites, and the shore-bound Tapes disrupted Botten 1 site, there would have been a sparsity of site representation for the period around 8200 cal BP.

5.1.6. *Focus area 6: sola, Tananger and Hafrsfjord, Rogaland County*

The focus area encompassing sites around Hafrsfjord, Sola airport, the Sømme bay, and Tananger peninsula, is characterised by gentle sloping hills reaching up to 80 m.a.s.l., flat farmland, and sloping sandy bays between crags (Fig. 1, Supplementary Material Figures A11 and A12). The Tapes transgression reached its peak of approximately 9.5 m. a.s.l. around 6700–6200 uncal BP (cf. Prøsch-Danielsen, 2006). In the Mesolithic, the Sømme bay at the southern shores of Hafrsfjord would have been a relatively shallow lagoon, sheltered from the harshest storms from the west (e.g. Meling et al., 2020). As the simulation model also demonstrates, sites located within Hafrsfjord may have been relatively well sheltered from the tsunami (Fig. 4).

Plots of dates from 20 sites with one or more settlement phases (Fig. 5.6; Supplementary Material Table A6) using the sea level curve (Prøsch-Danielsen, 2006) show some discrepancies with regards to the trough between the purportedly double-peaked transgression. Although still used for sea-level dating in Nord-Jæren, our plots demonstrate that the extent of the second peak may require recalibration. Nevertheless, the plotted sites still confirm the strong tendency of people living very close to the shores that is found all along the western coast. The plotted sites also confirm the tendency of settling in rock shelters in the Middle

Mesolithic as seen in focus area 5. In the Middle Mesolithic, prior to the Storegga tsunami, it seems there was also a tendency for sites to be located a few meters higher up in the terrain compared to later in the Late Mesolithic, when sites were mostly focused either at elevations within 3.5 m of the contemporary shoreline, or much higher >9 m. Yet when also including the typologically dated sites, the impression of greater flexibility in the Late Mesolithic site location pattern (6–20 m.a.s.l.), compared to those north of focus area 4, is strengthened (Fig. 6.6). Sites located at some elevation above the contemporary shore may reflect an awareness of the hazards that come from living on vulnerable coastlines (see Fitzhugh, 2012). Ascertaining the reason for their situation at such elevations is not possible, but tsunamis were not unprecedented for those living on the early Holocene coasts of southwestern Norway (Bøe et al., 2007). There are, however, various sites located closer to the shoreline, and we might expect there to be a clearer aversion to near-coastal elevations following Storegga, which is not apparent.

5.2. *Regional result comparison of site elevation*

All six of the focus areas have been thoroughly test-pit surveyed at various elevations due to the relatively intensive archaeological investigations undertaken by teams from the University museums and county archaeologists during the last 30 years (see details and referred to reports for each focus area in Supplementary material: Appendix A). Surveyed areas without evidence of activity indicate that people either were not there, or at the very least did not leave sufficient material trace to preserve. Many Early Mesolithic sites have been submerged or buried (and in some cases, no doubt destroyed) by the Tapes transgression. Skatestraumen (Focus area 2) and Sola, Tananger and Hafrsfjord (Focus area 6) are particularly lacking with regards to this period. At northeastern Aukra (Focus area 1) and Fosnstraumen (Focus area 3), some dates show activity 10–15 m above the contemporary shore, higher than in the later Mesolithic.

