Isostasy, eustasy and crustal sensitivity

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ABSTRACT

Studies in Southern Scandinavia have revealed a "high crustal sensitivity" even to minor changes in the load of ice (glacio-isostasy) and water (hydro-isostasy). Therefore, one might expect that coast, shelves and even ocean floors were hydro-isostatically deformed by the rising ocean level after the last ice age. There are, in fact, strong indications that the increasing load in connection with the rising ocean level really deformed not only several coasts and shelves of the world but also the ocean floor in general. Therefore, "ocean volume changes" (new term) are not equivalent to eustatic changes as earlier assumed

Late Quaternary isostatic changes in Southern Scandinavia

The results of a comprehensive study of the Late Quaternary ice recession, chronology and shorelevel displacement in Southern Scandinavia made it possible—for the first time—to reconstruct the isostatic (and eustatic) changes in a very detailed way (Mörner, 1969*a*). The area investigated covers the marginal zone of the last glaciation (Weichselian) and also the marginal area of the Fennoscandian shield.

The intensity of upheaval, the direction of tilting, the distribution of sediments, the negligible tide, the good pollen chronology, etc., all make the Swedish West Coast and the Kattegatt Sea uniquely suitable for a detailed investigation of shorelevel displacement.

About 33 different shorelines were determined and followed 350–200 km in the direction of tilting, i.e. from fairly strongly uplifted isobases to very slightly uplifted and even subsided isobases (Mörner 1969*a*, Pls. 4–6, Figs. 142–148). They must be regarded as very well fixed in age and gradient (Mörner 1969*a*, 1969*b*, 1970*a*, 1971*b*).

These shorelines were used for the construction of time-gradient curves (Fig. 1), showing the intensity of upheaval-tilting in a very detailed way. The time-gradient curve (Fig. 1) does not decrease smoothly and uniformly, but fluctuates. This is an important fact and shows that the upheaval and tilting were easily influenced by other factors. The shorelines, on the other hand, are quite straight and regular. Compared to the shorelevel displacement curves, the pollen analysis and the ice recession, the time-gradient curve could directly be linked to the changes in sea level, the changes in climate and the changes of the ice margin. It is quite obvious (Fig. 1) that the intensity of upheaval was decreased during cold periods with advance of the ice, and accelerated during warm periods with rapid ice recession and/or periods of eustatic transgressions (Mörner, 1969*a* p. 409).

This means that the upheaval was a balance (Fig. 2) very sensitively responding (even minor) changes in the load of ice inland (glacio-isostasy) and changes in the load of water seawards (hydro-isostasy). We may thus speak of a high "crustal sensitivity".

Also, the centre of upheaval and the margin and axis of tilting changed geographic position. The whole isostatic picture is illustrated in Fig. 3 and can be summarised in the following way (cf. Mörner, 1969*a*, Fig. 146, pp. 415–420).

1. 11750–10750 BC block upheaval of centre A.

2. 10750–7700 BC tilting from centre B with the axis of tilting moving inland with some fluctuations.

2*a*. Strong and rapid upheaval during the Ågård Interstadial at 10750–10450 BC (decreasing ice load, increasing water load).

