THE KATTEGATT SEA
A TEST AREA FOR REGIONAL EUSTASY, ISOSTASY AND OCEAN CIRCULATION

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The Kattegatt Sea is located at the border between glacial isostatic uplift of the Fennoscandian Shield and subsidence of the North Sea Basin, as well as at the border between the Atlantic and the Baltic. This offers unique possibilit-ies of deciphering the delicate interplay between eustasy and isostasy and between the pulsation of the Gulf Stream, the climate in NW Europe and the variations in the Earth's rotation.

It has been possible to establish a "regional eustatic curve" that seems to explain most of the available records in northwestern Europe in a logical way, regardless of general uplift (Fennoscandia and Scotland) or subsidence (the North Sea Basin and subsiding coastal areas). From the geomorphological changes in coastal segments, it has been possible to reconstruct the changes in the prevailing wind direction through the last 10,000 years, or so. During the Holocene, 16 low-amplitude eustatic oscillations are recorded. They exhibit good correlation not only with terrestrial climatic changes but also with polar front movements in the Atlantic. This indicates that they are primarily driven by Gulf Stream pulzations in a feed-back mechanism linked to changes in the Earth's rate of rotation. The same relationship is well documented by instrumental records for the last 300 years.

INTRODUCTION

The Kattegatt Sea is a part of the Atlantic and constitutes a link between the North Sea and the Baltic Sea which, during the postglacial period, sometimes has been isolated from the sea as lakes but, for most of the Holocene, has been a brackish water body in level with the sea. It also forms a bridge between the old Fennoscandian craton and the surrounding deep sedimentary basins. With respect to the glacial isostatic depression of the crust and subsequent uplift, the Kattegatt Sea occupies a border zone between postglacial uplift of the Fennoscandian Shield and subsidence of the North Sea basin. This key position is illustrated in Fig. 1.

The Kattegatt Sea and surrounding coastal areas is therefore an ideal place for detailed studies of the interaction between isostasy and eustasy (Mörner, 1969) and general paeleoenvironment, ocean circulation and regional eustasy (Mörner, 1984a, b).

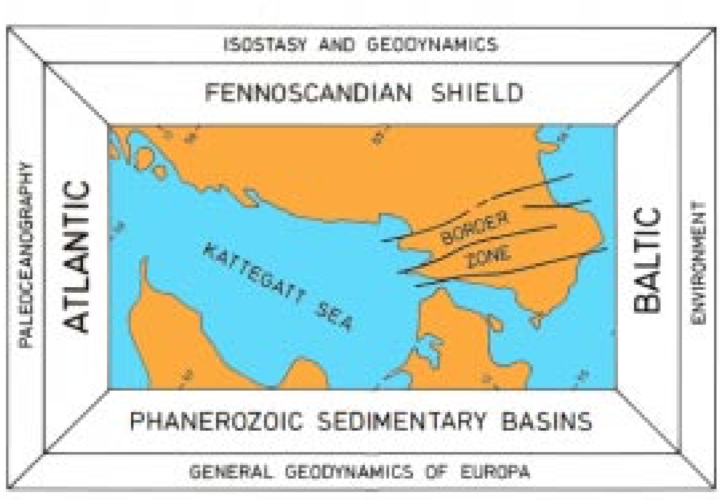

Fig. 1. The Kattegatt Sea and its geodynamic key position.

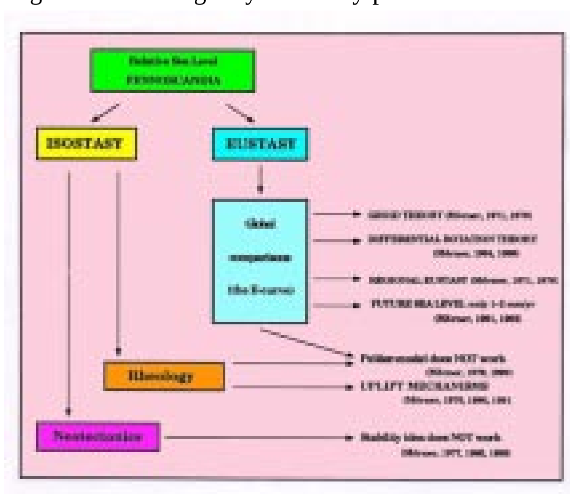

Fig. 2. The author´s analyses and main results.

Fig. 2 illustrates the author´s analyses, results and main conclusions and theories from the first separation of the isostatic and eustatic components in the relative sea level changes (Mörner, 1969, 1971a). The present paper will more or less follow this scheme.