The southern three focus areas are also lacking in data from the Middle Mesolithic period because of the transgression. However, radiocarbon dates from this period show activity 15–20 m above contemporary sea-level, suggesting a flexible relationship with regards to proximity to the shore. Many Late Mesolithic sites postdate the tsunami, and are also less liable to have been affected taphonomically by the transgression. At the three northernmost focus areas that were more severely hit by the tsunami, northeastern Aukra, (Focus area 1), Skatestraumen (Focus area 2) and Fosnstraumen (Focus area 3), sites are clustered at the shore both around the time of the wave, and in the centuries that followed. Although the dating resolution does not allow us to answer the question of a possible halt in occupations near the shore just after the tsunami, there is nothing in our data to indicate such a hiatus. Site elevations at Skatestraumen situated between 10 and 12 m become relatively lower in the later Mesolithic, but the timing of this does not suggest any association with the Storegga tsunami. At northeastern Aukra (Focus area 1) and the northern, east part of Karmøy and Fosenhalvøya (Focus area 5) there is some short-lived deviation in elevation, with some evidence of activity at slightly higher elevations immediately following the tsunami, although in northeastern Aukra this is a continuation of a pattern that appears to have begun earlier. At the northern, east part of Karmøy and Fosenhalvøya it is not clear whether this reflects a change in site location preference, or some other factor.

In the northern focus areas (see Fig. 1: 1) northeastern Aukra; 2) Skatestraumen; and 3) Fosnstraumen), sites are homogenously shore-bound, with no radiocarbon dated sites more than 5–7 m above the contemporary shoreline. In the southern focus areas (see Fig. 1: 4) Bømlo-Stord; 5) northern east Karmøy and Fosenhalvøya; and 6) Sola, Tananger and Hafrsfjord), the pattern is more varied. Most sites cluster near shore-level, but there are also traces of activity higher in the terrain. Site location preference appears, to some degree, to reflect topographic constraints, but some focus areas with broadly similar topographic relief (e.g. northeastern Aukra; Fosnstraumen; northern, east Karmøy and Fosenhalvøya; and Sola, Tananger and Hafrsfjord) nevertheless show differing site elevations. Whether these differences reflect regionally contingent responses to the 8.2 ka BP cold event, a general trend for local variability in site location, or differences in taphonomy and archaeological visibility, is not possible to say. However, it is clear that in the centuries that followed the Storegga tsunami, even (and seemingly especially) in focus areas that experienced severe run-up, there was no lasting aversion to shore-bound site locations. This tendency is contrary to our initial hypothesis. Moreover, it is also a pattern contrary to what might be anticipated based on similar observations in the tsunami afflicted landscape of the Kuril Islands in the Pacific (Fitzhugh, 2012: 30–31). Whatever impact the tsunami (or indeed the 8.2 ka BP cold event) had upon Mesolithic hunter-fisher-gatherers in Western Norway, it was not sufficient to deter their predilection for the shore, at least to any lasting or archaeologically visible extent (Figs 5. and 6).

6. Discussion

Storegga tsunami deposits indicate that run-up was highest in the north, closer to the location of the slide, with at least >12 m recorded at Sula, near Ålesund in Møre og Romsdal (Fig. 2 (location B). Observed deposits were used to infer that wave height diminished to heights of generally below 3–5 m south of the Boknafjord, in Rogaland (Prøsch-Danielsen, 2006, Table 3). Initial testing of the model broadly matches these observations, with run-up elevation highest at the north (including around Sula), diminishing as it travelled south, and generally lower than 5 m south of Bjørnafjorden (Fig. 4), although peaking higher at some locations (Fig. 4. 4-6) including around the Tananger peninsula. The latitudinal inclination of the Norwegian landmass south of the slide may have helped reduce the impact upon some more southerly locations, however, with landscapes typified by a generally lower relief, lower run-up heights and large wave periods may nevertheless have resulted in significant inundation.

Run-up deposits only provide a minimum indicator of attained run-up height, but they often far exceed estimates produced by numerical simulation models (Dawson et al., 2019). Accurate reconstruction of bathymetry and topography, key determinants of run-up height, have, in the past, posed a challenge for numerical simulations (Hill et al., 2014), and may result in considerable run-up variability within a single locale (Smith et al., 2004: 2315; Fig. 3) making onshore run-up difficult to project. However, for this model, run-up is projected at 15 m or higher for much of the coastline between focus areas 2 and 1 (Fig. 4), moderately in excess of the geologically observed run-up deposits from this area (Fig. 2; Table 3), but otherwise potentially indicative of broad agreement between the observed and modelled run-up, bearing in mind the conservative minimum estimates indicated by observed run-up deposits. The agreement between the results of the model and observed run-up heights is something that may be further tested in the future.