2*b*. Strongly retarded upheaval during the

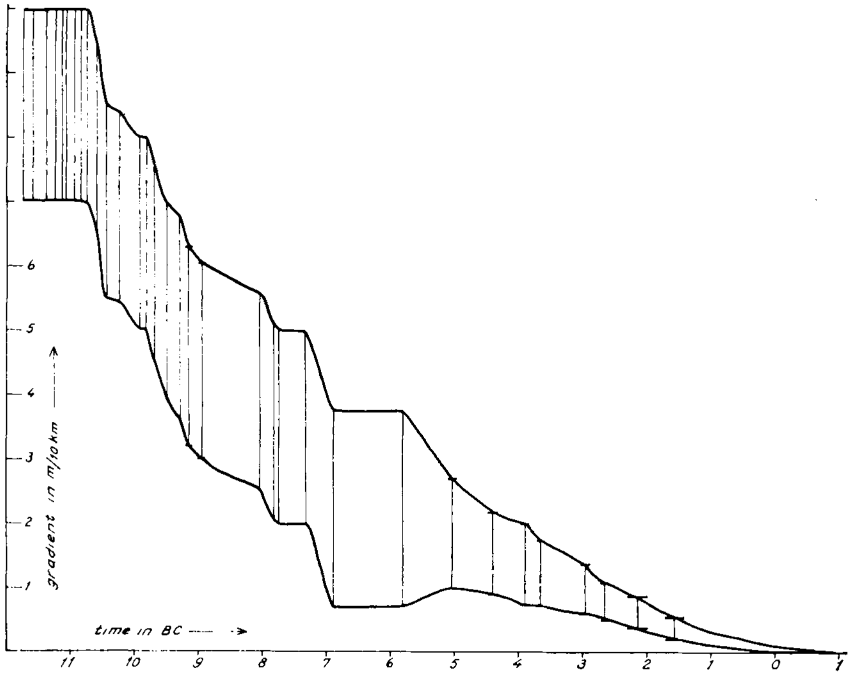
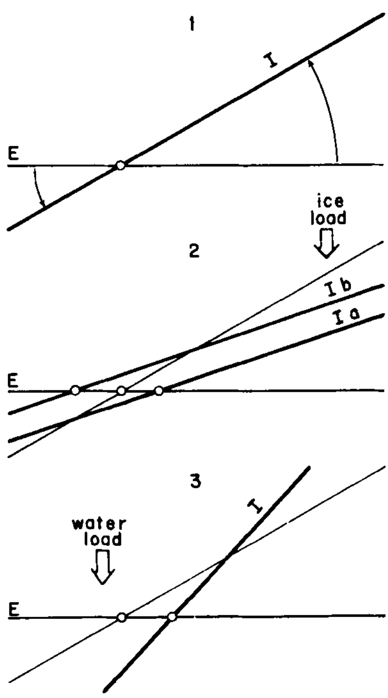


Fig. 1. Time-gradient curves for the shorelines (vertical lines) in Southern Scandinavia. These curves directly give the intensity of the isostatic upheaval. The curves fluctuate up to 5 000 BC, after which they decrease more or less continuously to the present.



Fjärås Stadial at 10450–10400 BC (increased ice load).

2*c*. Rapid upheaval during the Bölling Interstadial at 10400–9950 BC (decreased ice load, increased water load).

2*d*. No upheaval during the Older Dryas (or Berghem) Stadial at 9950–9800 BC (increased ice load).

2*e*. Rapid upheaval during the Alleröd Interstadial at 9800–9000 BC (decreased ice load, increased water load).

2*f*. Retarded upheaval during the Younger Dryas (or Ra-Billingen-Salpausselkä) Stadial at 9000–8050 BC (increased ice load).

2*g*. Rapid upheaval in earliest Postglacial time at 8050–7800 BC (decreased ice load, increased water load).

2*h*. Decreased upheaval during the Eidfjord

Fig. 2. The isostatic balance in Southern Scandinavia. E = eustatic level. I = isostatic uplift. 1. Normal upheaval due to removed ice load. 2. Retarded upheaval (compared to 1) due to increase of ice load. 3. Accelerated upheaval (compared to 1) dut to increase of water load.

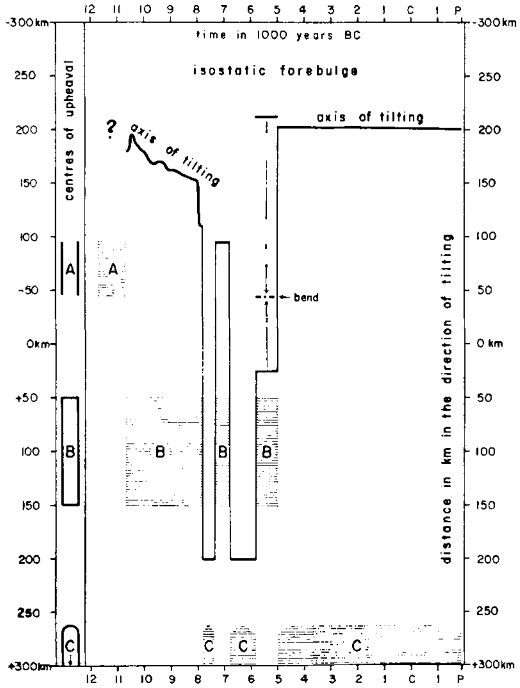


Fig. 3. Time–distance reconstruction of the isostatic upheaval in Southern Scandinaiva (cf. the text). A, B and C = the geographic position of the three centres of upheaval. Hatched areas = the time of action of the three different centres. Heavy line = the axis of tilting, outside which there was an isostatic fore bulge. The bend was created by the reactivation of centre B.