RELATIVE SEA LEVEL

About 40 individual shorelines were identified and followed for about 250-300 km in the direction of tilting (Fig. 3; Mörner, 1969, 1980a). The Late Glacial shorelines were established via their relation to successively younger synchronous positions of the receding ice margin (Mörner, 1969, 1979a). The Holocene shorelines are represented by synchronous geomorphic features that can be followed in the field over extensive areas. This is true because each of these shorelines is formed during the peak of a small eustatic oscillation (Mörner, 1969, 1971a, 1976a, 1980b, c).

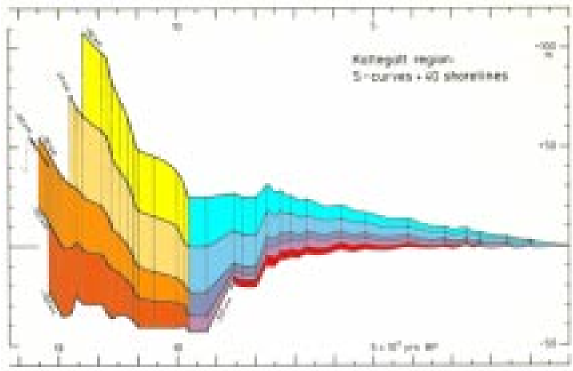

Fig. 3. The Kattegatt shoreline spectrum with 40 shorelines extending for some 250-300 km in the direction of tilting (Mörner, 1980a).

Fig. 4. The Gothenburg relative sea level curve (Mörner, 1976b).

Fig. 4 illustrates the relative sea level changes in Gothenburg (Mörner, 1976b); a Late Glacial regression from the Marine Limit (ML), an Early Holocene low point or Regression Limit (RL), a subsequent transgression up the the Postglacial Limit (PL; which becomes successively younger towards the periphery of uplift), and finally an oscillatory regression down to the present position.

The Viskan Valley was the primary investigation area (Mörner, 1969). Fig. 5 gives the

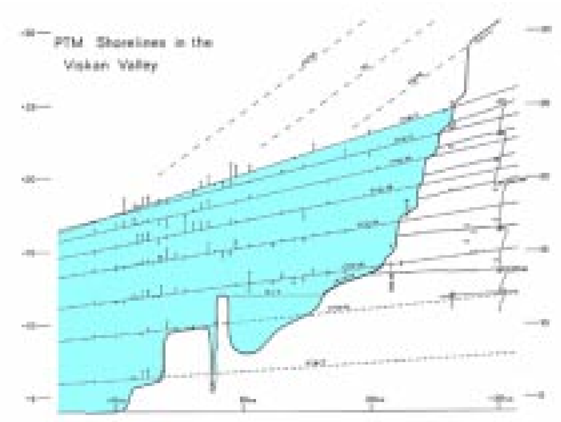

Fig. 5. The PTM shorelines in the Viskan Valley (Mörner, 1980b, c). The buried, Early Holocene, ALV shorelines (dotted) and Younger Dryas shorelines (dashed) are also included. The PTM shorelines are based on shore marks, delta levels (and delta characteristics), buried river beds with silting-up dates (U-signs), dated isolation levels (arrows) and diatom diagrams (BP 300 + others).

PTM (Postglacial Transgression Maximum) shoreline that are defined in age and elevation by multiple criteria.

Fig. 6 gives the sea level curve for the Bjäre Peninsula in SW Sweden. The shoremarks are usually excellently preserved. A total of 37 radiocarbon dates back up the chronology within this limited area (Mörner, 1980b, c). From the sedimentary dynamics of the different shorelines, it has even been possible to establish a record of the changes in prevailing wind direction (Fig. 7). The fact that individual shorelines can be identified,