The tsunami made land just over an hour after initiation. Run-up for focus areas 4, 5 and 6 were, with some exceptions, largely below 5 m, but local maximum water height close to the shoreline varies considerably, and low shorelines may have been vulnerable to inundation. Drawdown was marked in focus areas 1 and 2, where negative polarity preceded the arrival of the first run up with considerable drawdown (−15 m) offshore in focus area 1. Coastlines in each focus area experienced multiple waves, with subsequent waves often comparable to, or greater than earlier attained heights, potentially making the coastlines particularly risky for any who may have prematurely returned to the shore—the highest run-up in focus area 2 was attained c. 3.5 h after initiation (Fig. 3d).

Bondevik and colleagues have posited that coastal basins, narrow fjords and inlets may be well protected from storm surges, but not necessarily from open-water tsunami penetration (1998: 536; see also Bøe et al., 2007; Sejrup et al., 2001), and Fig. 3c shows that by 225 min after the wave initiation, some fjord mouths to the north and south of location 1 experienced severe run-up, in some cases penetrating deep up the fjord systems, but equally, however, some fjords and coastlines would have afforded some protection from some of the tsunami. In the worst affected areas, where the Norwegian coastline inclines east, from Skatestraumen (Focus area 2) up to Hitra (an island approximately 100 km to the northeast of Aukra, Focus Area 1), the tsunami appears to have had particularly severe run-up, in excess of 6–7 m (often much higher) across most affected coastlines and penetrating deep within the fjords. Nevertheless, the settlement elevations for focus areas 1 and 2 show a continued preference (yet some disruption around the event) for shore bound locations.

While there are differences between the different focus areas, no changes in site elevation appear to align with the tsunami, and a preference for coastal or near coastal elevations with varying degrees of flexibility is apparent in every focus area following (and before in most cases) the period in question. We may tentatively infer a continued pattern from the preceding centuries, if the Tapes transgression and the taphonomic erasure of the tsunami itself are considered as probable factors in their lack of visibility. Focus areas (4–6) to the south, where run-up was generally lower, hint at greater flexibility in site elevation choice (see also Berg-Hansen, 2009). The tendency for site locations to be less strictly shore-bound along the south-western coast has been noted for some time (Bang-Andersen, 1995), but nevertheless reflects a preference for nearshore elevations and coastal living. Living away from the sea, and with lower wave run-up attained at these latitudes, may have afforded greater protection, but on the other hand, some of the lower lying coastal stretches of this landscape may have been vulnerable to more widespread inundation (e.g. Prøsch-Danielsen, 2006), particularly in areas where coastlines were subject to longer wave periods. The flexibility exhibited here may show a response to increased storminess often assumed as a concomitant of the climatic 8.2 ka BP cold event (although see Goslin et al., 2018), and where elevation of a few meters in a low-lying landscape may have been advantageous. Equally, the patterns in the more northerly Focus areas 1–3 may reflect a degree of geographic determinism; the closer emphasis on coastal living apparent in the northern focus areas may result from a lack of suitable higher elevations in locations where coastal plateaus often abut steep cliffs. However, the continued prevalence of shore-bound sites across all focus areas suggests that, short of a deviation undetectable in the available data resolution, a maritime focus remained important for Mesolithic hunter-fisher-gatherers in this region, despite the Storegga tsunami.

Documented tsunamis from recent times, as well as ethnohistoric and archaeological accounts, show that temporary relocation if not abandonment is common in the wake of a tsunami (Bird, 1987; Hutchinson and McMillan, 1997; Goff and McFadgen, 2001; Davies, 2002; Pareschi et al., 2006; Fitzhugh, 2012; Goff and Nunn, 2016; Barnes, 2017). The enduring and markedly coastal orientation of Mesolithic hunter-fisher-gatherers in Western Norway suggests that any abandonment of the coast must indeed have been short-lived; potentially too short to resolve visibly in the archaeological record. The attractiveness of coastal ecosystems (not to mention a familiarity and sense of home) may have pulled people back, and areas of the coastline that escaped the worst effects of the tsunami may have required only modest relocation (see Fitzhugh, 2012: 31).