(or Preboreal) Stadial at about 7800–7750 BC (decreased water load, changing centre).

3. 7700–7330 BC tilting from centre C with the axis as well as the margin of tilting inside centre B (rapidly and strongly decreased ice load).

4. 7330–6850 BC tilting from centre B due to rapid and strong increase of the water load (major eustatic transgression).

5. 6850–5800 BC tilting from centre C with the axis as well as the margin of tilting inside centre B (end of increased water load).

6. 5800–5000 BC tilting from centre B due to rapid and strong increase of the water load (eustatic transgression). This strong reactivation of centre B (the Highland of Småland) created the bend at −43.4 km, as the outer part did not follow the upheaval. All older shorelines were equally bent (Mörner, 1969*a*, Pls. 4–6). The area of the bend sunk in relation to both the area inside and outside.

7. 5000 BC and onwards tilting from centre C with the axis of tilting stable at −200 km.

In general the land upheaval decreased with time and distance towards the periphery, and the centre of upheaval moved inland in three steps. This means in general a fairly simple picture of upheaval, to which, however, the very high glacio-isostatic and hydro-isostatic sensitivity were added.

General hydro-isostatic changes of the world

A. *The shelves and coasts*

The detection of obvious hydro-isostatic changes in Scandinavia is important, as it partly gives evidence of Higgins' (1965) and Bloom's (1965, 1967) more theoretical discussions about crustal deformation due to the load of water, and partly means that we must expect a hydro-isostatic deformation of transgressed shelves and coasts.

I have earlier shown (Mörner, 1970*a*, Fig. 3; 1971*a*; 1971*b*) that a hydro-isostatic deformation of a coast of shelf may have occurred with or without a compensational upheaval inside the axis of subsidence (Fig. 4). If there was a compensational upheaval (Fig. 4, alternative 3), the isostatic movements would change from upheaval to subsidence as the transgression went on. In comparison with my eustatic curve, several sea level curves (e.g. Florida, Bermuda, Louisiana, parts of Micronesia) show an isostatic reversal (Fig. 5). This reversal is one of the explanations to what I called "the real Holocene eustatic sea level problem" (Mörner, 1970*a*, 1971*a*), viz. that the different "eustatic" curves converge, instead of diverging, back in time (Fig. 6). The other explanation to this problem is that the eustatic ocean level was

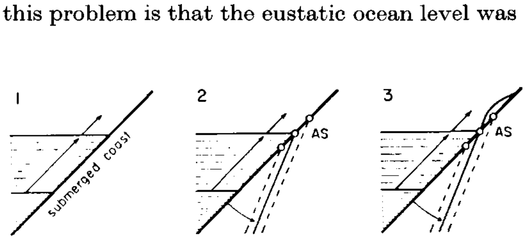


Fig. 4. Theoretical model of the response of a submerged coast to the load of added water. Hatched areas = sea. Arrows = eustatic transgression of a coast. AS = axis of subsidence. 1. No deformation. 2. Subsidence outside AS (three locations). 3. Subsidence outside and compensational upheaval inside AS (three locations).

