Holocene Eustatic Oscillations of the Baltic Sea Level

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ABSTRACT

Geochronological, biostratigraphic and geomorphological researches have been used to refine the Holocene northern Baltic territories of the USSR. The Baltic Sea coast over this epoch has been characterized by neotectonic movements, so that without knowledge of relationships between vertical movement rates of crustal motion and eustatic oscillations it is difficult to conduct inter-regional correlations. To determine the eustatic curve for the Baltic the author assumed the rate of long-term (inherited) vertical movements in the past 10,000 years to be constant, and on this basis glacioisostatic uplift curves were plotted. The Baltic eustatic curve suggests a progressive alternation of transgressive and regressive conditions for regions with different glacioisostatic uplift gradients. In the early and middle Holocene time there are four transgressive/regressive cycles (9,700 - 9,000, 9,000 - 7,900, 7,900 - 6,700 and 6,700 - 5,600 14C yr BP) have been identified which can be correlated with the Yoldia, Ancylus and two Littorina stages. The height of the Ancylus Lake level was nearly 16 m above the world ocean level. The proposed eustatic curve for the Baltic is used to make interregional correlations.

ADDITIONAL INDEX WORDS: Baltic Sea, eustatic oscillations, Holocene, sea level.

INTRODUCTION

The problem of world ocean level oscillations has been attracting a great deal of attention in the past decades. A successful solution of this problem would enable a better understanding to be reached of the intricate processes of development and decay of Pleistocene continental glaciers, as well as the dynamics of present glaciation. Geomorphological and radiocarbon data have been used to plot dozens of curves of eustatic level oscillations either for the world ocean or individual seas during the past 10-15,000 years. All these curves fall essentially into two groups: those exponentially approaching the present level and the oscillating ones characterizing short-term regressions, against a background of an overall rise and a temporary rise above the present level in the second half of the Holocene.

Many new factors have lately come to light (e.g. FARRELL and CLARK, 1976), testifying to a very complex distribution pattern of melt water in the world ocean and emphasizing the necessity of studying regional eustatic oscillations in different parts of the world ocean and in the seas linked with it, particularly the Baltic.

Discoveries of coastal land forms at various elevations, associated fossils and buried lagoonal and lacustrine-swampy deposits have made it possible for the entire Baltic Sea coast to be integrated on the basis of geomorphologic, biostratigraphic and geochronological researches into a systematization of the geological history of the basin. However, these studies have also revealed the intricate development of the basin and some of the difficulties involved in reconstructing eustatic sea level oscillations for the area. The works of HAUSEN (1933), RAMSAY (1929), SAURAMO (1939), ORVIKU (1960, 1969), KAARIAINEN (1966) and many others have helped to work out and elaborate concepts on late and postglacial crustal movements in the eastern Baltic. However, because of differences in the intensity and sign of these movements it was impossible to identify the component of eustatic oscillations.
**Geochronology of the early Holocene Baltic in the USSR's northern Baltic territories**

The primary task for establishing eustatic oscillations in the basin involves geomorphological and biostratigraphic identification of individual indicator levels and their accurate referencing to the time scale. As a result of many years of research (KESSEL and RAUKAS, 1967; PUNNING, 1969; KESSEL and PUNNING, 1969a, b, 1974, 1976) it is now possible to reconstruct the development history of this part of the Baltic basin.

In front of the retreating continental ice margin separate proglacial lakes formed in depressions of the basin. Upon liberation from ice on the Slupsk Bank, the eastern coast of the Gulf of Riga and the northern slope of the Pandivere Upland, these proglacial lakes were able to join up with the main Baltic glacial lake (KVASOV, 1975). After the retreat of the ice from the Bilingen ridge in the middle part of Sweden at about 8,015 BC (NILSSON, 1968), seawater found its way into the Baltic and this was the beginning of the first Holocene marine stage, known as the Yoldia Sea. Yoldia Sea deposits have been traced solely within a narrow coastal strip. On the basis of a few data principally obtained in southwestern Estonia, the length of the Yoldian stage was estimated by us to have lasted 700 years (from 10,000 to 9,300 yr BP) with the transgression culminating from 9,700 to 9,500 yr BP (KESSEL and PUNNING, 1969).