The ecological impacts, while pronounced, would have been locally variable, with potential for profound disruption at small spatial scales (Cooke et al., 2022). However, damage and disruption may also have recovered quite rapidly in some places (Svendsen, 2016; Ito et al., 2016; Cooke et al., 2022; Goff et al., 2011, 2012; Paterson et al., 2012). Even around the archipelagic coasts and in penetrated fjord systems, where fjord cod, demersal fish, anadromous fish and, evidently, saithe (Bondevik et al., 1997a) may have been among key, vulnerable species, overall population impact may have been small (Losey, 2005) or quick to recover (Ito et al., 2016). It seems unlikely that the negative ecological impacts of the tsunami would have lasted for much more than a decade at most, and may even have temporarily boosted productivity among some key resource species for a short time. This in turn may have helped facilitate return to, or relocation within the landscape, rather than a shift away from coastal living altogether.

The respective environmental impacts from the broadly convergent 8.2 ka BP cold event would have been different from those of the Storegga tsunami, but evidence of this in Western Norway appears mixed. Outside of central montane areas, it was, until recently, assumed that the main changes of note may have been in marine circulation, affecting temperature and salinity, but new research (Bondevik et al., 2023) has brought the severity and scale of this into question. The extent to which marine fauna were impacted is unclear, but a continued preference for coastal occupation suggests that these ecosystems retained importance, matching assessments of much cooler periods during the earlier Holocene (Breivik, 2014). An increased shift towards sedentism has been suggested for this period, but this interpretation has recently been contested (Åstveit and Tøssebro, 2023), and it is not clear to what extent such a change may or may not relate specifically to the 8.2 ka BP event.

The impacts of the Storegga tsunami, by contrast, would have been markedly different; pronounced in some areas perhaps, but regionally variable, and potentially quite short-lived. The destructive nature of the tsunami, combined with the contemporary marine transgression, limits the extent to which we may hope to see evidence of the immediate aftermath. Palaeodemographic modelling may offer insight into whether the mortality sustained from the event had a lasting impact upon populations (Kilhavn and Megarry forthcoming), but such methods, as have been used in considerations of impact from the UK (Waddington and Wicks, 2017), are not necessarily suited to parsing specific causality among temporally convergent phenomena with potentially cumulative and interlinking efffects (although see Wicks and Mithen, 2014; Waddington and Wicks, 2017; Mithen and Wicks, 2021 for extended discussion of this topic).

7. Conclusion

In some tsunami prone areas, hunter-gatherer settlement patterns appear to be located with the hazards posed by extreme waves in mind (Fitzhugh, 2012). Ethnographic records of the Nuu-chah-nulth village on Pachena bay, demonstrate a recognition of the benefits of living on higher ground:

> "*They had practically no way or time to save themselves. I think it was at nighttime that the land shook …. I think a big wave smashed into the beach. The Pachena Bay people were lost. … But they who lived at Ma:lts'a:s, "House-Up-Against- Hill" the wave did not reach because they were on high ground.*" (Arima et al., 1991).

The coastal hunter-fisher-gatherers of Western Norway no doubt knew the risks of living by the sea, but may well have been unprepared for a wave of such unprecedented size as the Storegga tsunami, at least in the areas where run-up and inundation was greatest. Lives must almost undoubtedly have been lost, and communities potentially devastated by the wave. Even in areas where the wave, or worst waves, were preceded by pronounced draw-down, there would probably have been less than an hour at most in many cases to read the warning signs and retreat to suitably higher ground. The disruption to, or perhaps even depletion of, key resources ahead of winter months may have been keenly felt in areas where run-up was highest (i.e. focus areas 1 and 2), and may have taken several years to recover or re-stabilise. We may question, however, the extent to which this disruption was sufficiently severe or widespread to motivate a shift away from coastal living (Fitzhugh, 2012; Losey, 2005; Åstveit and Tøssebro, 2023). Coastlines may have been viable if not even attractive ecosystems within a matter of years or perhaps even months, especially if, in places, disruption from the tsunami resulted in a temporary boom among some key resource species. If coastal avoidance rather than temporary relocation was practiced in the wake of the tsunami, it was seemingly too short-lived to have clearly tracked within the archaeological record and may not necessarily have been the result of environmental forcing.

