Eiszeitalter u. Gegenwart	Band 23/24	Seite 107-115	Öhringen/Württ., 15. Oktober 1973

Radiocarbon Measurements and the Holocene and Late Würm Sealevel Rise

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With 2 diagrams, 1 map and 3 tables

Summary. The rapid rise of sealevel in the Holocene and Late Würm is in essence of glacio-eustatic nature. The tectonic movements were the most important disturbing factor, and the influence of all other factors is not known. The 147 radiocarbon samples from all over the world were selected and the curve repressenting the Holocene sealevel rise was calculated by the least-squares method. At the beginning of the Holocene, i. e. 10,000 years ago, the sealevel was 31 m lower than today. Since there are not enough radiocarbon data from tectonically stable regions to calcute directly the Late Würm sealevel positions, the author tried to calculate them eliminating the subsidence component from the Mississippi delta eustatic curve. In this way he arrived at the conclusion that the lowest position of sealevel during the last glacial stage was at —96.4 m. This maximal sealevel lowering was attained 25,000 years ago.

A. Introduction

One of the most important problems of Quaternary research are the sealevel fluctuations. The exceptional complexity of the Quaternary Period and the fragmentary nature of the data are the reasons that all our investigations are based on certain assumptions or in some cases on proved facts as follows.

1. The sealevel rise is a world-wide, universal process, and the data from all seas and oceans can be fitted together to reconstruct the past picture of the process.

2. Late Quaternary sealevel fluctuations, i. e. the Holocene and Late Würm rapid rise of the sealevel are in essence of glacio-eustatic nature due to the melting of the ice.

3. Individual radiocarbon samples scatter rather widely from the curve describing the general trend, and it is not possible to distinguish effects due to the eustatic change in sealevel from those arising from local tectonic change. The best way is to avoid tectonically disturbed areas.

4. In both Fennoscandia and North America the updoming is primarily the result of the removal of temporary loads of glacier ice. The outer limit of the upwarped region parallels the limit of the latest glaciation (GUTENBERG 1941; FLINT 1957). Due to this reason we avoided the radiocarbon samples from the areas where there has been upwarping due to isostatic recovery, first of all the coasts of Scandinavia and the North American Continent northwards of the Massachusetts coast. Radiocarbon data from the New Jersey, New York, Connecticut and Massachusetts coasts excellently agree with the curve based on the data from other parts of the world. All radiocarbon samples from these states have been laid down close to the zero isobase.

5. It is a well-known fact that the delta regions are constantly subsiding reflecting the tectonic instability and the compaction of loose river sediments. Data from the Rhine and Mississippi deltas have not been taken into consideration in our calculations of the generalized Holocene glacio-eustatic curve, since it is clear that they partly reflect local tectonic down-warping.

6. There are many other factors other than glacial control which are capable of changing the sealevel (systematic review VALENTIN 1954). Such a factor is the thermal coefficient of the sea water, and the resulting sealevel change due to the warming of the

world ocean. However, this was synchronous with the glacio-eustatic change and of the same sign and it could not be separately measured. Similarly, it is not possible to say anything about the drop in sealevel as the delayed isostatic response to the loading of the sea bed caused by the previous rapid rise of the sealevel.

7. Many prominent authors have published curves representing the Holocene or even the Late Würm sealevel fluctuations. The difference between them is not basic, and they give valuable information about the general trend. The reason why many radiocarbon samples have been disregarded is that they depart widely from the general trend of data from the same or other locations and only those locations are included from which the selected measurements are supported by similar measurements from other places.

8. The mathematical treatment of the whole set of individual points (radiocarbon samples) cannot solve the problem, i. e. it is not possible to calculate the exact positions of sealevel because of the great scattering of empirical points (radiocarbon semples), especially going deeper in the past. The procedure is inverse: fitting a curve to a set of points. After the degree of the function has been determined, the best fitting polynominal of that degree may then be fitted by the method of least squares. Inherent in the method is the need for the greatest possible number of empirical points.