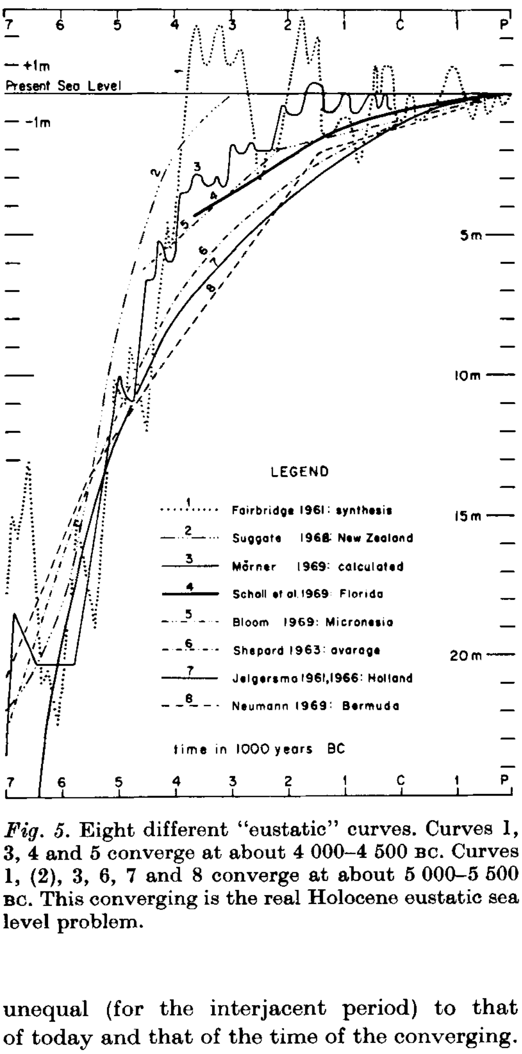


Fig. 5. Eight different "eustatic" curves. Curves 1, 3, 4 and 5 converge at about 4 000–4 500 BC. Curves 1, (2), 3, 6, 7 and 8 converge at about 5 000–5 500 BC. This converging is the real Holocene eustatic sea level problem.

unequal (for the interjacent period) to that of today and that of the time of the converging. Probably we have to consider both the isostatic and the eustatic differences.

B. *The ocean floors*

Flint (1969) found that the addition and removal of water from the ocean by the melting and building up of glaciers of an ice age would have been capable to rise and drop the sea level by 132 m, if the ocean floors would not have sunk and gone up, respectively, by about 1/3 of the thickness of the water body added or removed; giving a eustatic change of only 88 m. Flint suggested a 10 % smaller figure for the last glaciation maximum (Würm-Weichselian-Wisconsin); i.e. 120 m and 80 m, respectively.

The eustatic curve presented by me (Mörner, 1969*a*, 1969*b*, 1969*c*, 1970*a*, 1971*a*, 1971*b*) is calculated in a way, which means that it should give the true eustatic changes—after any possible isostatic change (subsidence) of the ocean floor and the shelves of the world. I found a eustatic position during the last glaciation maximum (18000–16000 BC) at −85 to 90 m, which means very close agreement with the calculation by Flint. This is a strong argument for accepting the hydro-isostatic subsidence of the ocean floor during the transgression after an ice age as a reality (Flint, 1969; Bloom, 1967; Mörner, 1970*a*). On the other hand, there is—as shown below—no ground to expect an upheaval of the ocean floors by the same amount (as assumed by Flint, 1969) during the drop of sea level in connection with the building up of the glaciers.

Compared to Milliman & Emery's (1968) sea level curve for the North American Atlantic shelf + their data from 11 other shelves, my curve really suggests a hydro-isostatic subsidence not only of the shelves but also of the ocean floor in general (Fig. 7).

Bloom has discussed (1967) and studied (1969) the hydro-isostatic changes. According to him (1967) a stable coast "would record only about two-thirds of the glacial-eustatic fluctuation of sea level as calculated from the

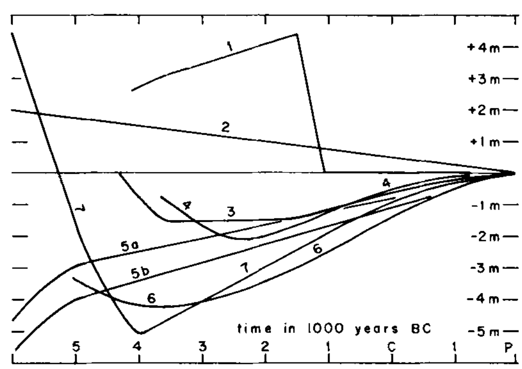


Fig. 6. Isostatic changes of 7 different areas compared to the Mörner eustatic curve. 1. Northeast Australia (Hopley, 1969), 2. Christchurch, New Zealand (Suggate, 1968; Mörner, 1969*a*, Fig. 159). 3. Parts of Micronesia (Bloom, 1969). 4. Florida (Scholl, 1964; Scholl et al., 1969; Mörner, 1969*a*, Fig. 156). 5. The Netherlands (Jergersma, 1961, 1966; Mörner, 1969*a*, Fig. 153). 6. Louisiana (Coleman & Smith, 1964) and 7. Bermuda (Neumann, 1969).