However, a new dating of a lagoonal sapropel from the Syayamagi swamp near Tallinn raises certain doubts as to the trustworthiness of these conclusions. A complex of lagoonal sapropels at 42 m elevation, according to Pork's data (KESSEL and PORK, 1971) contains in its bottom part a brackishwater to freshwater diatom flora which is replaced in the upper part by freshwater to lacustrine facies. This means that sedimentation had started in a lagoon which was converted later into a coastal lake. The age of lagoonal sapropels, 8,915±90 yr BP (Ta-135), permits us to establish the time when the level of the regressive Baltic was at a level now elevated to 42 m in height.

It is to be noted that no unambiguous radiocarbon datings permitting a boundary of the Yoldia Sea to be dated with greater accuracy have so far been obtained from any other area adjoining the Baltic basin. The absence of molluscan shells in offshore deposits and a low salinity (1·27%) of water in the basin likewise add to the difficulty of identifying datum deposits of the Yoldia Sea. It is not to be ruled out that the deposits in south-western Estonia previously dated by us as Echinous stage (KESSEL and PUNNING, 1969) in reality were formed in a regression of the Yoldia Sea.

About 8,900 years ago, due to (isostatic) land uplift, a linkup between the Baltic and the world ocean in the Degerfors area in the middle part of Sweden was interrupted (OLSSON and FREDEN, 1969) which created the Ancylus lake in the Baltic basin. The water level in the closed basin was rapidly rising due to intensive thawing of the ice sheet. Lithologic-geomorphological researches were used as a basis for clear identification of coastal formations of the Ancylus lake at numerous places in western and northern Estonia, which in contrast to the Yoldian or the Echinous formations have been dated with respect to typical freshwater molluscan fauna and a diatom complex. The maximum level of the Ancylus lake transgressive phase in northern Estonia, in the vicinity of Tallinn, is 37 m higher than the present sea level. Serving as datum points in northern Estonia are also lagoonal sapropels in the Kakhala (8,595±75, Ta-59) and Yulemiste (8,400±90, Ta-691) areas.

The age and length of the Ancylus stage, as well as its culmination time have been determined by us by dating the organogenic deposits occurring in the Ancylus lagoons or buried beneath Ancylus coastal formations (KESSEL and PUNNING, 1969b, 1974). In numerous sections both for the northern and western Estonia we have dated buried peat bogs where sedimentation had discontinued on account of lake transgression 8,600–8,400 yr BP. In an overgrown lagoon (lyelyakhtme) near Tallinn, sapropels ceased to accumulate 8,260±70 yr BP (Ta-272) and peat formation commenced. About 8,000 yr BP peat formation had begun over a wide emerging strip both in the Leningrad area and in northern and western Estonia. On the evidence of all data combined the culmination of the Ancylus transgression in this region took place between 8,400 and 8,200 yr BP.

The Ancylus lake regression continued until 7,600 yr BP when there was apparently a minor transgression in the transition time between the Ancylus and Littorina stages. Deposits of this transgression have so far been established by us only in single section in south-western Estonia. In the Kolga section Kessel has identified a brackish-water flora of diatoms characteristic of the Mastogloian stage (KESSEL and PUNNING, 1969b). The radiocarbon sapropel age, viz. 7,505±165 (Ta-126), tentatively yields also the time of transgression culmination.
The height of the respective coastal forms extrapolated for the territory of northern Estonia, 22 m, is, however, in good agreement with the heights of indicator lines of early Littorina transgressions.

The progress of the Littorina Sea has been studied by us in the Leningrad region, Estonia (KESSEL, PUNNING, 1969b, 1976) and Latvia (GRINBERGS et al., 1975). Depending on the rate of vertical crustal movements, the highest Littorina Sea shorelines are of different ages, so that studies at sites with different neotectonic gradients have made it possible to identify and date four transgressive phases. In northern Estonia a transgression culmination was dated 6,900 yr BP; in southwestern Estonia the corresponding phases were dated 6,400, 6,000 and 4,700 yr BP. The respective coastal formations in northern Estonia lie at absolute elevations of 23, 21, 20, and 13 m, and in the southwest at 6-8 m elevations (KESSEL and MIIDEL, 1973).

During the Limnia stage the Baltic Sea had a regressive character. Until today we have succeeded in confidently dating only one of its development stages about 4,000 years ago. The corresponding coastal deposits in northern Estonia reach an elevation of about 12 m above sea level.

Changes in the level of the Baltic basin

After fifteen years of research activities we have succeeded in achieving a fairly confident dating of about 10 development phases of the Baltic basin in the Holocene, each having corresponding coastal formations characterized by biostratigraphic and geomorphological methods.

