Reconstructing Holocene Sea-level Change in the White Sea (Russia)

A Senior Honors Thesis

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ABSTRACT: This study provides a Holocene relative sea-level reconstruction of the White Sea, Russia. Accurate relative sea-level reconstructions calibrate Earth-ice models that are used in analyzing global satellite data such as data from the Gravity Recovery and Climate Experiment (GRACE) and provide context for modern sea-level change. Foraminifera from a core of salt-marsh peat taken above the current high tide line were used as sea-level indicators to reconstruct relative sea level along the southern coast of the White Sea in northwestern Russia. Analysis of modern salt-marsh foraminifera show a marsh dominated by two species: *Balticammina pseudomacrescens* in the high marsh and *Miliammina spp.* in the lower marsh. Partitioning around medoids statistical analysis shows four primary groups of foraminifera and their relationship to mean tide level, representing high marsh, low marsh, sub-tidal, and freshwater upland ecological zones. Analysis of foraminifera in the core show an abundance of *B. pseudomacrescens,* placing core samples into the high marsh zone. Relative sea level was calculated to be 2.33 ± 0.59 m higher than it is today, indicating relative sea level fall. Radiocarbon dates from plant samples above and below the analyzed marsh samples in the core constrained the sea level change to 2804 ± 52 years before present (BP; 1950AD). Comparing these data to a predicted sea level curve shows a lower than expected relative sea level. This may be due to local effects such as tectonics or subsidence, or to an inconsistency with the assumed mantle characteristics indicating that a reevaluation of mantle properties may be necessary.

Introduction

Salt marshes at continental margins preserve records of past relative sea level (RSL; Scott and Medioli, 1978). Reconstructions of relative sea level change since the Last Glacial Maximum are important for two reasons:

1) They provide context for current and future trends. These trends can only be meaningfully understood when viewed against long term, pre-anthropogenic trends.

2) They test and constrain Earth-ice models (e.g. Lambeck et al., 1998). The Earth model parametizes the geophysical behavior of the solid Earth in response to mass redistribution which is primarily controlled by mantle structure and composition. The ice model describes the evolving distribution of land-based ice through time and across space. Relative sea-level reconstructions can be used to tune these models and therefore estimate parameters that cannot be measured directly (e.g. mantle viscosity).

Conceptually, relative sea level is the net outcome of four factors:

1) eustatic sea level which is the mass and volume of water in the global ocean,
2) isostasy which is the response of the lithosphere to loading and unloading of mass,
3) tectonic effects that can cause vertical land level change, and
4) local effects, such as subsidence from sediment compaction or changes in coastal geomorphology .

Thus, relative sea level varies both spatially and temporally because these four factors (and combinations of them) are not constant in time and space. Clark et al. (1978) developed the first Earth-ice models and divided the globe into six Holocene relative sea-level zones corresponding to distance away from the glacial margin at the Last Glacial Maximum. The zones represent “near field,” which was covered in ice such as zone 1; “intermediate field” near the glacial margin such as zone 2, and “far field” removed from glacier margin such that the glacio-isostatic rebound effect is negligible such as zone 3. The White Sea study area (fig. 1) lies at the transition zone between region 1 and region 2 (fig. 2), near the glacial margin of the Fennoscandian Ice Sheet (fig. 3) (Clark et al., 1978). The zones have different predicted relative sea level curves, which differ by isostatic sea level change. For example, a relative sea level curve for a location off the northwestern Norwegian coast (zone 1) predicts RSL fall (fig. 4a), whereas the RSL curve for New Jersey (zone 2) predicts RSL rise (fig. 4b) over the same time period. Regions in zone 1 have been depressed by the mass of the ice sheets, and will experience glacio-isostatic uplift when the mass is removed. Relative sea-level in these locations falls since the rate of glacio-isostatic uplift is greater than the rate of eustatic sea level rise. Regions in zone 2 are on the forebulge, which subsides when the ice sheets retreat. Relative sea-level in these locations rises since the land surface falls and eustatic sea level rises. Over the past 6000 years, eustatic sea level change is assumed to be negligible (in the Earth-ice models, eustatic sea-level change is zero).

During the Last Glacial Maximum, the Fennoscandian Ice Sheet covered northern Eurasia, from western Scandinavia to western Russia (fig. 3; Schmidt et al., 2014). Previous GIA models by Lambeck et al., 1998 have modelled isostatic rebound for Scandinavia, however there have been limited studies in the White Sea region near the arctic coast. A curve showing relative sea level in the study area over the past 18 kyr (1000 yrs before 1950AD) was calculated by Prof. Richard Peltier at the University of Toronto, and shows a relative sea level fall of nearly

100 m in 10kyr at Luda Village using ice model ICE6G-C and earth model VM5a (fig. 5; Peltier, Personal Communication). This research aims to make a relative sea level reconstruction curve that will ultimately be compared to the Peltier model, using salt marsh sediments.

Relative sea level can be reconstructed by using proxies preserved in salt-marsh sediment (Scott and Medioli, 1978; Gehrels, 1994). Salt marshes are divided into discrete vertical ecologic zones that are determined by duration and frequency of flooding at various heights in the marsh. These zones are occupied by plants and animals that live at specific heights in the marsh: for example, in North American Northeastern Atlantic salt marshes, the marsh plant *Spartina alterniflora* is abundant in low marshes, compared to *Spartina patens* inhabiting the mid and upper marsh zones (Kemp et al., 2009).

Foraminifera are preferred sea level indicators since they occupy narrow and well-defined zones in the marsh sequence and are typically preserved better than plant remains (Scott and Medioli, 1978). Foraminifera are favored over plants because foraminifera occupy narrower zones than plants and the abundance of foraminifera in salt marshes (typically 100s to 1000s per sediment sample) allows for more rigorous statistical analyses. Foraminifera preserved in sediment cores (the so-called "fossil' assemblage) are assumed to have the same ecological preferences and tolerances as modern foraminifera from the same region (Scott and Medioli, 1978; Gehrels, 1994).

This study examines marsh cores from the White Sea region in northern Russia and aims to create a RSL reconstruction that can be used in Earth-ice models of northwestern Russia. Foraminiferal assemblages from sediment cores and radiocarbon dating will be used to develop a reconstruction of Holocene RSL change. The resulting curve will be compared to Peltier's predicted curve, and discrepancies between the calculated and theoretical models will be discussed. Using foraminifera to reconstruct sea level is a three step process. First, samples from a nearby modern salt marsh are collected that encompass the entire range of the marsh, from tidal flat to lower woodland. The marsh samples are then analyzed for foraminifera by type and abundance, and the marsh is divided into elevational zones relative to sea level that correspond to a certain foraminiferal assemblage. Since foraminifera are assumed to occupy the same ecological area through time, foraminifera in the core place the core to its appropriate location relative to past sea level. Numerical ages for the sea level change are found through radiocarbon dating of the marsh samples.

