Evidence for a rapid sea-level rise 7600 yr ago

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ABSTRACT

Dating the transgression and subsequent regression in marginal basins of the southeastern Swedish Baltic Sea provides a new perspective of global ice-volume changes and the isostatic adjustment of the mantle after the retreat of the Scandinavian Ice Sheet from this area. Superimposed upon a smooth pattern of local sea-level rise, acceleration occurred ca. 7600 calibrated (cal) yr B.P., evidenced as a nearly synchronous flooding in six elevated basins ranging from 3.0 to 7.2 m above present sea level. We ascribe this rapid local sea-level rise of ~4.5 m to a sudden increase in ocean mass, most likely caused by the final decay of the Labrador sector of the Laurentide Ice Sheet. The subsequent monotonic fall of local sea level from ca. 6500 cal yr B.P. to the present is mainly an expression of the slow isostatic adjustment of the mantle.

Keywords: Holocene, Baltic Sea, rapid sea-level rise, lake isolation, crustal rebound, Laurentide Ice Sheet decay.

INTRODUCTION

Dating the accretion of coral reefs reveals a smooth pattern of postglacial sea-level rise (Fairbanks, 1989; Chappell and Polach, 1991; Bard et al., 1996) as major continental ice sheets in the Northern Hemisphere disappeared. However, in the Caribbean-Atlantic region, a reef back stepping ca. 7500 calibrated (cal) yr B.P. has been interpreted as a rapid sea-level rise of 6.5 m (Blanchon and Shaw, 1995). The validity of this event has been subject to debate, because no rapid sea-level rise corresponding to this event has been observed from coral records in the neighboring areas (e.g., Bard et al., 1996; Montaggioni et al., 1997; Toscano and Lundberg, 1998). Recent work on dating salt-marsh drowning on the eastern U.S. coast (Bratton et al., 2003), together with data from northwest Europe (Christensen, 1995, 1997; Lemke, 2004; Behre, 2007), has renewed interest in this question. All of these records indicate the same amplitude of sea-level rise, and thus imply a global expression of this event. If it is global, and because it occurred under climate boundary conditions similar to the present, determining its magnitude and rate may provide a better understanding on how future sea level responds to global warming and the potential melting of polar ice sheets (Alley et al., 2005), particularly the land-based Greenland Ice Sheet.

The accuracy of coral records depends on the knowledge of growth position of coral communities to mean sea level and the temporal variability of marine radiocarbon reservoir age (Clark, 1995). Sea-level reconstructions through dating salt-marsh basal peat in open marine settings are subject to the uncertainties of tidal amplitude. Therefore, these data sets should be tested with other independent evidence, ideally from areas of tectonic stability and small tidal range.

STUDY AREA AND METHODS

In previously glaciated areas, local sea-level changes are primarily governed by the relative rates of crustal rebound and global sea-level rise. We reconstruct Holocene sea-level history on the southeastern Swedish Baltic coast by systematically dating the lacustrine to marine and marine to lacustrine transitions in sediment sequences from eight closed basins with a sill of known elevation (Fig. 1). In addition to these sites, a beach ridge at Olsäng (Fig. 1A), situated 8.0 m above sea level (asl) and representing the highest Holocene sea level in this area, was dated. A sample from peat immediately below the beach ridge yields a radiocarbon date of 5690 ± 70 yr B.P., a maximum age for the beach ridge. Due to the narrow connection with the Atlantic, the Baltic Sea is a brackish-water body with an extremely low amplitude tide of <5 cm (Ekman and Stigebrandt, 1990). The meteorological tide caused by storm surges can result in a perturbation of ±25 cm in the sea level (Stigebrandt and Gustafsson, 2003), and this transient sea-level change can be reflected in sedimentary records of the basin, when the mean sea level is close to the sill. However, such an event has no significance for the reconstructions of mean sea level. Another significant advantage is that these sites are distributed more or less along the 10 m isobase, a contour of postglacial land uplift (Fig. 1A, inset), thereby reducing the possible influences of differential isostatic uplift. These preconditions ensure excellent constraints on past sea-level changes for the period after the retreat of the Scandinavian Ice Sheet, when the Baltic was in open contact with the Atlantic.