In rather early studies (HAUSEN, 1913; RAMSAY et al., 1929) it was already shown that the central and southern parts of the Baltic shield were subject to vertical movements in the post-glacial time, the total amplitude of the movements decreasing southwards (KAHAINEN, 1966; NIKOLAIV et al., 1967).

Neotectonic movements are, as a rule, subdivided into two components (ORVIK, 1960); an inherited type and a glacioisostatic one, the latter being due to the removal of the glacial load and the restoration of the original state of strained asthenosphere. The Baltic shield and the adjoining East-European platform are relatively stable tectonically. Apart from wave-like glacioisostatic movements, this region is subject to a tectonic regime inherited from the Paleozoic. It appears that the inherited tectonic regime set up in the Holocene has not essentially changed and, therefore, this component may be assumed approximately constant. This inference has been drawn by numerous researchers studying the movement of the Baltic shorelines (KESSEL and MIIDEL, 1973; ERONEN, 1974; MÖRNER et al., 1976).

Figure 1 shows water level indicators for northern Estonia (Tallinn area), dated by the radiocarbon method. In the early Holocene there are lagoonal sapropels, and in the middle and late Holocene there are coastal forms, corresponding to the successive culminations of development phases of the Baltic. The rate of present uplift in the Tallinn area is 2.5 mm/yr (ZHELIN, 1964). Extrapolating this rate to 1,000 years back and separating the respective values from datum level heights, we obtain a "reduced" spectrum. The heights of the specific "reduced" shorelines depends on the position of the Baltic level with respect to the present one at the moment of formation of the coastal form or the accumulation of lagoonal deposits and a total glacioisostatic uplift of the area concerning until the present time.

The results of radiocarbon dating of specimens from old coastal deposits in tectonically stable platform areas indicate that the ocean level following the retreat of continental glaciers was rising in a fluctuating manner with an alternation of long transgressive periods and short-term regressions. Particularly informative among these curves are the ones proposed by FAIRBRIDGE (1971, 1976), MÖRNER (1976), TERS (1973) and TOOLEY (1974). All these curves are based on abundant factual material and therefore discrepancies between them can only be explained away by the effect of tectonic movements that are not easily accountable. Fairbridge's curve appears to our mind to be particularly valid, especially for the interval of 12,000 - 5,000 years ago. Multiple transgressions above the present level in the second half of the Holocene are denied by numerous researchers. Eustatic oscillations in the Baltic are expected to be synchronous with the world ocean oscillations, Except for the Ancylus lake which was isolated from the world ocean. It is to be noted that undertaking the reconstructions we also tried other eustatic curves, but we found Fairbridge's to be in agreement with our data.

Fairbridge's eustatic curve is shown in Figure 1. At present all requisite data are available for calculation of the total glacioisostatic uplift with reference to different moments in time. The points in the figure, obtained by summing up the heights of reduced sign levels and the respective world ocean levels with an opposite sign, give the magnitudes of
glacioisostatic rise, whilst joining up the points is expected to yield a curve of glacioisostatic rise.

It is known that a glacioisostatic uplift is characterized by a logarithmic dependence (Artushkov, 1967; Bergqvist, 1977; Kelley, 1973). The locus of the obtained points in Figure 1 is a logarithmic curve. Only the time interval of 8,800 - 7,600 years ago (Ancylius stage) fails to correspond to it. Thus, we can conclude that our prerequisites were correct and Fairbridge's eustatic curve offers a fairly plausible explanation to the dynamics of Baltic shorelines. Understandably, during the Ancylius stage the Baltic Sea was isolated from the world ocean and, because of the inflow of thaw waters into the basin, its level rising. In the opinion of some researchers the Ancylius Lake level was 10 - 30 m above the world ocean level. On our evidence, the maximum stand of the Baltic (16 m) above the world ocean level was about 8,200 years ago.

The glacioisostatic curve obtained is approaching the abscissa and about 5,000 years ago the rate of glacioisostatic rise in the eastern Baltic was practically zero. Mathematical calculations on Artushkov's data (1967) give us the termination time of a complete compensation about 7,000 yr BP. For different territories adjoining to the Baltic Sea we have obtained the respective estimates ranging from 7,000 to 3,000 yr BP (Grachev and Dolukhanov, 1970; Kessel and Midel, 1973; Mörner, 1976). For the isostatic uplift rate equal to zero the heights of reduced shorelines will directly indicate the oscillations of Baltic Sea levels.