Study Area

The study area is an estuary near the village of Luda in northwestern Russia on the southern shore of the White Sea, nearly 1000 km north of Moscow and 100 km west of Arkhangelsk (fig. 1). The region was covered by the Fennoscandanian Ice Sheet during the Weichselian glaciation, which began 115 kyr BP and ended 11.5 kyr BP (Grosswald, 1980) (fig. 3), and is thought to be part of the tectonically stable East European Craton (Roberts and Siedlecka, 2002). The region is situated just outside the Arctic Circle and experiences a subarctic climate, where summers are short and cool, and winters are long and cold. Salt marshes form in low energy protected bays such as the Luda estuary, and encompass four vegetation zones that are related to the elevation of the sample relative to the tidal column. The uppermost marsh is characterized by a birch forest, which transitions to a high marsh dominated by *Phragmites* as elevation falls. The *Phragmites* zone is gradually replaced by the lower marsh plants *Scripus*, sea plantain, and *Juncus geradii*. The lowest samples represent tidal flat and consist of sand and eel grass.

Methods

In this study, modern samples were taken from three salt marshes on the southern shore of the White Sea. The foraminiferal assemblages in the core were matched to assemblages found in the modern transects. The foraminiferal assemblages in the core were assigned an elevation relative to the tidal cycle based on what foraminifera were present.

Sampling

To describe the modern distribution of foraminifera on White Sea salt marshes we established an intertidal transect at three sites (named Wolfy, Old Bobby, and Humphrey) on the east coast of Luda Bay. Each transect ran from shallow sub-tidal to supra tidal environments and was comprised of ~20 sampling stations positioned at regular changes in elevation and to include the principal floral zones. The uppermost transect is characterized by a birch forest, which transitions to a high marsh dominated by *Phragmites* as elevation falls. The *Phragmites* zone is gradually replaced by the lower marsh plants *Scripus*, sea plantain, and *Juncus geradii*. The lowest samples represent tidal flat and consist of sand and eel grass.

The modern transect samples were collected by scooping the top layer (1cm) of sediment from the land surface. At each sample site, the elevation, distance between sites, and vegetation were noted. Additionally, samples were taken by boat from a shallow, sub-tidal region of the bay. The samples were preserved in solution of 30% ethanol containing Rose Bengal stain along with a small chip of calcite to buffer against dissolution. The Rose Bengal stain only stains living organisms, and was added to differentiate between live and dead foraminifera. After collection the samples were refrigerated until analysis.

Cores used for foraminiferal study were collected from a site a few kilometers south of Luda Village at various intervals along the main road. Core samples were collected with a Russian Corer. Although five, half-meter long cores were collected, only one, "*Jo Taylor*", was used to reconstruct past environments because it was the only one with abundant foraminifera.

Laboratory Analysis

In the laboratory, a core log and percentages of peat, sand, and clay were recorded, as well as any identifiable organic matter. A cursory examination for foraminifera was also conducted. Two samples of plant matter from core Jo Taylor were sent to a laboratory for ^{14}C dating. The two samples were taken from above and below the marsh sediment. Cores were divided into 1cm slices representing the transition from tidal flat to forest upland. Modern transect and core samples were passed through a 500 µm sieve atop a 63 µm sieve and examined for foraminifera under a binocular microscope. Approximately 100 dead foraminifera were counted in each sample, and although both the live and dead foraminifera were recorded, only the dead foraminifera were used in the statistical analyses. Only the dead population was used since it is considered to be more appropriate analog to the preserved fossilized assemblage than the dead and live or only live modern assemblage (Horton, 1999; Murray and Bowser, 2000; Horton and Murray, 2006). The foraminifera counts were converted to a percentage relative abundance per sample to be used in statistical analyses.

Modern transect samples containing abundant sand were set aside to be "floated" using a density separation technique. When a liquid of a density lower than sand and greater than foraminifera is added to the sample, the foraminifera float and the sand sinks, leaving the foraminifera on top of the dense liquid, in this case sodium polytungstate. The solution was poured into a funnel attached to a plastic tube which was firmly clamped on the bottom and suspended over a 100 ml beaker. The dried sediment was sprinkled gently over the solution and allowed to sit, allowing the less dense sediment to float. After a few minutes the clamp on the bottom of the tube was slowly released, and the denser sediment was released into the beaker, leaving the foraminifera floating in the liquid in the funnel and tube. The liquid and dense sediment were placed into a funnel lined with filter paper to separate out the liquid to be used in the future.

Foraminifera taxonomy was determined using description and images from Horton and Murray, 2006. *Balticammina pseudomacrescens* and *Jadammina mancrescens* were counted as a single species, and live at the same height in the marsh. Two species of the genus *Miliammina* were identified (*Miliammina fusca* and *Miliammina spp*.); counts of these two species were placed into a single group (*Miliammina* spp.). These two species live at the same height in the marsh.

Transect Description

Wolfy is a 115 m long transect comprised of samples representing the transition from tidal flat to forest. The transect ranges from tidal flat at the lowest elevations to *Scirpus* in the low marsh, to *Phragmites* in the high marsh, to birch woodland at the highest sample. In samples from transect sites 4-7 *B. pseudomacrescens* was the dominant species with an abundance of 95-100%. In samples from transect sites 8-19, *Miliammina spp.* was the dominant species with an abundance of 68-97%. The lowest sample is 0.59 m below mean tide level, and the highest sample is 2.44 m above mean tide level. Figure 6 is a schematic diagram of a transect showing samples in the transect encompassing the high marsh through tidal flat.

Old Bobby is a 274 meter long transect comprised of samples representing the transition from tidal flat to low forest. The transect ranges from subtidal eel grass, to *Juncus geradii* in the low marsh, *Phragmites* in the high marsh, and birch forest at the highest sample. In samples from transect sites 5-10 *B. pseudomacrescens* was the dominant species with an abundance of 76-100%. In samples from transect sites 10-20, *Miliammina spp.* was the dominant species with an abundance of 96-100%. The lowest sample is 0.63 m below mean tide level, and the highest sample is 0.75 m above mean tide level.

Humphrey is a 486 meter long transect comprised of samples representing the transition from sub-tidal environment to low forest. The transect ranges from subtidal eel grass, to *Juncus geradii* in the low marsh, *Phragmites* in the high marsh, and birch forest at the highest sample. In samples from transect sites 7-11 *B. pseudomacrescens* was the dominant species with an abundance of 91-99%. In samples from transect sites 11-20, *Miliammina spp.*was the dominant species with an abundance of 77-97%.The lowest sample is 0.59 m below mean tide level, and the highest sample is 0.96 m above mean tide level.