The concomitant environmental impacts of the 8.2 ka BP event would have been less pronounced, and potentially unfolded over decades if not centuries. Given the mixed faunal economies of Mesolithic assemblages, coastal hunter-fisher-gatherers may have been well positioned to exploit alternative options in the event of alterations to patch distribution or temporarily reduced availability of specific taxa. Overall, the effect upon the coasts of Western Norway appears modest, if unclear. The early-mid Holocene marine transgression, however, has almost certainly biased against archaeological (if not palaeotsunami deposit) preservation across different parts of the West Norwegian coast. The transgression peak is generally highest in the areas where the highest wave run-up has been modelled and recorded, but in southern areas where run-up was lower, more sites may lay beneath the transgression maximum (Prøsch-Danielsen, 2006). The Tapes transgression, if not the tsunami itself, are probably both important factors in the lower number of sites known from the centuries preceding the tsunami at lower elevations in at least some focus areas (Figs. 2 and 5).

The numerical simulation highlights considerable regional variability of the tsunami's run-up across the six focus areas. Accordingly, we may expect that environmental damage and vulnerability would have varied considerably also, allowing for more regionally attuned understandings of impact. Run-up, and presumably associated ecological disruption, were highest in the north, closer to the initiation of the tsunami. In focus areas 1 and 2, damage and loss sustained by the tsunami may have been high. Although variable at different points, few locales here would have avoided waves of >6 m (Fig. 4). Further south, where run-up was reduced, lower lying coastal plains may nevertheless have been vulnerable to inundation. Striking at a crucial period, before the winter months, the tsunami may have damaged or wiped-out settlements, boats, fish traps and gear, and other equipment or stockpiled resources, exacerbating any loss of life sustained at sea or in the run-up affected areas. Although local variability of run-up was pronounced, some areas favoured by coastal hunter-fisher-gatherers were clearly hit (Bondevik, 2003; Svendsen, 2016; Nyland et al., 2021), even if others may have escaped some of the worst effects.

The development of a numerical simulation model for tsunami run-up across West Norway allows us to consider impacts, be they sedimentological, environmental, or archaeological, at a higher regional scale of resolution than has previously been possible. Quantification of sites and their elevations across the six different focus areas for which the model was applied show little deviation from a preference for coastal living throughout this period, despite the variability in run-up (Figures 4–6). Modest variability in the patterns of site elevation across the different focus areas does not appear to reflect the impact of the tsunami. In the aftermath of a tsunami, settlements may be abandoned, at least temporarily, but sometimes lastingly (Goff et al., 2012). However, in the case of Western Norway, this was either too short-lived to track within the resolution afforded by the archaeological record (see Goff et al., 2012: 1068) or marked regional variability of tsunami impact meant that only modest relocation was required (see Fitzhugh, 2012), and not necessarily away from the coasts. For areas where coastlines were widely affected by high run-up (Focus areas 1 and 2), this may reflect topographic constraints within the landscape with regards to suitable habitation location, or the enduring attraction of coastal resources. Ongoing research may yet elucidate new patterns in social or material culture change relating to the tsunami (Nyland and Damlien, forthcoming), however, at present, it is not clear that the tsunami effected any great immediate change in technological traditions, tendencies in site location preference, or an overarching focus upon coastal resource exploitation.

Author contributions - CRediT

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data used is accessible through information contained within Supplementary Material.

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Appendix A. Supplementary data

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