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Late Holocene sea-level change in Arctic Norway

Robert L. Barnett [a,*], W. Roland Gehrels [a,1], Dan J. Charman [b], Margot H. Saher [a,2], William A. Marshall [a]

[a] School of Geography, Earth and Environmental Sciences, Plymouth University, Drake Circus, Plymouth, Devon, PL4 8AA, UK
[b] Geography, College of Life and Environmental Sciences, University of Exeter, Amory Building, Rennes Drive, Exeter, EX4 4RJ, UK

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A B S T R A C T

Relative sea-level data from the pre-industrial era are required for validating geophysical models of glacio-isostatic adjustment as well as for testing models used to make sea-level predictions based on future climate change scenarios. We present the first late Holocene (past ~3300 years) relative sea-level reconstruction for northwestern Norway based on investigations in South Hinnøya in the Vesterålen – Lofoton archipelago. Sea-level changes are reconstructed from analyses of salt-marsh and estuarine sediments and the micro-organisms (foraminifera and testate amoebae) preserved within. The 'indicative meaning' of the microfauna is established from their modern distributions. Records are dated by radiocarbon, ^{201}Pb, ^{137}Cs and chemostratigraphical analyses. Our results show a continuous relative sea-level decline of 0.7–0.9 mm yr^{-1} for South Hinnøya during the late Holocene. The reconstruction extends the relative sea-level trend recorded by local tide gauge data which is only available for the past ~25 years. Our reconstruction demonstrates that existing models of shoreline elevations and GIA overpredict sea-level positions during the late Holocene. We suggest that models might be adjusted in order to reconcile modelled and reconstructed sea-level changes and ultimately improve understanding of GIA in Fennoscandia.

1. Introduction

Since the Last Glacial Maximum, Norway's northwest coastline has experienced net relative sea level (RSL) fall due to the rapid isostatic land uplift that followed the retreat of the Fennoscandian Ice Sheet (Svendsen and Mangerud, 1987). RSL data collected in the region derive from studies of isolation basins, raised shorelines and associated deposits (Marthinussen, 1960, 1962; Møller, 1982, 1984, 1986; Vorren and Moe, 1986; Vorren et al., 1988; Corner and Haugane, 1993; Balascio et al., 2011). These data identify an early Holocene regression (Marthinussen, 1962), followed by a period of transgression which culminated in the mid Holocene Tapes highstand (Møller, 1986).

Models of glacio-isostatic adjustment (GIA) are used to predict Holocene sea-level histories in Norway (Lambeck et al., 1998a) and are validated against field evidence (Lambeck et al., 1998b). The GIA model of Lambeck et al. (1998a) makes use of four studies from the Lofoten – Vesterålen archipelago, off northwest Norway, to substantiate their RSL predictions. The publications provide sea-level constraints for the pre-, early-, and mid Holocene, but no sea-level index points (SLIPs) exist for the past 3000 years (Møller, 1984, 1986; Vorren and Moe, 1986; Vorren et al., 1988). Additional sea-level data from the Lofoten – Vesterålen archipelago, especially for the late Holocene, are required to constrain the (ongoing) GIA component for the region. These data are useful for predicting future RSL changes which are dependent on these models (Simpson et al., 2014).

With the onset of more rapid global sea-level rise in the near future (Bindoff et al., 2007; Church et al., 2013), combined with the deceleration of crustal rebound in this part of northern Norway (Lambeck et al., 1998b), it has been shown that many locations along the Norwegian coast will see a rise in sea level in the order of tens of centimetres during the 21st century (Simpson et al., 2014). High end estimates from the same study and time period suggest that much of Norway's coastline may experience half a metre of RSL rise or more. As many as 110,000 buildings are located less than 1 m above present sea level in Norway (Almås and Hygen, 2012) which gives perspective to the threat of sea-level rise over the next 100

* Corresponding author. Present address: Centre GEOTOP, 201 Pavillon Président-Kennedy, 7ième étage, Local PK-7150, Montréal, Québec, H2X 3Y7, Canada. Tel.: +1 514 967 6871; fax: +1 514 987 3635.
E-mail address: robert.langdon.barnett@gmail.com (R.L. Barnett).
[1] Present address: Environment, University of York, Heslington, York, YO10 5DD, UK.
[2] Present address: School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey, LL59 5AB, UK.

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years. The municipality of Nordland, where the field sites are located, has the second highest concentration of buildings situated less than 1 m above mean sea level (MSL) in Norway. Under the worst case scenarios, this municipality may experience an average sea-level rise of 90 cm or higher along its coastlines (Vasskog et al., 2009; Simpson et al., 2012). This rise of mean sea level, combined with added threat from more frequent and more severe storm surges, means that isostatically uplifting regions such as northern Norway are not immune to the effects of future climate change.

Sea-level data derived from proxy information generate longer records than those provided by instrumental measurements. The most widely used proxy sea-level indicators in mid latitude sites are derived from salt-marsh sediments and are capable of reconstructing past sea levels with precisions as high as ±5 cm (Gehrels and Woodworth, 2013). Extensive salt marshes are rare along steep, glaciated Arctic coastlines. The few published North Atlantic high latitude salt-marsh based sea-level studies include work in Greenland by Woodroffe and Long (2009) and Long et al. (2010) and in Iceland by Gehrels et al. (2006b) and Saher et al. (in review). Virtually all existing sea-level data originating from salt-marsh sediments make use of either foraminifera or diatoms as sea-level indicators (e.g. Scott and Medioli, 1982; Gehrels, 1994; Horton and Edwards, 2006; Long et al., 2010; Barlow et al., 2013). The type and abundance of species for both organism groups vary with elevation across the marsh in response to the duration of tidal inundation. Once the relationship between modern assemblage composition and elevation relative to sea level has been established, fossil assemblages can be analysed and used to infer past sea-level histories.