The sill of most basins, composed of thin boulder-rich till or sandy sediments resting on Precambrian granite, may have been partly eroded during the transgression or aggraded after the regression. We estimate that this alteration may introduce a maximum error of ~40 cm, according to the thickness of the undisturbed till in this area. Age control for the cores was provided by radiocarbon dating of terrigenous plant macrofossils except for Inlängan, Siretorp, and Hallarum, where bulk organic matter samples were dated. A regional radiocarbon reservoir age anomaly of 108 ± 24 yr (Berglund, 1971) was used to correct the bulk organic matter samples for the marine stage of the Baltic Sea. All radiocarbon dates were calibrated using the CALIB 5.0 program (Reimer et al., 2004). Identifications of sedimentary facies are based on analyses of diatoms, dinoflagellate cysts, and aquatic macrofossils. We use a fully coupled and gravitationally consistent ice-water-earth model to calculate the isostatic uplift and its contribution to sea level at each site using the model parameters described in Lambeck and Purcell (2003). The time-dependent eustatic sea-level function used here was described in Lambeck and Chappell (2001).

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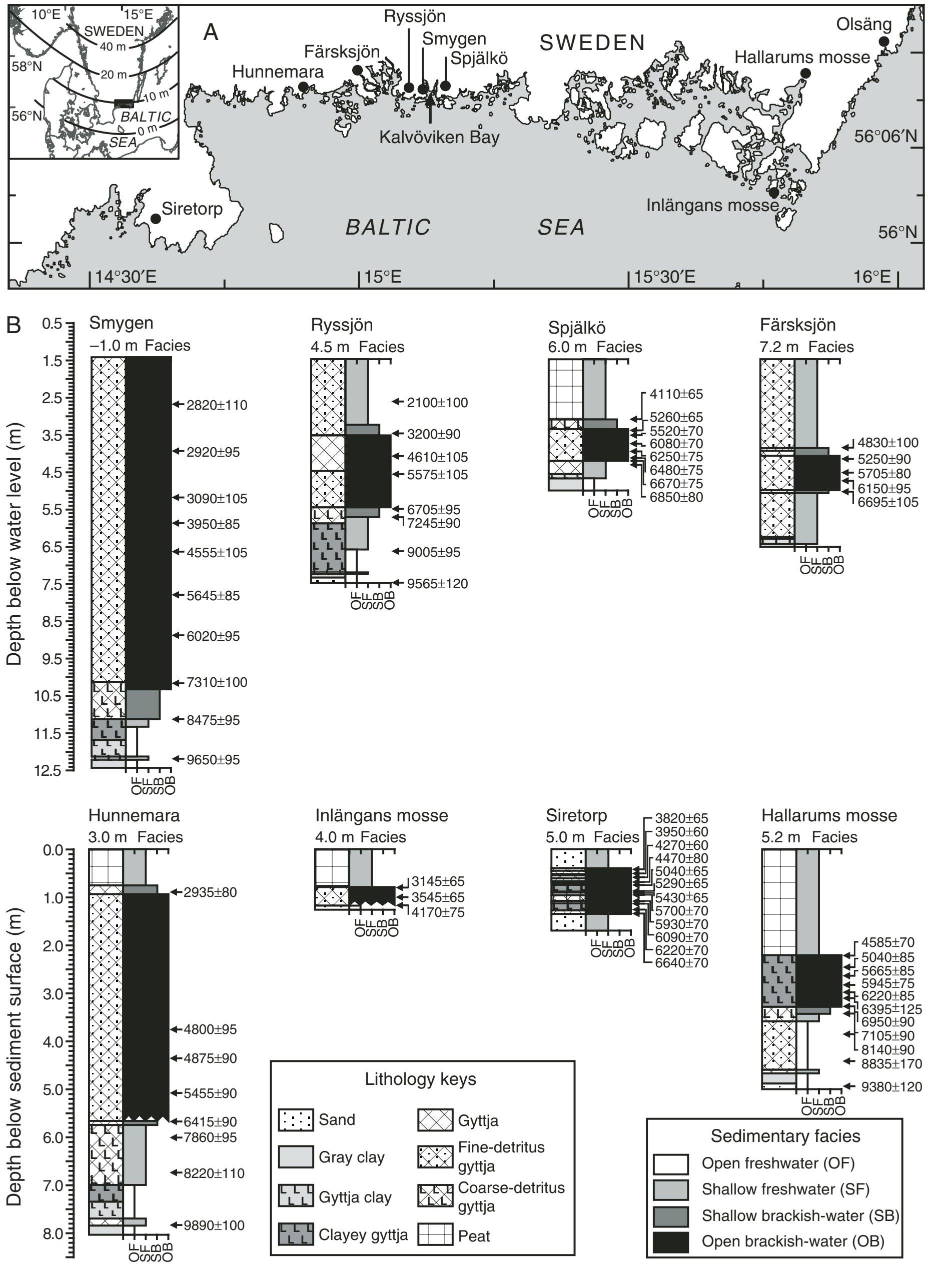