Shortly, according to present knowledge the Holocene and the Late Würm sealevel rise was in essence glacio-eustatic; the tectonic movements are by far the most important disturbing factor. It is believed that all other factors have not been fundamentally important.

B. The Sealevel Rise in the Holocene

In order to calculate the curve representing the Holocene sealevel rise we selected 147 radiocarbon samples from all over the world.[1]) As is known, x denotes the oldness, and y denotes the depth of the sample which is believed to have been laid down at the depth at which it was found. Since error is inherent in the calculation of both x and y, the best way to avoid this is to treat them statistically, i. e. to treat as many radiocarbon samples as possible.

In similar articles it is customery to quote all details about the radiocarbon samples. In this case this is not possible because such a table would be enormous. We shall confine ourselves only to the geographical distribution of the samples. In order to fit the curve as well as possible, especially at the most important point (at the beginning of the Holocene), we added a few radiocarbon samples somewhat older that 10,000 years.

By far the greatest number of the radiocarbon samples are derived from North America. North Carolina: I-1576, I-1577, I-1578, I-1579 (Redfield 1967). The shelf off northeast USA: W-1400, W-1401, W-1402, W-1403 (Merill et al. 1965), W-1491, W-2013, S-186, S-210 (Emery & Garrison 1967). Massachusetts coast: W-570, W-582, W-584, W-586, W-639, W-675, W-676, W-970, W-971, W-973, W-1092, W-1093, W-1094, W-1095, W-1096, W-1098, W-1099 (Rubin & Alexander 1960), C-417, C-418 (Libby 1955). Three samples without a laboratory number (Barghoorn, quoted by Redfield & Rubin 1962), W-1451, W-1452, W-1453, I-1441, I-1442, I-1967, I-1968, I-2216, I-2217 (Redfield 1967). Connecticut: Y-1054, Y-1055, Y-1056, Y-1057, Y-1058, Y-1074, Y-1077, Y-1175, Y-1176, Y-1177, Y-1179 (Bloom & Stuiver 1963), Y-840, Y-855 (Stuiver & Deevey 1961), W-1082 (Upson et al. 1964), C-114 (Arnold & Libby 1951) and W-945 (Ives et al. 1964). New Jersey: Y-1131, Y-1281, Y-1282, Y-1283, Y-1284 (Stuiver & Daddario 1963). Virginia: ML-191, ML-192, ML-193, ML-194 (Newman & Rusnak 1965), ML-89, ML-90 (Östlund et al. 1965), ML-153, ML-195, ML-196 (Harrison et al. 1965). New York: L-562, L-617 (Olson & Broecker 1961), C-943 (Libby 1954), L-606A (Newman & Fairbridge 1962, quoted by Redfield & Rubin 1962), L-863A, I-2076 (Redfield 1967). California: LJ-333, LJ-381, LJ-607, LJ-912, LJ-918, LJ-919 (Hubbs et al. 1965). Texas: W-228, W-229 (Rubin & Suess 1956). Florida: FSU-33 (Stipp et al. 1966). Hawaii Islands: LJ-753 (Hubbs et al. 1965).

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[1]) For various reasons the author was not able to consult all of the literature concerning this problem.

From off the coast of the United Kingdom are derived the samples: Q-134, Q-181 (GODWIN & WILLIS 1959), Q-31, Q-265, Q-401 (GODWIN & WILLIS 1961), Q-663 (GODWIN & WILLIS 1964). Q-790, Q-791, Q-792, Q-793, Q-810, Q-811 (GODWIN et al. 1965). From the North Sea bottom is the sample Q-105 (GODWIN & WILLIS 1959).

The radiocarbon samples derived from Bahamas and Bermuda Islands are: LJ-228, LJ-229, LJ-230 (HUBBS et al. 1962), PIC-15, PIC-16 (KOWALSKI & SCHRODT 1966), L-366B, L-366I (BROECKER & KULP 1957), L-111A (KULP 1952), L-140B (KULP et al. 1952), ML-186, I-1683, I-1684, I-1685, I-1689, I-1762, I-1763, I-1764, I-1765, I-1969, I-1971, I-1972, I-1973, I-1974, I-1975, I-1976 (REDFIELD 1967).