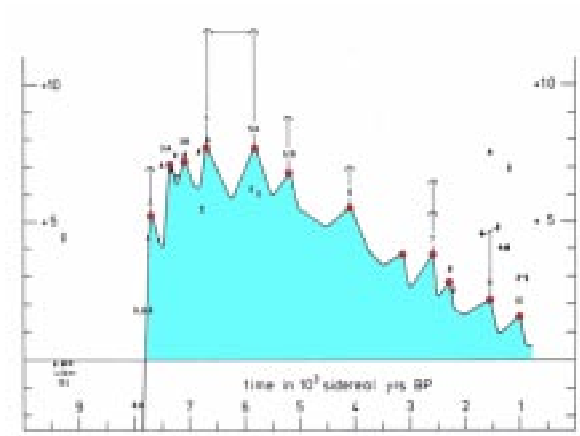

Fig. 6. Relative sea level curve for the Torekov-Båstad area (the -50 km point) on the Bjäre Peninsula (Mörner, 1980b, c) based on morphology, stratigraphy and 37 radiocarbon dates. Encircled ponts = mean sea level of the PTM shorelines with semi-circles marking the crests of related beach ridges. Arrows = radiocarbon dates of transgressions (upwards) and regressions (downwards). All the oscillations from PTM-2 to PTM-5A are well dated and stratigraphically separated. The PTM-5B to PTM-7 are all well separated (but not dated here). The PTM-9 and PTM-10 oscillations are well dated.

Fig. 7. Prevailing paleowind directions as established from the beach morphology on the Bjäre Peninsula (Fig. 6) and in the Laholm Bay (Mörner, 1980a, b, 1984c).

dated and followed over extensive areas is the base of the possibility of separating the isostatic and eustatic components, as well as for the precision in time/amplitude conclusions (Mörner, 1969, 1971a, 1976a, 1980b). Because of these multiple shoreline and shorelevel displacement records from different isobase latitudes, it is possible to pinpoint eustatic oscillations within time-slices as small as about 50-100 years and amplitudes in the order of some dm (when separated from the isostatic factor).

In areas of single sea level curves, the margins of error in time and amplitude rapidly increases. This has been well studied and calculated by Shennan (1989) for English sites.

SEPARATION OF ISOSTASY AND EUSTASY

The method of separating the isostatic and eustatic factors behind the relative sea level changes and shoreline spectrum (Fig. 3) has been fully described elsewhere (Mörner, 1969, 1971a, 1976a) and will not be further discussed here. We just conclude that this has been possible.

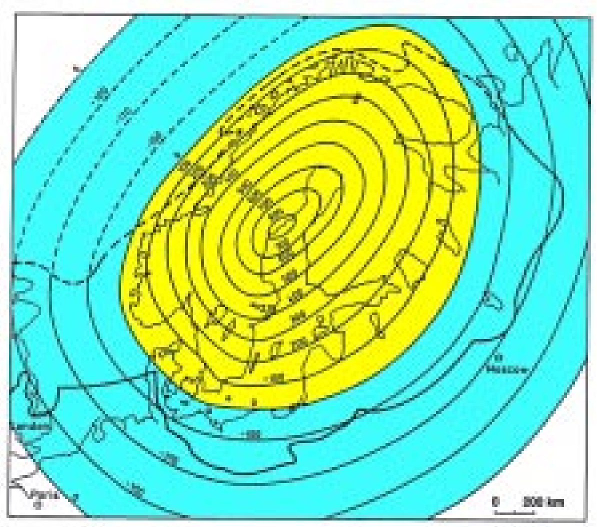

Fig. 8. Contours of the total absolute uplift and subsidence in relation to the last glaciation of the Fennoscandian Shield (Mörner, 1979b, 1980a).

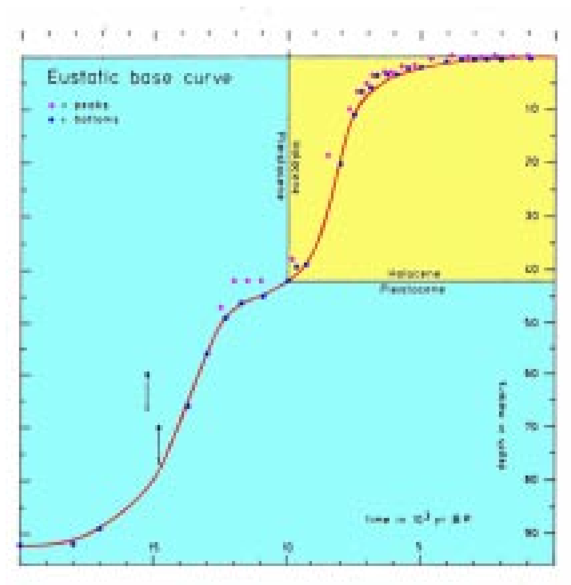

Fig. 9. Eustatic base curve ignoring the transgression maxima (stars) and combining the regression lows (dots) providing the superimposition of two simple exponentail curves (Mörner & Rickard, 1973; Mörner, 1976b). There is a striking similarity with the Barbados curve of Fairbanks (1989).