The bay grab samples are composed of calcareous foraminifera representing the foraminiferal assemblage of bay sediments. The assemblage is composed of a variety of foraminifera species, including *Ammobaculites balkwilli*, *Ammoscalaria pseudospiralis, Elphidium spp.*

Identifying Groups of Foraminifera

Distinctive groups of foraminifera were identified in a regional dataset that was developed by combining data from the three modern transects and grab samples using an objective and quantitative statistical technique (Partitioning Around Mediods; PAM). PAM was preferred over hierarchical cluster analysis because it partitions data into groups for which within group variability is minimized, and between group variability is maximized (Kaufman and Rousseeuw, 1990). A *silhouette width* between 1 and -1 is calculated for each sample where a value of 1 indicates that the sample's characteristics match the identified group characteristics and is thus correctly classified in that group. A silhouette width value of -1 indicates that the sample does not match the group's characteristics, and is thus poorly classified. Values of 0 indicated a group comprised of a single sample, which consequently have no within-group variance.

The regional dataset was comprised of 52 samples and included 16 species. We used the maximum silhouette width (0.738) averaged across all samples as the threshold for identifying how many regional groups of foraminifera were present and to assign all samples to a group. This analysis showed that three distinct groups of foraminifera could be characterized (fig. 7). Figure 8 shows the elevational range of each group was that was estimated from the lowest and highest member samples.

Group 1, representing the high marsh zone, has an average silhouette width of 0.75. Foraminiferal assemblages in this cluster are characterized by a *B. pseudomacrescens* content greater than 50% and *M. fusca* content of under 50%. In general, samples in the cluster contain significantly more *B. pseudomancresens* than *M. fusca*, with each sample being an average of 91.6% *B. pseudomancresens* and 7.1% *M. fusca*. The elevation of this zone is from 0.30 m to 1.48 m above mean tide level. All three transects contain this well-defined group, so local variability between sites is minimal.

Group 2, the low marsh zone, has an average silhouette width of 0.76. Foraminiferal assemblages in this cluster are characterized by a *M. fusca* content greater than 50%, and a *B. pseudomancresens* content of under 35%. In general, samples in the cluster contain significantly more *M. fusca* than *B. pseudomancresens*, with each sample containing an average of 90.1% *M. fusca* and 3.7% *B. pseudomancresens*. The elevation of this zone with respect to mean tide level is -0.63 m to 0.58 m. Low silhouette values in groups one and two represent samples where abundances of *B. pseudomacrescens* and *M. fusca* were nearly equal. All three transects contain this well-defined group, so local variability between sites is minimal.

Group 3 has an average silhouette width of 0.5. It is composed of the grab samples taken from Luda Bay that are characterized by high abundances of calcareous foraminifera including *Elphidium spp.* and *Islandiella norcrossi*.

In addition to the three groups differentiated by PAM, we recognized a forth group which was comprised of samples from freshwater, upland environments and characterized by the absence of foraminifera. Since these samples did not have any species abundance data they were not included in the PAM analysis, but represent an ecologically important group that should be distinguished from the others.

Core Description

Jo Taylor is a 50 cm segment of a 275 cm long core taken from a site a few kilometers south of Luda village (fig. 1). The segment is the lower 50 cm of the core and represents a depth of 225-275 cm. Figure 9 shows the composition of sediment in the core, the distribution of foraminifera, and the location of the radiocarbon samples. The top of the core is located at an elevation of 5.81

m above MTL. The upper part of the core segment (225-248 cm) is composed of red and black peat. At 248-261 cm the peat becomes dark brown: the first foraminifera are found in this section at 255 cm and continue to be found to a depth of 263 cm. The sediment becomes gray silty marsh clay at 261-263 cm, and is blue clay from 263-275 cm.

Radiocarbon samples were taken from stems of marsh plants found at 254 cm and 263 cm depths in the core. The two samples are from horizons above and below the marsh regression sequence, constraining the dates of sea level change in that interval. The radiocarbon age of the higher sample is 2680 $\pm$ 20 ^{14}C yr BP, and the age of the lower sample is 2720 $\pm$ 20 ^{14}C yr BP. Using the most current radiocarbon calibration data set, IntCal13 (Reimer et al., 2013), the age of the higher sample is calibrated to 2752 – 2844 calibrated yr BP (2σ range), and the age of the lower sample is calibrated to 2769 – 2855 calibrated yr BP (2σ range).

Foraminiferal assemblages were identified in the middle section of the core from 8 samples in a depth range of 255-263 cm. All core samples from Jo Taylor were dominated by *B. pseudomacrescens.* The uppermost core sample (depth of 255 cm) was 100% *B. pseudomacrescens,* and the lowermost core sample (depth of 263 cm) was 80% *B. pseudomacrescens* and 20% *M. fusca.* Overall, each centimeter-long core sample contained an average of 96.6% *B. pseudomacrescens*, matching the zone 1 assemblage identified by PAM.

RSL Calculations

Relative sea level is calculated using the following equation

RSL = Sample Elevation – Reference Water Level where both quantities are expressed with respect to mean tide level. Sample elevation is established by measuring sample depth in a core vs. a measured surface elevation. The reference water level is estimated from the analogy between foraminifera preserved in core samples and their counterparts observed on the modern transects from the east coast of Luda Bay. It is the midpoint of the indicative range, which is the range of sample elevations within each group. Thus, the relative sea level at a period in time can be calculated, and is constrained by the radiocarbon dates and the magnitude of the indicative range. Figure 10 shows the relationship between the core, MTL, and RSL in the marsh sequence, and the equation used to solve RSL.

The core top elevation of Jo Taylor is 5.81 m above MTL and the dated core samples were recovered from depths of 2.54 m to 2.64 m. Therefore the sample elevation was 3.22 ± 0.05 m above MTL. The foraminifera preserved in the dated part of the Jo Taylor core were most analogous to the assemblage defined as Group 1 from the regional modern data set. This group occupies an elevation range from 0.30 m to 1.48 m above MTL. The mid-point of this range (0.89 m above MTL) was used as the reference water level for the core samples from Jo Taylor.

RSL in Luda Bay was calculated to be 2.33 ± 0.59 m above present at 2804 ± 52 yr BP. The total vertical error was calculated by taking the square root of the sum of squares of the indicative range (± 0.59 m) and the range of sample elevation (± 0.05 m). The age error was the 2σ calibrated maximum age from the lower dated sample at 2.64 m and the minimum age from the upper dated sample at 2.54 m. The Earth-ice model for Luda Bay calculated by Peltier (personal communication, 2015) estimates RSL at 2750 calibrated yr BP to be +4.55 m. Figure 11 shows the difference between the modelled and calculated values of relative sea level.

Discussion

1.1 Foraminifera as Sea-Level Indicators

In order to reconstruct RSL using a sea level indicator, the indicator must meet certain criteria. The species must live at a particular location in the tidal range, such as between mean low water and mean tide level for example. Foraminifera live at specific zones in a marsh sequence that are related to tidal levels. Most foraminifera can be defined as "high marsh" or "low marsh" species. Foraminifera used in this study live in well define zones in the marsh: *B. pseudomacrescens* live in the highest marsh, while *Miliammina spp.* occupy the lower marsh. Figure 8 shows the four unique groups of foraminifera that correspond to elevations within the tidal frame. Contemporary foraminiferal zones are assumed to be analogous to the fossil assemblage, so contemporary marsh samples were used to determine foraminiferal zones within the modern marsh, which were used to infer elevation range of the fossil assemblage (Scott and Medioli, 1978). Foraminifera in the White Sea salt marshes live in well-defined zones in the marsh and therefore can be used as a sea level indicator in the same manner as foraminifera in other locations.