Figure 1. A: Location of isolation basins in southeastern Sweden as well as the mid-Holocene uplift isobase (inset). B: Core logs and sedimentary facies identified from multiple stratigraphic sequence analyses (Berglund, 1964; Liljegren, 1982; Yu et al., 2003, 2004, 2005). Arrows indicate dated levels and the radiocarbon dates. Elevation of the sill for each site is indicated at top of log.

RESULTS

Sedimentary Facies and Chronology

Four disparate sedimentary facies have been identified for most of the sites (Fig. 1B). The open freshwater (OF) facies are characterized by abundant planktonic freshwater diatoms and thus indicate a wide connection of the basin to the Baltic during the Baltic Ice Lake and the Ancylus Lake stages (cf. Björck, 1995). The shallow freshwater (SF) facies are marked by the dominance of benthic freshwater diatoms, representing an isolation of the basin from the Baltic. The shallow brackish-water (SB) facies are defined by abundant brackish-water diatoms with freshwater affinity, indicating a weak connection of the basin to the Baltic, perhaps only during stormy season. The open brackish-water (OB) facies, marked by the occurrences of sea grasses, dinoflagellates, and planktonic brackish-marine diatoms, represent a wide connection of the basin to the Baltic Sea. The detailed palaeoecologies of the sites have been published elsewhere, e.g., Hallarums mosse and Inlängans mosse (Berglund, 1964), Spjälkö (Liljegren, 1982), Ryssjön (Yu et al., 2003), Färsksjön and Siretorp (Yu et al., 2004), and Smygen and Hunnemara (Yu et al., 2005).

We obtained 65 radiocarbon dates (Fig. 1B) that provide a firm age control on the timing of the sedimentary facies, particularly the OB facies. Note that the levels exactly representing the lacustrine-marine and marine-lacustrine transitions at most sites were well dated, except for Smygen (Fig. 1B). For this site we have established an age-depth model to refine the onset of transgression (Yu et al., 2005).

Local Holocene Mean Sea-Level Record

Measuring the elevation of the sills and dating transgressions into and regressions out of these basins (i.e., the timing of the OB sedimentary facies) enabled us to reconstruct local mean sea-level changes when the Baltic Sea was widely connected to the Atlantic (Fig. 2). The SB facies occur very briefly and are missing in the stratigraphic context of some basins. Where present, these facies indicate an intermittent connection of the basin to the Baltic Sea due to extreme meteorological tides, and thus have not been considered in our reconstruction of mean sea level.

Our data show that local sea level rose steadily from 8600 to 6500 cal yr B.P. (Fig. 2), coherent with the ice-volume–equivalent global sea-level rise (Fairbanks, 1989; Chappell and Polach, 1991; Bard et al., 1996). Superimposed on this trend, a rapid rise of ~4.5 m occurred ca. 7600 cal yr B.P., indicated by a nearly synchronous flooding in six elevated basins with a sill ranging from 3.0 to 7.2 m asl. In some basins, e.g., Hunnemara and Inlängan, strong inflow of seawater may have been established through the narrow inlet associated with this rapid sea-level rise, which in turn led to destructive erosion and thus a sediment hiatus in the coring place (Fig. 1B). Local sea level then began to fall monotonically down toward the present position. This process is mainly an expression of the slow isostatic adjustment of the mantle, while global sea level remained nearly constant (Lambeck and Chappell, 2001).