Allowing for corrections in the intervals from 8,800 to 7,000 and from 5,000 till present time, we obtain a eustatic curve for the Baltic (Figure 2). Knowing eustatic oscillations and the rate of isostatic rise, we can reconstruct the complete curve of shoreline displacement in northern Estonia both during transgressive and regressive development phases.

**Using the eustatic curve for the Baltic Sea to study its development history**

The knowledge of eustatic oscillations enables us to carry out interregional correlations. To this end, we must know the rate of inherited vertical tectonic movements in the territory concerned, the
latter in the first approximation being compared with the present one, and the parameters of the glacioisostatic curve. For the latter to be described more adequately, we give this curve for northern Estonia in the semilogarithmic system of coordinates (Figure 3). We obtain a straight line described by the equation \( \log h_t = kt \log h_o \), where \( h_t \) and \( h_o \) are, correspondingly, the magnitudes of complete compensation relative to the moment of removal of loading \( t_o \) and of residual compensation at the moment of time \( t \) (\( t \) is a time interval in thousands years from the zero-moment). To be able to plot such curves it is sufficient to have two dated coastal forms or lagoonal deposits marking the elevation of the sea level in the past with respect to the present level. The fact that practically all values of residual compensation obtained (see Figure 2) lie on the straight line in Figure 3 is another evidence for the validity of the proposed eustatic curve for the Baltic Sea. It is to be noted that because of incomplete compensation the formula \( h_t = h_o c^{-kt} \) in reality converts into \( h_t = h_o c^{-kt} \), in this case \( K > k \), if \( h_t > h_t \) (Kelly, 1973). This means that a relative difference between \( h_t \) (true) and \( h_o \) (observed) rises with a decrease in residual decompensation, and the practical utilization of the curve appears to be feasible until 7,000 or 6,000 yr BP.

Figure 3 shows glacioisostatic rise curves for territories with a large uplift gradient (southeastern Finland, northern Estonia, Saaremaa Island) and small one (southwestern Estonia, southern Sweden). The plotting of the curves is based on datings of lagoonal sapropels (Punning, 1968; Berglund, 1964; Erön, 1974, 1976); the rates of inherited lift in the reconstructions were assumed to be the following: southeastern Finland (Helsinki) - 3.0 mm/yr (Erön, 1974); northern Estonia (Tallinn) - 2.5 mm/yr; Saaremaa I. - 2.0 mm/yr; southwestern Estonia (Parni) - 1.1 mm/yr (Zhein, 1964); and southern Sweden - 1.4 mm/yr (Berglund, 1964).

The \( k \) values decrease from -0.56 in the Helsinki area to -0.14 in the Blekinge, which is quite understandable (in terms of former ice coverage).

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![Figure 2](image-url)  
Figure 2. Shoreline displacements in northern Estonia and southeastern Finland: a - eustatic curve for the Baltic; b - calculated shorelines; 1 - Tallinn; 2 - Helsinki.
Relationships between the rates of water level rise in the basin and of total tectonic uplift in any region enables us to reconstruct the change-over of regressive and transgressive phases for the given region. If \( \frac{dE}{dT} > 1 \), this means that the given territory was flooded, whilst in the case of \( \frac{dE}{dT} < 1 \) there existed conditions favourable to the formation of lagoons and their conversion into coastal lakes or to the formation of coastal landforms under short decelerations or regressions (\( \frac{dE}{dT} = 1 \)). The values of \( dE \) can be found from the eustatic curve for the Baltic Sea and \( dT \) can be calculated from the formula \( T = h + T_p \), where \( h \) is the rate of present vertical movement.

Figure 4 gives the \( \frac{dE}{dT} \) relationships for 200-year periods for different regions. Quite prominent are four transgressive periods common to all investigation points. Regression in-between them permit us to divide the early-middle Holocene history of the Baltic Sea basin into four transgressive-regressive cycles: 9,700 - 9,000, 9,000 - 7,900, 7,900 - 6,700, 6,700 - 5,600 years ago. As to time, they can be correlated with the Yoldian, Ancylus and two Littorina stages, transitional semi-freshwater conditions prevailing in the basin during the change-overs of marine-to-lacustrine-to-marine conditions.