1.2 Foraminifera at High Latitudes

Although sea level reconstructions using foraminiferal proxy indicators have traditionally used temperate salt marshes in tectonically stable regions (Gehrels, 1994; Horton, 1999; Kemp et al., 2013), foraminifera in high latitude salt marshes are also sea-level indicators (Barnett et. al., 2015; Kemp et al., 2012; Southall et al., 2006), despite having a less diverse foraminifera population. The advantage of high latitude salt marsh reconstruction is their ability to preserve periods of glacio-isostatic rebound that can be used in GIA models (Barnett et. al., 2015).

This study found that salt marshes in the White Sea are dominated by two species, *B. pseudomacresens* in the high marsh and *Miliammina spp* in the low marsh. Many mid- and low-latitude salt marshes, by contrast, have greater species diversity. In a study of salt marsh foraminifera along the U.S. Atlantic coast, Wright et al. (2011) identified four distinct high and low marsh groups corresponding to the distribution of eighteen species of foraminifera. In a study of salt marshes from the Atlantic coast of SW Europe, Leorri et al. (2010) identified 3-4 high and low marsh groups with up to 44 species of foraminifera. In other high latitude sites, Barnett et al. (2015) identified a high marsh group composed of primarily a single foraminifera species (*Jadammina macrescens);* and a relative sea level reconstruction in southwest Alaska by Kemp et al. (2013) identified one high marsh group composed solely of *B. pseudomacrescens*. From these data it can be concluded that global foraminifera diversity varies by climate, with only a few species living in high latitude climates.

2. Earth-Ice Model

The relative sea level curves produced by this study and the model follow the zone 1 relative sea level trend predicted by Clark et al. (1978) of sea level fall (fig. 4a). The relative sea level curve developed by Peltier (personal communication, 2015) uses the Earth model VM5A, ice model ICE 6G-C, and a eustatic sea level curve to predict relative sea level for the Luda Village location though time. The model determines relative sea level as the sum of models of localized isostatic sea level change and global eustatic sea level change. Discrepancies in calculated relative sea level and reconstructed relative sea level may arise due to differences in assumed isostatic sea level and global curves for eustatic sea level. Local tectonic or other small scale effects such as subsidence can also affect relative sea level change. These effects are not accounted for in the model, but may have affected the reconstruction.

2.1 Earth Model

The Earth component of the Earth-ice model contains mantle parameters such as viscosity, depth, and layering thickness, that have been estimated from seismic tomographic studies. Differences between the modelled and calculated curve may be due to errors in the values of mantle parameters. If the mantle has a lower viscosity than the model suggests, isostatic adjustment may occur more slowly than in the model, and overestimate the amount of relative sea level rise. Relative sea level studies can further constrain and check these mantle values. Using an accurate relative sea level reconstruction, mantle properties can be changed in the model to yield a relative sea level prediction curve that best fits the measured relative sea level.

Studies by Engelhart et al. (2011) along the U.S. Atlantic coast exemplify how Earth and ice properties can be changed to yield a model that provides a closer estimate to the relative sea level curve. Figure 12 shows a calculated sea level curve and a two model curves with different mantle viscosities for northern Maine through northern Massachusetts (Engelhart et al., 2011). These locations were near the margin of the Laurentide ice sheet during the Last Glacial Maximum; in a location comparable to the position of the White Sea study site to the Fennoscandian ice sheet. The figure shows that the relative sea level predictions in near and intermediate field sites such as Maine and the White Sea are more sensitive to the Earth model than to the choice of ice model: the VM5b model with either of the ice models fits better than the VM5a model with either of the ice models. Any changes to the Earth-ice model should begin with tweaking the Earth model due to the greater influence of the Earth model at this latitude. Figure 13 is a relative sea level curve for the Kola Peninsula showing two different earth models (Peltier, personal communication 2015), and demonstrates the effect of mantle parameters on relative sea level in the White Sea. In figures 12 and 13 the difference between the two model curves is several meters, signifying that mantle parameters may account for the difference between calculated and modelled relative sea level in this study.

2.2 Ice Model

The ice model used in the relative sea level curve is the ice thickness, extent, and dates of the Fennoscandian ice sheet during the Last Glacial Maximum. The ice model can be modified in the same manner as the Earth model (Engelhart et al., 2011) to provide a more accurate reconstruction. The ice model may not accurately reflect the glacial history of Fennoscandia, and the difference between the model and reconstruction may be due to imperfections in presumed ice location or extent; thickness, or temporal aspects, of the model.

3. Tectonics

Tectonic activity can influence relative sea level by causing uplift or subsidence of the land surface that is independent of movement from isostatic readjustment. Tectonic influence on relative sea level is generally more pronounced in tectonically active areas such as those near a plate boundary. The calculated value for relative sea level is lower than the model estimate, and could be explained by tectonic subsidence of the land surface. Subsidence would make the calculated relative sea level appear lower than a model that assumed no tectonic influence. The neotectonic setting of the southern White Sea area is largely unknown The southeastern White Sea region lies southwest of the Kola Craton in the Belmorian Mobile Belt (Samsonov et al., 2009). The area is thought to be underlain by various east-west trending normal faults (Zhuravlev and Shipilov, 2007), however it is unclear if these faults are active.

4. Local Effects

Local effects are the fourth factor that influences relative sea level. These effects include compaction of sediments in the core, and changes in tidal range, ocean currents, and sea water temperature. Sediments deposited on a marsh surface compact underlying sediments, causing subsidence. If compaction occurred, the sample depth would be effected by post-depostional lowering. The measured depth of core samples would be higher than the actual depth (total sediment deposited atop samples) had compaction not occurred. Compaction at a rate of 0.79 mm yr^{-1} would be needed to account for all of the difference between the model and the calculated relative sea levels. This is a high rate of subsidence: analysis of dynamic topography on the U.S. Atlantic coast by Rowley et al., (2013) indicates that this high rate of subsidence is unlikely to account for the majority of the difference between sea level curves. The effect of compaction could be mitigated by expanding the regional variability of the cores: many cores over a wide area will minimize the overall amount of compaction on a regional scale.

Calculation of mean sea level was determined by modelling the tidal range for the modern transect locations. This tidal range is assumed to be constant through time, however changes in costal geomorphology or lunar gravitational effects can change tidal heights on a small scale. Ocean currents can influence the value of relative sea level. Along the U.S. mid-Atlantic coast, studies indicate that a weaker Gulf Stream is related to the increase in sea level rise (Ezer et al., 2013). Considering that the climate 3000 yr BP is similar to that of today, it is unlikely that current patterns have changed significantly, although they may change in the near future.