More recently a third microfossil group, testate amoebae, has been developed as a proxy tool for sea-level reconstructions (Gehrels et al., 2006a, 2001; Charman et al., 2010, 2002, 1998; Ooms et al., 2012, 2011; Barnett et al., 2013). In wetlands, these organisms primarily respond to hydrological variability, but they are also sensitive to salinity and display zonation with respect to elevation in salt marshes. Testate amoebae generally show a stronger vertical distribution across salt marshes than diatoms and foraminifera (Gehrels et al., 2001; Charman et al., 2010). In addition, testate amoebae also occur in supratidal settings, beyond the upper limits of foraminifera, but their lower limit does usually not extend below the level of the mean high water of spring tide (Gehrels et al., 2001; Charman et al., 2010).

The primary aim of this study is to provide new high-quality sea-level data for a location in the Vesterålen archipelago that can be used to better constrain GIA models for Scandinavia. A novel aspect of this work for Scandinavia is that we derive sea-level index points from estuarine deposits, rather than isolation basins. We use a multi-proxy approach, with salt-marsh testate amoebae providing a sea-level reconstruction for the past century, and foraminifera for the remainder of the past 3000 years.

2. Study area

This study is located on the south coast of Hinnøya, an island belonging to the Vesterålen archipelago off Norway's northwest coast (Fig. 1). This area has a temperate climate, influenced by the warm (~5–10 °C; Hansen and Østerhus, 2000) waters of the Norwegian Current. Mean monthly atmospheric temperatures range from 2° in December, to 13 °C in July (Norwegian Meteorological Institute; based on the period 1964–1990) and snow cover is experienced through January and February. The local geology across the Lofoten and Vesterålen islands comprises a Precambrian basement complex of Archaean gneisses containing Caledonian aged granitic plutons (Malm and Ormaasen, 1978; Koistinen et al., 2001; Nordgulen et al., 2006). The steep coastline of the Lofoten and Vesterålen islands has been heavily influenced by glaciation and there are few locations where low energy, intertidal deposits accumulate. In July 2010, two salt marshes were identified in coastal inlets flanked by headlands (Fig. 1) based on distinctive patterns of intertidal plant zonation. Reconnaissance coring uncovered several metres of intertidal sediments that were deemed suitable for the reconstruction of sea-level changes.

The smaller field site at Storosen contains a narrow (~40 m wide) salt marsh (3.5 km^2) with shallow stratigraphy. The vegetation of the higher part of the salt marsh is dominated by *Juncus gerardii*, whereas in the lower salt marsh *Plantago maritima* and *Juncus ranarius* thrive. Foraminifera and testate amoebae were sampled along two surface transects.

The field site at Svinøyosen is larger than the Storosen marsh. Here, a well-developed salt marsh (12 km^2) is located at the landward end of a narrow (100 m wide) coastal inlet. An intertidal channel in the 1 km long inlet is fed during low tide by a freshwater stream which delivers sediment from the catchment area. The Svinøyosen marsh is underlain by a sequence of Holocene sediments, over 2 m thick in places. The floral zonation here is similar to that described above, with the addition of *Triglochin maritima* in the low marsh. A further four surface sampling transects were established at Svinøyosen to sample foraminifera and testate amoebae and three coring transects were used to document the lithostratigraphy and to provide sediments for palaeoenvironmental analyses.

3. Methods

3.1. Modern sampling

When microfaunal assemblages are used to reconstruct sea-level changes it is necessary to establish first the local relationship between modern microfauna and elevation. This then forms the basis to assign an indicative meaning to fossilised assemblages (Gehrels, 1994). The modern environment was sampled for foraminifera and testate amoebae using two surface sampling transects at Storosen, and four at Svinøyosen. These transects started near the terrestrial edge of the salt marshes, extended through the high and low marsh zones, and out onto tidal mud flats. In Svinøyosen, the additional transects were used to extend the sampling into the intertidal realm (from 1.5 m above to 0.6 m below MSL) in order to obtain modern analogue samples for lower marsh and tidal flat facies. Samples were taken at regular vertical intervals of ~4 cm and surveyed to a benchmark using a Trimble 5600 total station (vertical error ±0.002 m), or theodolite and staff (vertical error ±0.01 cm). Benchmark elevations were measured using a Trimble DGPS RTK base station (vertical error ±0.007 m) and referenced to MSL of the coordinate system group of Norway (NGO48), and the geoid model Norway Geoid 2008. Tidal height data for the field site were interpolated from two nearby secondary ports, Kabelvåg and Lødingen using Admiralty Tide Tables (Table 1).

Surface samples were prepared for foraminiferal analyses following Gehrels (2002), based on the preparation procedures of Scott and Medioli (1980). Taxonomy for foraminifera follows Murray (1979, 1971) and Loeblich and Tappan (1988). A known volume of sediment from the top one cm of each sample was taken and stained with rose Bengal, prior to sieving through 300 μm and 63 μm mesh sieves. The 63–300 μm fraction was split into eight aliquots prior to counting. Both live (stained) and dead (unstained) assemblages were counted, although only assemblages composed of dead specimens are presented here and used to construct the modern training set. Dead assemblages are less susceptible to effects of seasonality and most resemble fossil assemblages (Murray, 1976, 1982, 2000). Testate amoebae sampling follows Barnett et al.