Conditions of formation of coastal landforms, marine and continental deposits at any specific moment in time are different, being dependent on the \( \frac{dE}{dT} \) ratio which is determined by the neotectonic characteristics of the site concerned.

It is well known that individual phases in the Littorina stage in different parts of the Baltic are metachronous. As seen from Figure 4, the smaller the magnitude of isostatic uplift curves (see Figure 3), i.e. the less the magnitude of compensation, the earlier begin all transgressions, a relatively slow transgression being replaced by a very sharp regression. Presumably, it is these principles (particularly the large differences in the beginnings of the transgression in the 1st and 3rd cycles) that underlie the distinctive identification of the Echinaeis and Mastogloian stages in certain areas of the Baltic. Obviously, these local transgressions cannot provide a basis for identifying independent stages in the development of the entire basin.

The eustatic curve for the Baltic Sea significantly

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Figure 3: Glacioeustatic uplift curves. 1 Tallinn; 2 Helsinki; 3 Parnawa; 4 Blekinge.
simplifies interregional correlations. Identification of individual stages or phases with respect to biostratigraphic features involves great difficulties, since characteristic parameters of the water in the basin, such as temperature and salinity, were changing rather slowly. Furthermore, initially, important differences were arising first of all between the main basin and its bays or lagoons. Stratigraphic comparisons with respect to deep-water deposits involve particular difficulties because of intermixing of differently-aged deposits.

Knowing the heights of two dated indicator lines and the rate of present vertical movement for the territory concerned, we can easily reconstruct the spectrum of shoreline levels by using the formula $H_t = tT_o + h_t - E$, where $H_t$ is the height of shorelines with respect to the present sea level; $T_o$ is the rate of vertical movement at the present time; $t$ is time; $h_t$ is residual compensation; and $E$ is the height of sea level with respect to the present one.

Figure 2 shows the reconstruction of shoreline displacements in northern Estonia and southeastern Finland. The latter region has been minutely studied by EroNEN (1974, 1976), resulting in the reconstruction of a shoreline curve (EroNEN, 1976) (see Figure 4) which is to a certain extent different from that obtained by us (see Figure 2). To calculate the glacioisostatic uplift, we employed the accumulation ages of the upper and lower sapropel layers in the Hangassuo section (EroNEN, 1976). It should be noted that data obtained in studying this section were also employed by EroNEN, but he believes that a peat had been deposited beneath it. In our opinion, such an assumption is not sufficiently valid, particularly because in dating basal layers of peat bogs we often obtain as excessively old age due to the "hard-water effect." A younger age for the Preboreal transgression is evidenced, moreover, by

![Figure 4](image-url)
the dating of basal layers in the Haapasuo swamp, 80 - 90 km southwest of Hangassuo swamp (ERONEN, 1976, 1964).

In southern Sweden, in Blekinge, BERGLUND (1964) studied buried lagoonal deposits at Serevika and Hallarumsa sites. The deposits contain as unquestionably Ancylus-Lake diatom flora, their age being dated from buried pine stumps. On the basis of these materials Berglund dated the Ancylus stage from 9,800 to 8,000 years ago. However, it seems evident that the wood remains are redeposited and their age cannot reflect the true existence time of the lagoon.

In the southern Baltic KOLP (1974) identified some submarine terraces and correlated them with certain stages in the development of the early Baltic Sea basin. Although in the Holocene the 0-iso base of this locality drifted (ERONEN, 1974) and it is difficult to reconstruct the magnitudes of tectonic movements, we believe that establishing relationships between terrace formation ages and the time scale, as done by Kolp, is not sufficiently valid. The recent dating 9,360±110 yr BP (Tn-318) with respect to organogenic deposits from a core near the island of Rügen from about 21 m depth indicates that identification of a Yoldian terrace at 60 m depth (KOLP, 1974) appears to be premature.

CONCLUSION

The eustatic curve for the Baltic Sea obtained by us for the late Holocene is not yet sufficiently accurate. Its refinement requires very accurate indicator lines, since the oscillation amplitude of the sea level in this time interval was relatively small.

Thus, with the help of the proposed eustatic curve for the Baltic we can make corrections in datings of deposits, carry out interregional correlations and correlate individual shorelines for the entire Baltic. If the spectrum of coastal forms has been clearly identified by means of biostratigraphic, geomorphologic and radiologic methods, it becomes possible to specify the magnitudes of neotectonic vertical movements.

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