ISOSTASY

The Fennoscandian uplift form an elliptic cone with a central uplift of about 830 m that is surrounded by a subsidence trough of about 170 m (Fig. 8). The establishment of a total uplift of about 830 m (Mörner, 1979b, 1980a, 1990) meant a significant revision of the old concept of a maximum uplift of only about 300 m. The new figure fits very well with geophysical models. However, it was also found that the uplift consisted of two different factors (Mörner, 1973a, 1977, 1979b, 1980a, 1990) and that the true glacial isostatic factor died out some 4500 ago.

The glacial isostatic picture established has fundamental bearings on our understanding of the rheological processes and properties in the upper mantle and lithosphere (Mörner, 1979b, 1980a, 1990). In combination with the eustatic results, this indicates that the global loading models (e.g. Clark, 1980; Peltier, 1982) do not explain the available observational data in a correct way (Mörner, 1981a, 1987a, 1989a, 1990).

The studies of the crustal components behind the relative sea level changes have also led to general and specific conclusions in neotectonics. The old idea of a "stable" craton has drastically changed. In association with the peak rates in isostasy, high-amplitude earthquakes and seismotectonic deformations seem rather to have been the rule that the exception (Mörner, 1977, 1985; Mörner et al., 1989). This has an important bearing on the issue of final deposition of high-level nuclear waste in the bedrock.

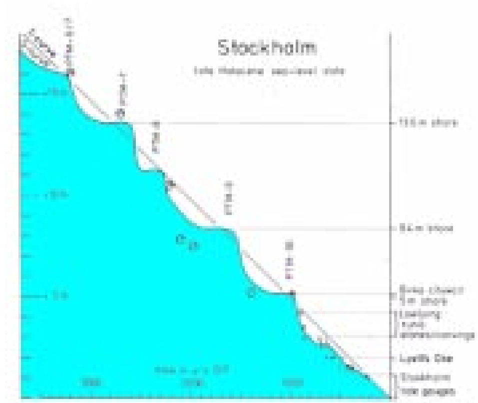

Fig. 10. The Stockholm relative sea level curve (S) and uplift component (I) with special emphasis of the detailed record of the last millennium (Mörner, 1984c).

EUSTASY

The eustatic component subtracted from the relative sea level spectrum is a low-amplitude oscillating curve (Mörner, 1969, 1971a, 1976a, 1980a, b, 1984c). Joining the regressional low points (Fig. 9), it is composed of two simple, superimposed, exponential curves ($4000 < t < 9000$, $\log D = 0.000336\ t - 1.46$ and $12000 < t < 14000$, $\log D = 0.000094\ t - 0.53$; with t denoting time in BP and D eustatic depth in m). The mean point of the two curves is at about 10,500-10,000 BP. The Fig. 9 eustatic base curve (Mörner & Rickard, 1973; Mörner, 1976b) is strikingly similar to the recently established eustatic curve from Barbados (Fairbanks, 1989) only there is a stretching/ compressioning component in the order of about 2:3 (Mörner, 1991, Fig. 1).

In order to prove the superiority of the Kattegatt eustatic solution with res-pect to other proposed “eustatic” curves - like those of Fairbridge (1961) and Shepard (1963) - the curve was tested both regionally and globally (Mörner, 1969, 1971a), an analysis that was extended both to the long-term records (Mörner, 1971b) and the short-term records (Mörner, 1973a). At the same time as these analyses fell out positively for the Kattegatt solution (Mörner, 1969, 1971a), it was found that a major component was missing (Mörner, 1971c, d) that gave rise to an unequal distribution of the ocean surface with respect to the present. Later, this missing component was found to be geoid deformations with time (Mörner, 1976c; first proposed at the IGCP-61 first meeting in Amsterdam in 1973). These findings meant that we, in fact, could not talk about global eustasy (the goal of IGCP-61), only regional eustasy (Mörner, 1971a, 1976a, b).