Corrections for Differential Isostatic Uplift

Because the ice margin in late glacial time was approximately parallel to the coast, as indicated by the strike of the 10 m isobase (Fig. 1A, inset), the predicted isostatic uplift is comparable for all sites, and only the predictions for Siretorp and Olsäng, the southernmost and northernmost sites, depart a bit from a representative result, for example, for the Kalvöviken Bay (Figs. 1A and 3A). The predicted sea level for the Kalvöviken Bay, based on ice-earth model parameters estimated from an inversion of a large Scandinavian

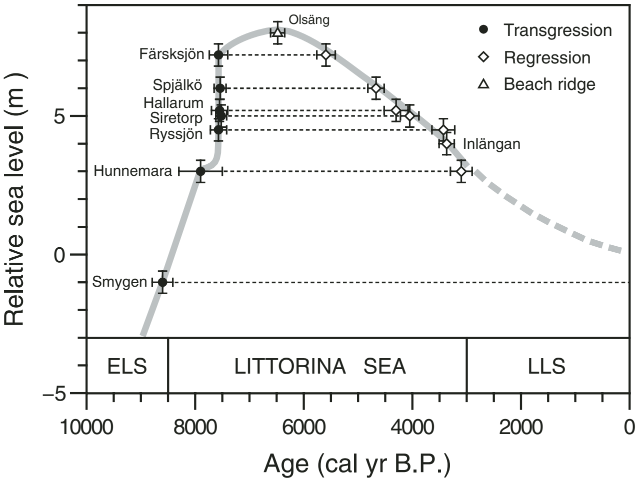

Figure 2. Holocene mean sea-level changes along southeastern Swedish Baltic coast. Horizontal bars represent 2σ calibrated age range, and vertical bars are defined by uncertainties of sill elevation. ELS—early Littorina Sea; LLS—late Littorina Sea. Dashed lines indicate duration of open brackish-water (OB) facies at the sites. Gray heavy line highlights trend of local mean sea-level changes.

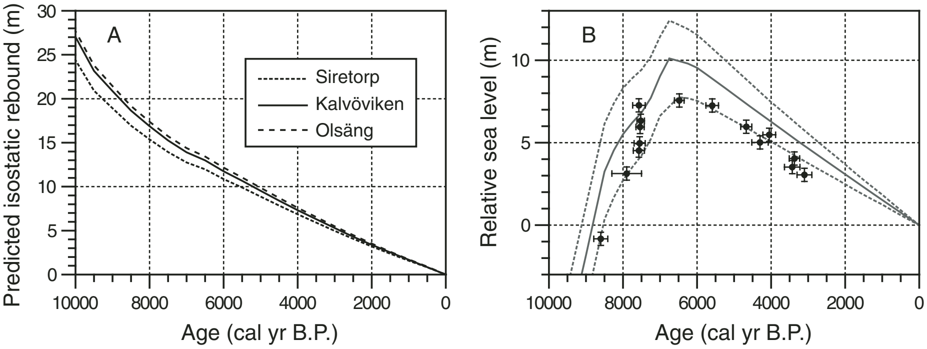

Figure 3. A: Predicted Holocene isostatic uplift for three sites on southeastern Swedish Baltic coast. B: Predicted relative sea level at Kalvöviken Bay plotted against observed sea-level data after being corrected for the differential isostatic uplift effect.

data set (Lambeck et al., 1998), is illustrated in Figure 3B and includes the upper and lower limits of the predicted change as the uncertainty in earth-model parameter estimates. We have therefore applied differential isostatic corrections to reduce the isostatic uplift data to a reference site (Kalvöviken Bay). Figure 3B also illustrates the observed sea levels reduced to the reference site and the original features of the uncorrected record (Fig. 2); in particular, the rapid sea-level rise ca. 7600 cal yr B.P. is still preserved. These corrections are model dependent, but the isostatic models are also consistent with a range of instrumental observations (Lambeck et al., 1998; Milne et al., 2001), all of which indicate that the differential isostatic corrections between the sites are small and that the observed rapid rise is not an artifact of different isostatic uplift rates at the sites.

DISCUSSION

We reconstruct a high-resolution local mean sea-level record in southeastern Sweden by dating transgression into and regression out of coastal basins with different sill elevations. In particular, our record reveals an ~4.5 m rapid sea-level rise ca. 7600 cal yr B.P. with a dating uncertainty of ~400 yr. We endeavored to date terrigenous plant macrofossils. Only three sites were dated on bulk organic matter, which may contain pre-aged carbon. However, the stratigraphic consistency of radiocarbon dates along these cores suggests that the reworking of pre-aged organic carbon is not important. It has been suggested that seismic subsidence may have been important for the apparent rise of local sea level (Mörner, 2004). However, there is no evidence in this region to support large-scale faulting during the Holocene. Thus we conclude that the rapid sea-level-rise event is representative for the entire region and broadly consistent with the evidence for global sea-level rise during this period.