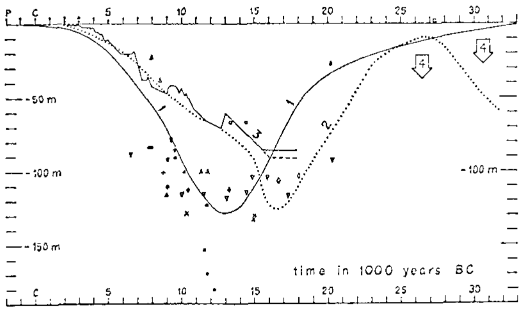


Fig. 7. Milliman & Emery's (1968) sea level curve for the North American Atlantic shelf + time–depth indications from 11 other shelves (for details see Milliman & Emergy 1968) compared to the eustatic curves by Curray (1965) and Mörner (1969*a*, 1970*a*). The Mörner (3) and Curray (2) curves lie very close together back to 12 800 BC. From the point of extension of the continental ice at 16 000–18 000 BC and at about 12 800 BC, the eustatic difference between these two glaciation maxima must be small and not at all as big as in Curray's curve. The difference between the Mörner curve (3) and the curve and data by Milliman & Emery (1) suggests a hydroisostatic subsidence not only by the shelf but also of the ocean floor in general. Arrows (4) mark the author's opinion—from a climatic point of view—that the eustatic level was far below the present during the interstadial about 30 000 years ago (Mörner, 1971*d*). The high-stand is believed to be of Brörup Interstadial age at about 80 000 years ago.

volume of glacier ice" (Bloom, 1967, p. 1491), while an oceanic island would record "the true magnitude of glacially controlled sea-level changes" (Bloom, 1967, p. 1490). His sea level curve from Micronesia (1969) is fairly similar (Fig. 5) to Scholl's curve from Florida (Scholl, 1964; Scholl et al., 1969). At the INQUA VIII Congress in Paris, Bloom (1969) proposed his curve to be "the standard for eustatic sea-level changes".

However, the changes of glacially controlled volume of ocean water cannot be called eustatic. We need a new term for these "ocean volume changes" in contrast to the eustatic changes which are the final changes of ocean level after the influence by the possible hydro-isostatic movements of the ocean floor as well as all other isostatic or other changes affecting the ocean level. We must distinguish between shore-level displacement (= relative sea level) curves, eustatic curves and ocean volume curves (Mörner, 1971*c*).

When discussing supposed "eustatic curves" we must consider these hydro-isostatic changes of the ocean floor and the shelf areas. In this connection it may also be significant that the reports on high Holocene sea level stands mainly come from Australia, South America

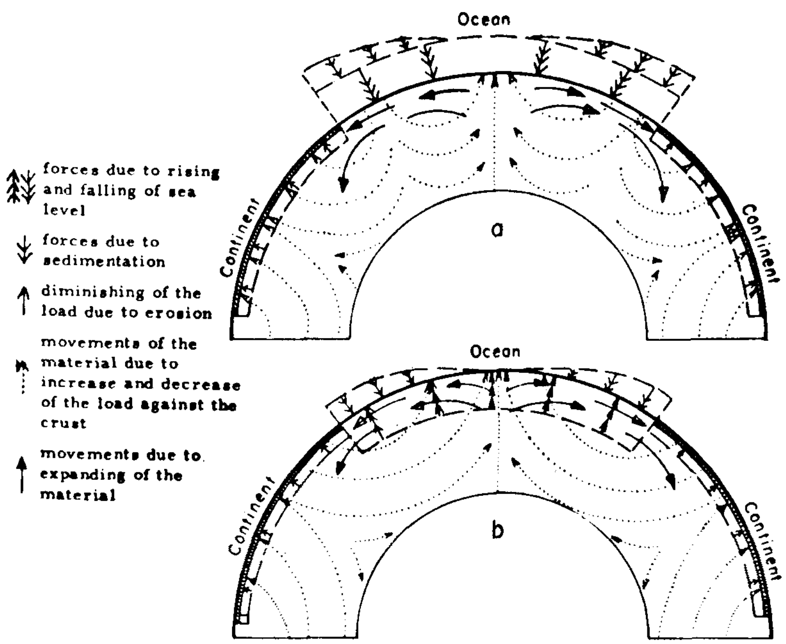


Fig. 8. The load and movements according to Kaitera's sea pressure hypothesis (from Kaitera, 1966) at a rising sea level (*a*) and at a falling sea level (*b*).