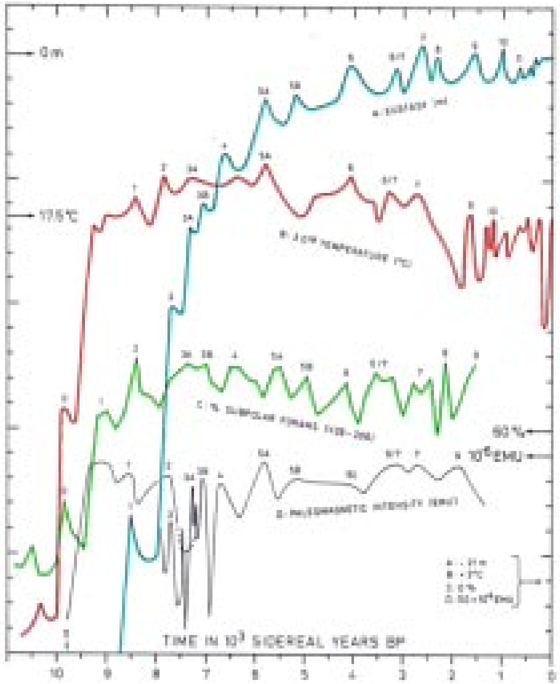

Fig. 11. Holocene short-term fluctuations in regional NW European eustasy (A, blue), continental temperature (B, red) and Gulf Stream variability (C, green) north-west of Iceland (a paleomagnetic intensity record, D, is also included) indicating ocean circulation changes and redistribution of mass and energy (Mörner, 1984a, b, 1987d, 1988a).

REGIONAL EUSTASY

In order to become a good regional eustatic curve, the Kattegatt solution had to be tested against all available records (e.g. Jelersma, 1961, 1966; Kooijmans, 1974; van de Plassche, 1982; Tooley, 1974; Shennan, 1982). These analyses (Mörner, 1976a, 1979c, 1980a, b) have shown that the Kattegatt eustatic solution is capable of explaining available relative sea level records in ways that seem logical from their geological setting. This seems also to apply for the critical analyses of the Dutch data by van de Plassche (1982) and of the English and general North Sea data by Shennan (1987). We, therefore, conclude that the Kattegatt solution really can serve as a good regional eustatic curve.

In combination with archeological and historical data from the Stockholm area, it has been possible to extend the curve with high precision also for the last two millennia (Fig. 10; Mörner, 1984c; cf. Åse, 1980). A eustatic peak (PTM-10) at about 950 AD is followed by a very marked regression. A Medieval peak (PTM-11) and two small regression (on each side of the PTM-12 peak) provide a remarkable similarity with the climatic record of Lamb (1982) with a Medieval warm peak and two Little Ice Ages in the 15th and 17th centuries.

THE CHANGING GEOID

With the observation (Mörner, 1971c) that a major component was missing in our analyses of sea level changes and the remarkable progress in space geo-desy, it did not take a long time till I realized (in 1972) that the missing factor had to be deformations of the gravity potential surface, i.e. the geoid (Mörner, 1976c). Undoubtedly, this marks a major change in sea level studies; the globality had to be substituted for regionality.

The global eustatic changes in view of geoid changes have been discussed in a number of papers (Mörner, 1976c, 1978b, 1980d, 1981a, b, c, 1983, 1986, 1987a, b, c) and will not be further discussed here. The same applies for the new definitions and nomenclatures necessary (e.g. Mörner, 1986).

DIFFERENTIAL ROTATION

After having introduced the geoid changes with time, it became clear that some regions possessed similarites that must be explained in still another way than what was commonly used. At the same time (Mörner, 1984b), it became obvious that most of the short-term high-amplitude climatic changes during the last 10,000-20,000 years are of global compensational type rather than representing general rises and falls. This implies an energy redistribution over the globe with a memory of up to some 50-150 years. The only agency that is capable of carrying and redistributing energy in this way, is the ocean. This led to the formulation of the theory of differential rotation and redistribution of energy and mass over the globe via ocean circulation changes (Mörner, 1984a, b, 1987b, d, 1988a, b, 1989b, c).

The regional northwest European eustatic curve includes 16 low-amplitude oscillations. These oscillations seem to correlate well with continental temperature records and the North Atlantic Gulf Stream pulsation (Fig. 11). This seems to be a clear indication of ocean circulation changes and redistribution of mass (sea level) and energy (temperature, paleoenvironment). This calls for a feed-back causational interchange of angular momentum between the hydrosphere and the "solid" Earth (Mörner, 1984a, b, 1987d, 1988a). It also explains an previous finding (Mörner, 1973b) that the eustatic changes like the fluctuations in six Atlantic high-sedimentation rate cores form frequency changing cyclic patterns; just as one would expect from an oceanic feed-back circulation system.

For the last 275 years, there are instrumental records of the changes in the Earth´s rate of rotation. This allows a test of the theory proposed. The accelerations and decelerations seem to agree perfectly well with the changes in sea level and climate as recorded in northwestern Europe (Mörner, 1987d, 1988a, b, 1989b, c).

FINAL REMARKS

This review documents the key position of the Kattegatt sea level records in a number of fundamental questions. It also documents the necessity of a continual search for new aspects and angles.

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