A similar rapid sea-level rise event has been identified elsewhere, suggesting that it is global in extent. For example, a sea-level rise of ~4 m during the time span 7900–7600 cal yr B.P. has been documented offshore along the German North Sea coast (Behre, 2007); the rise is related to a similar rise in southern Kattegat Sea dated to 7700–7400 cal yr B.P. (Christensen, 1997), as well as to a ~6 m rise in the southwest Baltic Sea dated as 8000–7700 cal yr B.P. (Lemke, 2004). This rapid sea-level rise also can be correlated with beach ridges along the Danish Kattegat and Öresund coasts (Christensen, 1995). In the Caribbean Sea, submarine terraces and drowned strandlines point to a stepped rise of sea level ca. 7500 cal yr B.P. (Blanchon and Jones, 1995; Blanchon et al., 2002), corresponding to the rapid sea-level rise in the Red Sea (Siddall et al., 2003) and on the Sunda Shelf (Bird et al., 2007). The spatial variation in the magnitude of this event is most likely due to localized tectonic conditions or the differential isostatic response of the mantle to water loading.

We propose a eustatic origin for this event. An Antarctic source of meltwater (e.g., Blanchon and Shaw, 1995) is not convincing, although seemingly supported by a spike of Antarctica-derived ice-rafted debris (IRD) blanketing the South Atlantic between 8000 and 7500 cal yr B.P. (Hodell et al., 2001). However, this IRD record is poorly defined because of the lack of reliable radiocarbon reservoir ages for the Southern Ocean. In addition, both ^{10}Be (Stone et al., 2003) and radiocarbon (Conway et al., 1999) dates show that the thinning of the West Antarctic Ice Sheet did not accelerate until after 7000 yr B.P. Carlson et al. (2007) proposed a Northern Hemispheric origin: their ^{10}Be dates reveal an ~600 km abrupt decay of the Labrador sector of the Laurentide Ice Sheet between 7400 and 6800 yr B.P., further supported by a sudden depletion of surface-water δ^{18}O isotopes in the Labrador Sea (Hillaire-Marcel et al., 2001).

The greatest uncertainty in predicting future sea-level changes is in the contribution of the polar ice sheets. In contrast to the Antarctic Ice Sheet, the land-based Greenland Ice Sheet appears to be the major source for the ongoing eustatic sea-level rise (Shepherd and Wingham, 2007). Our record reveals a rapid sea-level rise ca. 7600 cal yr B.P. with an amplitude similar to those identified elsewhere. Within the dating uncertainties, the rate of this rapid sea-level rise is estimated to be ~10 mm/yr, much higher than that observed over the last century. Our finding shows that sea level can rise rapidly without large continental ice sheets under climate boundary conditions similar to the present. If this rise came from the remnant Laurentide Ice Sheet, as originally proposed by Carlson et al. (2007), then a land-based ice sheet can decay relatively fast, boding ill for the Greenland Ice Sheet.

CONCLUSION

Dating the transgression and subsequent regression in marginal basins of the southeastern Swedish Baltic Sea provides a high-resolution local mean sea-level record. The local sea-level changes, reduced to the reference site, can be divided into two phases. (1) From ca. 8600 cal yr B.P., local mean sea level rose progressively and culminated ca. 6500 cal yr B.P., reflecting the dominance of the ice-volume component due to the melting of the remnant Laurentide Ice Sheet during the mid-Holocene thermal maximum. (2) From ca. 6500 cal yr B.P., local sea level fell monotonically down to the present position, mainly as a manifestation of the slow isostatic adjustment of the mantle. Our independent sea-level reconstructions with a firm age control provide conclusive evidence for a rapid sea-level rise ca. 7600 cal yr B.P. that previously remained equivocal. Given the Northern Hemispheric origin of this event, our finding is important for understanding the future response of the land-based Greenland Ice Sheet to global warming resulting from anthropogenic CO_2 emissions.

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