The final local influence on relative sea level is thermal expansion of the oceans. Relative sea level rises during periods of increasing surface temperature due to expansion of water. One estimate by Church and Godfrey. (1991), suggests 0.1 – 0.3 m rise in relative sea level for a 3^{o}C increase in temperature. If thermal expansion accounted for the difference between the modelled and calculated sea level curves, then ocean temperature would be decreasing, leading to a lower relative sea level value. This is an implausible explanation for the difference, since Earth's surface temperature has not decreased in the past 3000 yr.

Conclusion

Foraminifera can be used as sea level indicators since they live at defined zones corresponding to elevation in a saltmarsh. In the White Sea region, foraminiferal assemblages were more similar to other high-latitude salt marshes that exhibit lower species diversity than mid-low latitude salt marshes. Relative sea level reconstructions in many high latitude sites have foraminiferal assemblages composed of *B. pseudomacrescens* and *Miliammina spp*. Foraminiferal assemblages from the White Sea were also largely composed of *B. pseudomacrescens* and *Miliammina spp.*, with *B. pseudomacrescens* dominating the high marsh and *Miliammina spp.* designating the lower marsh. This study identified four unique groups of foraminifera that were used to infer marsh elevations of the core samples.

Past relative sea level was found subtracting the reference water level from the elevation in the core. The reference water level is the midpoint of the indicative range, which is the elevation range of the inferred foraminiferal zone found in the modern transects. From this, past relative sea level was calculated to be 2.33 ± 0.59 m above present. Radiocarbon ages of samples of plant material taken from above and below the marsh assemblage in the core constrain relative sea level change to 2804 ± 52 calibrated yr BP.

The sea level reconstruction was compared to a modelled relative sea level curve. The difference between the two curves is 2.22 m at 2750 calibrated yr BP. The modelled curve uses an Earth model, ice model, and eustatic sea level curve, and difference in any of these could result in a discrepancy between the calculated and modelled curves. Previous studies by Engelhart et al. (2011) showed that modelled relative sea level curves in regions near a glacial margin are particularly susceptible to changes in mantle properties. Regional processes such as tectonics and subsidence may have affected the study area and are not accounted for in the model.

Figures

Figure 1: Study area on the southern shore of the White Sea, Russia.

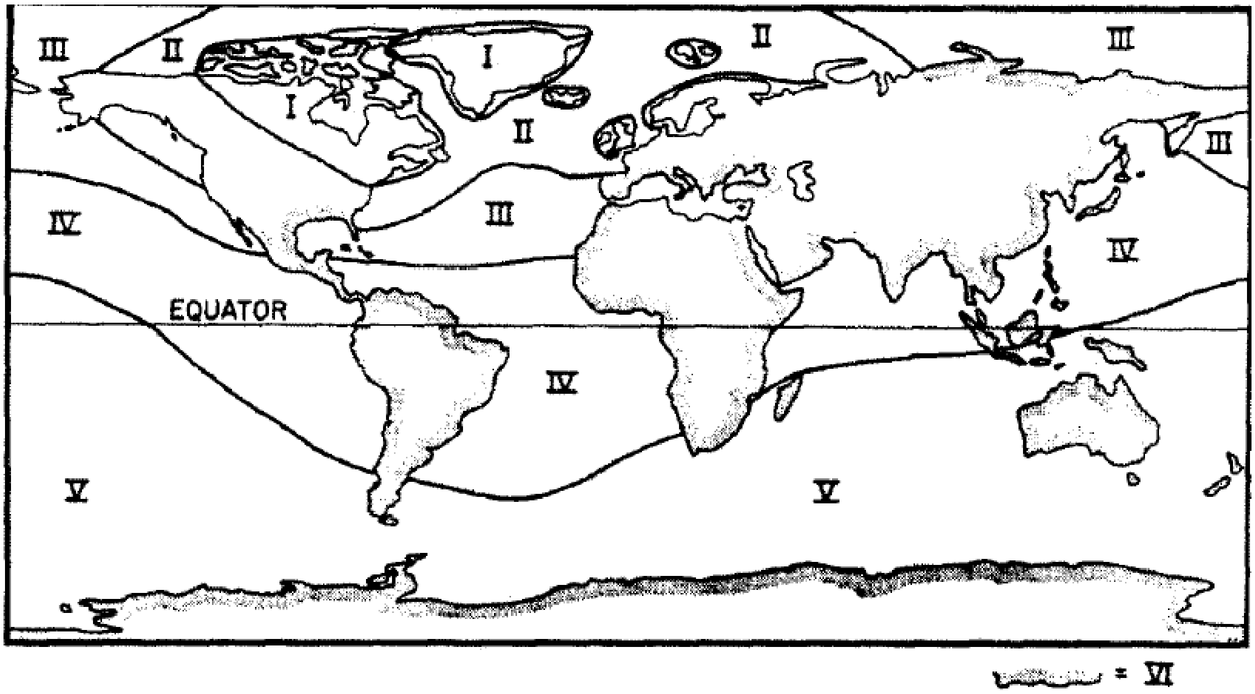

Figure 2: Illustration by Clark et al. (1978) of the six sea level zones relative to glacial isostacy. Sea level change due to uniform ice sheet melting is similar within each zone. Zones range from ice-covered zone 1 to equatorial zone IV. The White Sea region lies in zone 1, and New Jersey, for context, lies in zone 2.

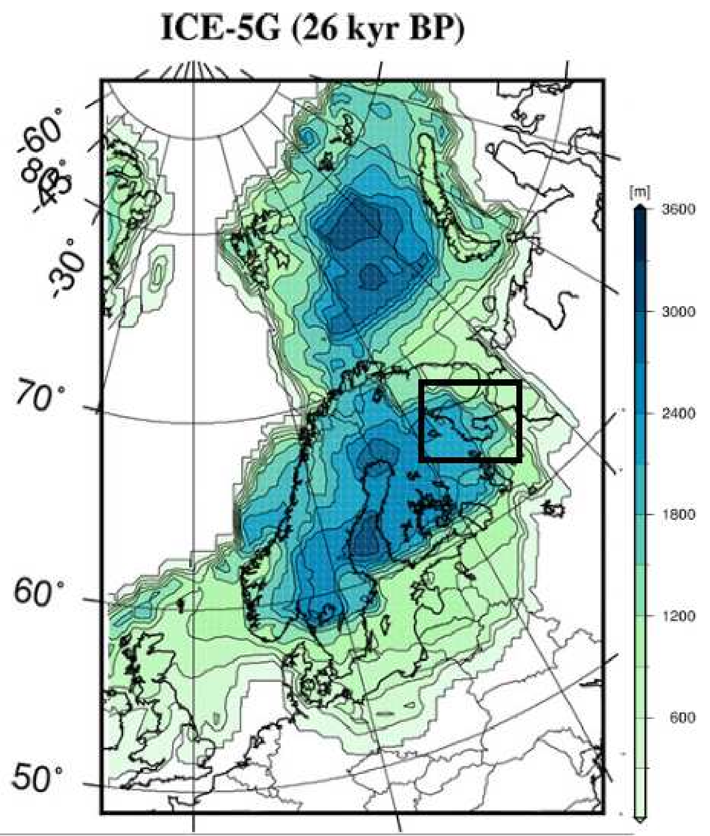

Figure 3: Ice sheet extent and thickness in northern Europe at the Last Glacial Maximum using ICE-5G model (Schmidt et al., 2014). White Sea region is outlined in black. Color graduation represents ice thickness.