Interglacial eustatic sea level	difference	Glacial eustatic sea level
Reuverian (higher)		
		(higher) Praetiglian
Tiglian (higher)		
		(higher) Eburonian
Waalian +100 m		
	100–95 m, 20, 75–80m	±0– +5m Menapian
Cromerian +60 m, +60 m, +50 m		−50–20 m, −70–40 m
	130 m, 20, 110 m	−80 m Elsterian
Holsteinian +30 m		
	135 m, 10–20, 125 (115) m	−105 m Saalian
Eemian +20 m, +10 m		
+2–5 m	100 m, 10, 90 m	−90–85 m Weichselian
Flandrian +0.4 m		

Fig. 9. The difference in sea level during the interglacials and glacials. The fall is always greater than the rise of sea level (by 10–20 m) in connection with an ice age. The ocean volume changes were greater than the fall of sea level. The table shows that the adding of water load deformed (down) the ocean floor more than the removal of load (up). *N.B.*: the sea levels and ages are preliminary.

and Africa, i.e. areas bordering the main ocean basins. Consequently, these continents may have gone slightly up when the ocean floor went down. On the other hand, these are also areas of continental drift.

The cyclisity of some elements (especially Mn and Cu) in deep sea cores is related to the glacial/interglacial changes (Boström & Bonatti, 1969) and supposed to derive from below the earth's crust of the sea floor. This cyclosity may also be related to the isostatic changes of the ocean floor between glacial and interglacial periods.

Discussing his "sea pressure hypothesis", Kaitera (1966) showed that an addition of load by a rise of ocean level directly influences the ocean floor, while a removal of load by a falling sea level would only partly influence the ocean floor (Fig. 8). This is very important for the discussion and interpretation of the general drop of interglacial sea levels during the Pleistocene (Fig. 9). It means that a decrease of the ocean volume by the building up of the glaciers of an ice age had litte effect on the ocean floor, while an increase of the ocean volume by the melting of the ice would have deformed the ocean floor hydro-isostatically (Fig. 9) by about 1/3 of the thickness of the water body added (cf. Mörner, 1971*b*, Table 6).

Summing up, there is evidence that the water load has been capable of deforming the earth's crust locally and very strong suggestions that it has also deformed the ocean floor in general. This means that the true eustatic curve would always give a smaller rise of sea level than the ocean volume curve. It also means that the search for a true eustatic curve is very hard and that a calculation from a suitably uplifted area, where the isostatic factor can be determined, probably is one of the best ways to find it. Furthermore, it was demonstrated that a hydro-isostatic deformation of a coast and shelf may have occurred with or without a compensational upheaval inland, but also that the eustatic ocean level during the last 7 000 years may have been unequally distributed compared to that of today.

Addendum

With a new method based on the changes with time of mean annual uplift, it was demonstrated (Mörner, *Palaeo*[3], in press) that the Scandinavian uplift is complex; partly caused by glacia-isostatic uplift, which decreases continously and is now more or less finished, and partly by another force, probably an old tectonic force, which keeps a constant rate and is reponsible for almost the whole of the present uplift. The explaines why the axis of tilting in Southern Scandinavia (Fig. 3) has remained stable for the last 7000 years.

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and held at Victoria University of Wellington, Wellington, New Zealand, 10–18 February, 1970 (Mörner, 1970*b*). The paper was multigraphed as: Contribution No. 171 of the Department of Geology at the University of Western Ontario, London, Canada, 1970.

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ИЗОСТАЗИЯ, ЕВСТАЗИЯ И ЧУВСТВИТЕЛЬНОСТЬ КОРЫ

Исследования в южной Скандинавии выявили «высокую чувствительность коры» даже к небольшим изменениям в нагрузке льдом (ледяная изостазия) и водой (гидроизостазия). Поэтому можно ожидать, что берега, шельфы и даже дно океана были гидроизостатически деформированы благодаря повышению уровня океана после последнего ледникового периода. Существуют сильные указания на то, что увеличивавшаяся в связи с повышением уровня океана нагрузка действительно деформировала не только ряд береговых и шельфовых областей, но и, в общем, дно океана. Поэтому объемные изменения «океана» (новый термин) не эквивалентны евстатическим изменениям, как предполагалось ранее.