From Australia and New Zealand are the samples: NZ-118, NZ-119, NZ-127, NZ-274, NZ-275, NZ-276, NZ-281, NZ-282 (GRANT-TAYLOR & RAFTER 1963), V-32 (BERMINGHAM 1966), W-95 (SUESS 1954).

Few radiocarbon samples are derived from other parts of the world. Mexico: LJ-568A, LJ-568B (HUBBS et al. 1965), O—45 (BRANNON et al. 1957). Eniwetok Island: L-482A, L-482B i L-482C (OLSON & BROECKER 1961). Gulf of Paria: 86 and 536 (DE VRIES & BARENDSEN 1954). Persian Gulf: Q-278 (GODWIN & WILLIS 1959). British Guiana: Without a laboratory number (VAN DER HAMMEN, quoted by EMERY & GARRISON 1967).

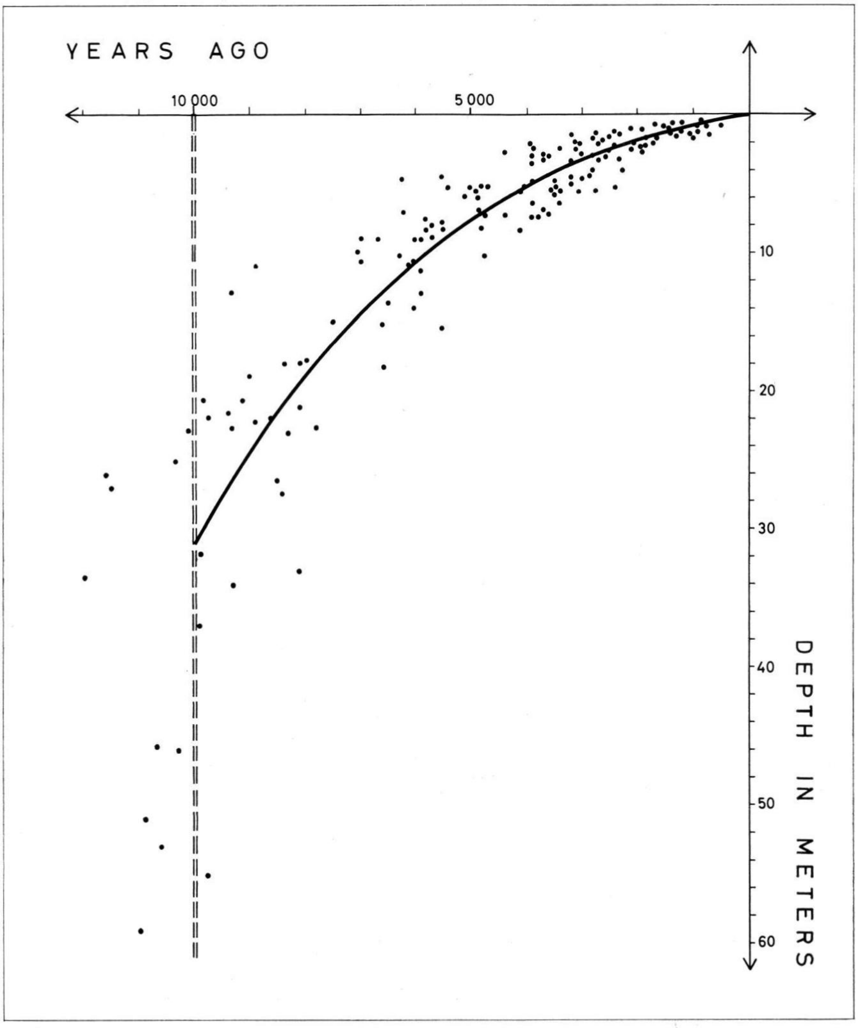

Fig. 1. The position of 147 radiocarbon samples from all over the world, and the curve (parabola) representing the Holocene sealevel rise.