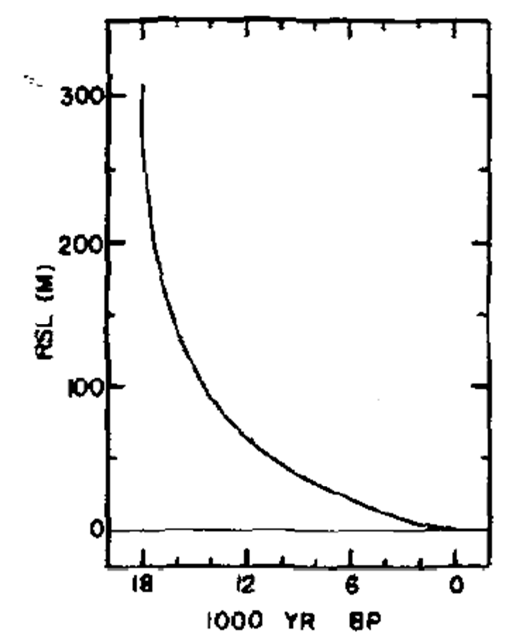

Figure 4a: Relative sea level change in Zone I at the center of the Fennoscandia ice sheet assuming uniform melting (Clark et al., 1978). Relative sea level drops in this zone due to glacial isostatic rebound of the crust when the ice cap is removed. Relative sea level is measured against RSL today (0m).

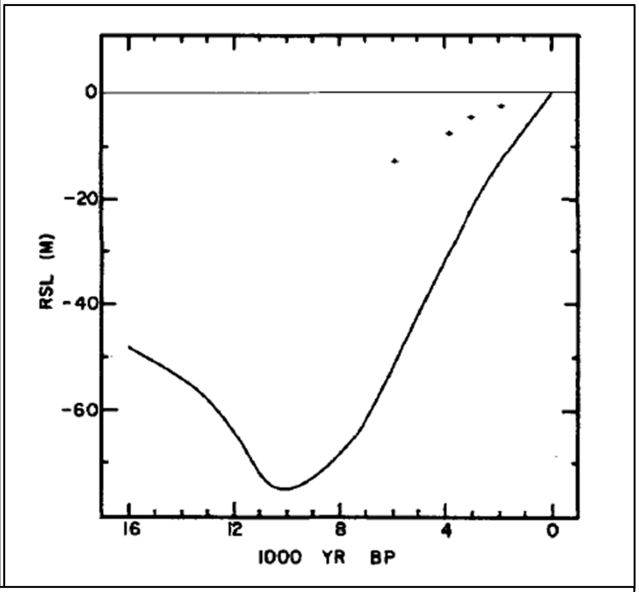

Figure 4b: Comparison of modelled (solid line) and measured (points) relative sea level change in Zone II at Brigantine, New Jersey assuming uniform melting (Clark et al., 1978). Relative sea level rises in this zone due to collapse of the forebulge. Relative sea level is measured against RSL today (0m).

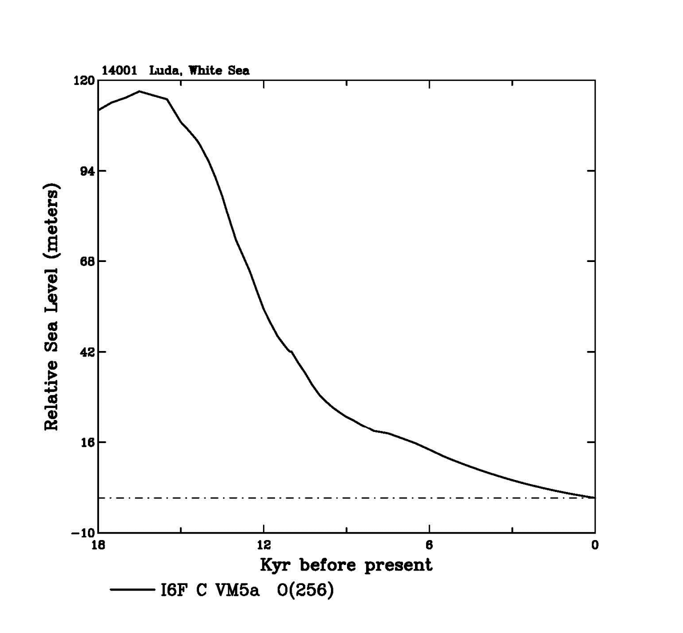

Figure 5: Model showing relative sea level fall for Luda Village developed by Peltier (Personal communication, 2015) using ice model ICE-6G and earth model VM5a. Relative sea level is

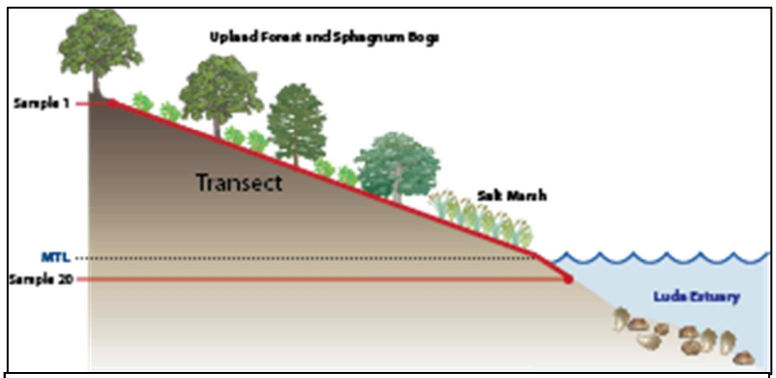

Figure 6: Sketch of marsh showing transect sampling from upland forest through the salt marsh to tidal flat near Luda Estuary.

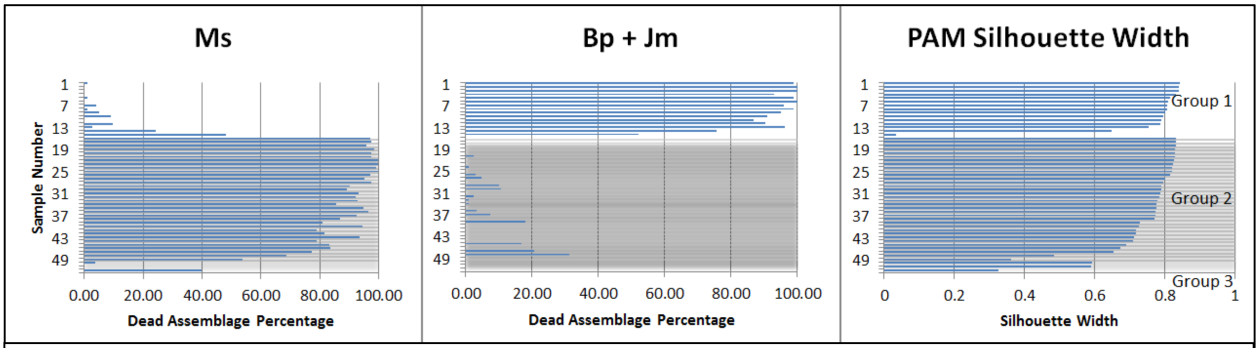

Figure 7: Graphs showing the abundance of *B. pseudomancresens* (left) and *M. spp* (center) in each group identified by PAM and the silhouette width of each group (right). Group 1 contains abundant *M. spp*, and group 2 contains abundant *B. pseudomancresens*. Group 3 represents the bay grab samples and contains a small amount of *M. spp*. Silhouette width is related to the variability between samples in the same group, a silhouette width closer to one indicates less variability between samples from different locations.

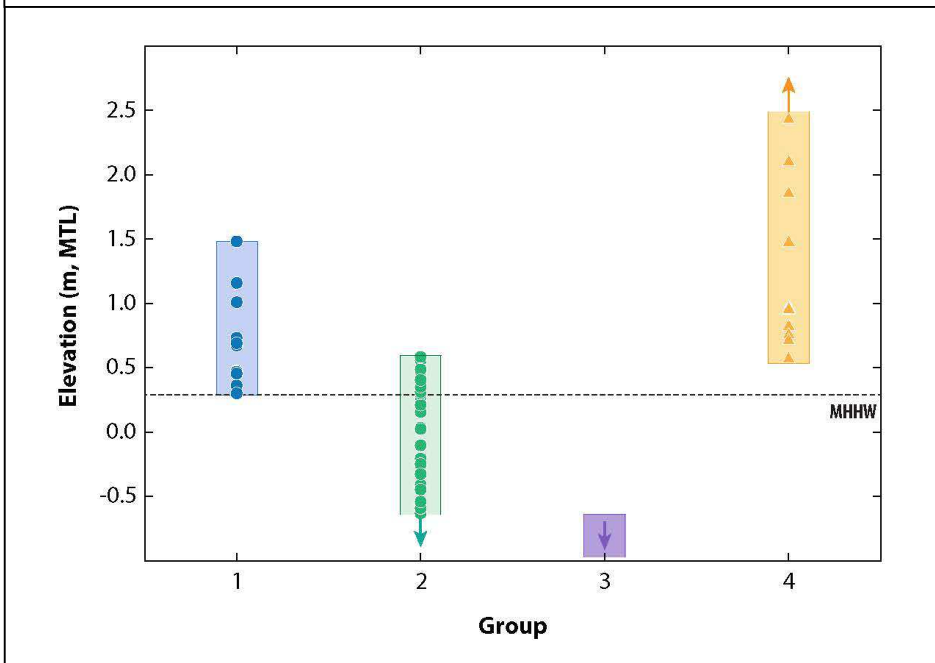

Figure 8: Graph showing the location of each group (identified by PAM) relative to mean tide level. Blue circles represent samples from the high marsh group dominated by *B. pseudomancresens*; green circles represent the low marsh group dominated by *M. spp*; purple represents the bay grab samples, and yellow triangles represent samples where no foraminifera were present.

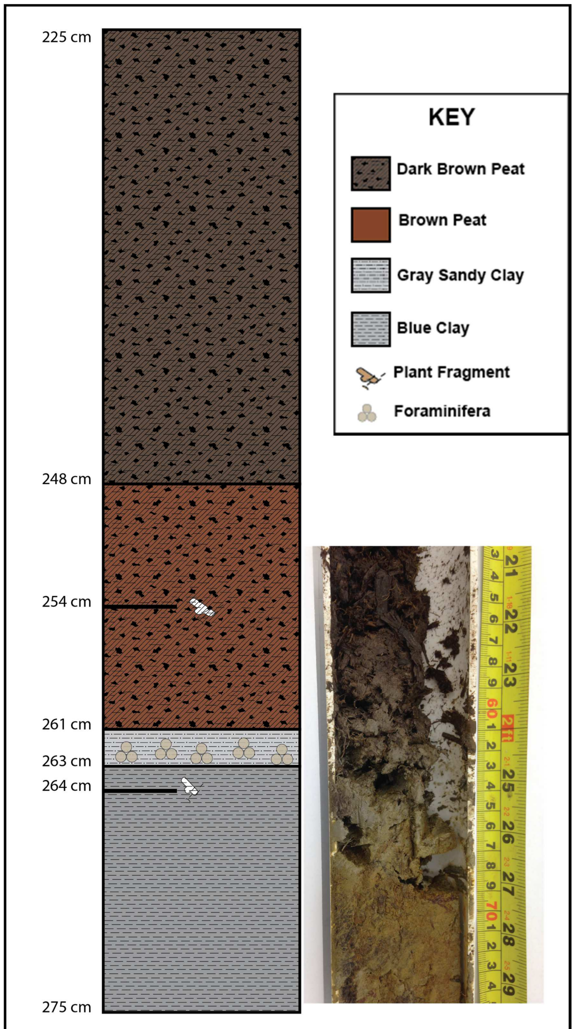

Figure 9: Photograph of core Jo Taylor and schematic log describing sediment and foraminifera abundance at various locations in the core.

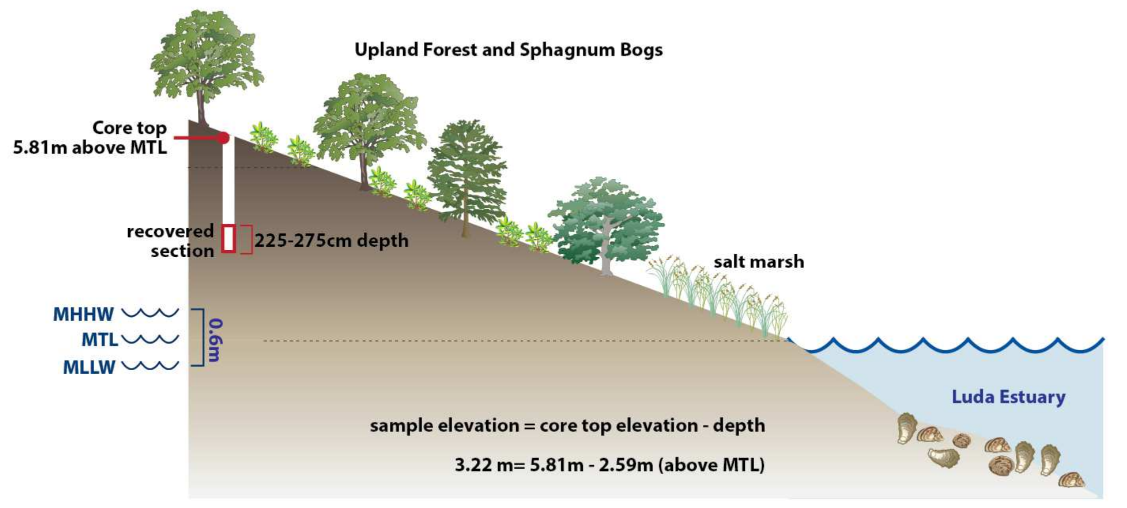

Figure 10: Schematic diagram of the relationships between the core location, estuary, salt marsh, and mean tide level (MTL).

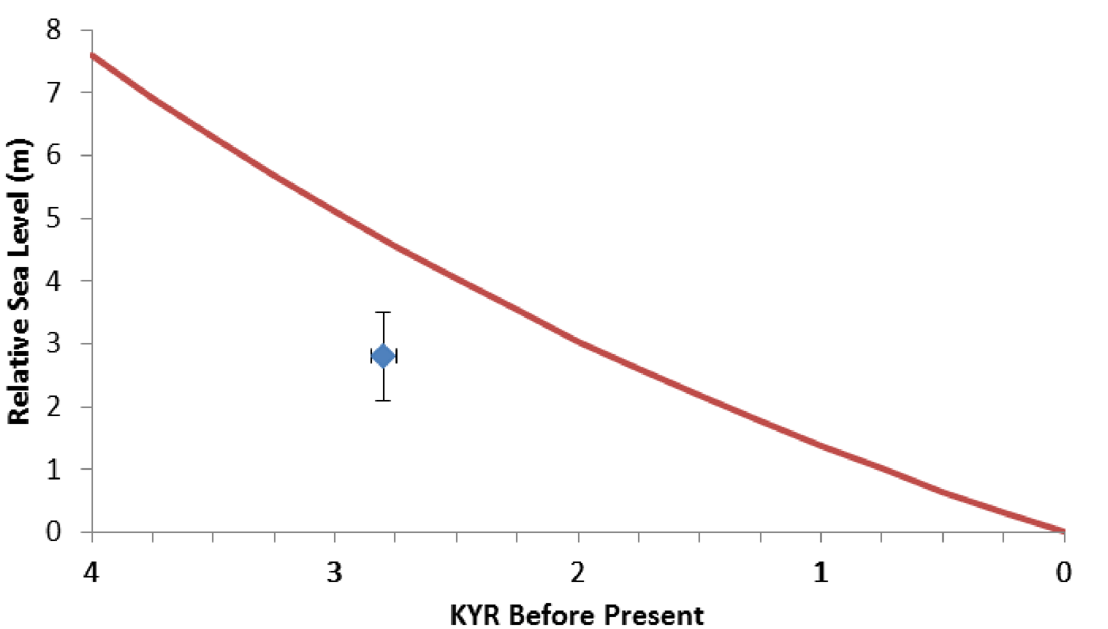

Figure 11: Graph showing modelled sea level curve in red (Peltier, Personal Communication 2015) compared to calculated relative sea level in blue. Relative sea level was calculated to be 2.33 ± 0.59m above present sea level 2804 ± 52 ybp.

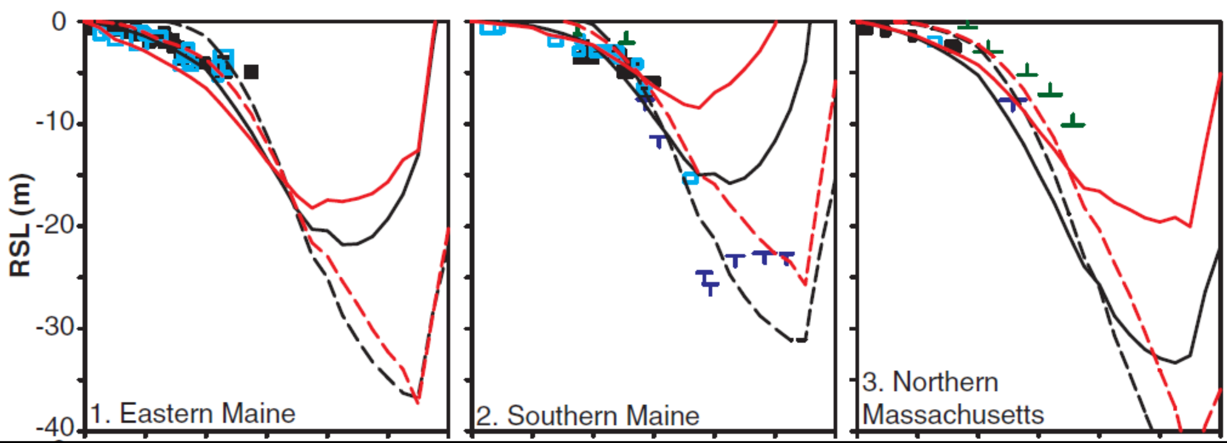

Figure 12: Graphs of relative sea level observations and models from Eastern Maine, Southern Maine, Northern Massachusetts, and Southern Massachusetts (Engelhart et al., 2011). Black boxes are index points. The model used either ICE-5G (black line) or Ice-6G (red line) ice models, with either VM5a (solid lines) or VM5b (dashed lines) earth models.

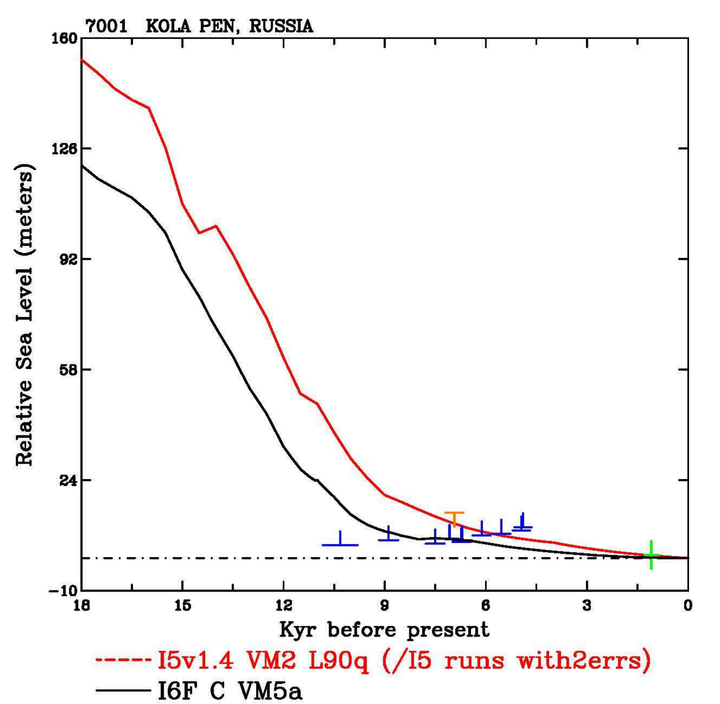

Figure 13: Model showing relative sea level fall for the Kola Peninsula developed by Peltier (Personal communication, 2015). Model uses ice model ICE-6G with earth model VM5a (black line), and I5v1.4 with VM2 L90q (red line).

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