The set of 147 radiocarbon samples is shown by a scatter diagram (fig. 1), from which the nature of the relationship between variables can be easily seen. The Holocene sealevel rise may be described by an arc of a third degree parabola. In such case three parameters *a*, *b* and *c* are to be determined by C. F. Gauss' method of the least squares.

The desired equation of a parabola representing the Holocene rise of the sealevel (fig. 1) is

$$y = 0.015\,208\,x^3 - 0.085\,641\,x^2 + 0.722\,466\,x. \qquad (1)$$

If we insert in the equation (1) the values for x = —1, —2, . . . , —10 (i. e. 1,000, 2,000, ... , 10,000 years ago) we find the position of the sealevel in the corresponding years (tab. 1).

In this case special attention must be paid to the last value: 10,000 years ago, i. e. at the end of the last glacial stage, or at the beginning of the Holocene, the sealevel was 30.99 m. (or roundly 31 m.) lower than today.

Tab. 1
The positions of the Holocene sealevel (in meters)

Years Before Present	1,000	2,000	3,000	4,000	5,000
Sealevel Positions	—0,82	—1,91	—3,35	—5,23	—7,65
Years Before Present	6,000	7,000	8,000	9,000	10,000
Sealevel Positions	—10,70	—14,47	—19,05	—24,53	—30,99

It is interesting to point out that our curve representing the Holocene sealevel rising does not agree with the hypothesis of a positive sealevel stand during the postglacial climatic optimum.

Lastly, upon the hypothesis that the rise in sealevel will continue to increase according to the above described trend, we may estimate the maximum position of the sealevel in the future (i. e. the maximum stand in the Holocene). Since the function representing the Holocene sealevel rise and expressed by the equation (1) is an odd function, its point of inflection at the same time should represent the highest Holocene sealevel position in the future. As is known, at the point of inflection the second derivative of the function at this point is equal to zero. The equation of our function is

$$y = 0.015\,208\,x^3 - 0.085\,641\,x^2 + 0.722\,466\,x.$$

First derivative

$$\frac{dx}{dy} = 0.045\,624\,x^2 - 0.171\,282\,x + 0.722\,466.$$

Second derivative

$$\frac{d^2y}{dx^2} = 0.091\,248\,x - 0.171\,282.$$

Equating $\frac{d^2y}{dx^2} = 0$ and solving this equation gives x = 1.9. Accordingly, x = 1.9 is the abscissa of the point of inflection. When x = 1.9 is inserted in the above equation we find y = 1.17. Supposing our assumptions to be correct we arrive at the conclusion that the sealevel will continue to rise in the next 1,900 years, when its position will be 1.17 m. higher than now.

C. Positions of Sealevel in the Late Würm

In Pleistocene research a certain practical meaning (land and sea distribution, the migrations of plants, animals and men) depends on the fact that the sealevel in the Late Würm was lower than in the Holocene. However, there are not enough radiocarbon data from tectonically stable regions of the world to calculate directly the positions of the sealevel by means of the least-squares method (as in the previous case). We shall try to solve this problem indirectly by a simple method. It is a well-known fact that by far the greatest number of sea-bottom radiocarbon samples are derived from Mississippi delta sediments. The trouble is that the Mississippi delta is constantly subsiding (compaction plus tectonic sinking). Our curve (fig. 1) which is based upon sufficient data from more or less stable regions should be a standard against which values and rates of tectonic (plus compaction) movements might be measured, namely, since the eustatic component is the same in all parts of the world, differences in relative change in sealevel at different localities indicate local differences in the tectonic component.

To calculate the Holocene and the Late Würm sealevel positions we selected 37 radiocarbon samples (fig. 2) from the Mississippi delta. This is only a part of a great number of radiocarbon samples which is at our disposition; many samples have no computational value due to lack of a precisely determined time component (e.g. older than 30,000 years, or the like). A certain number of radiocarbon samples have been disregarded because they depart too widely from the general trend.

We selected next samples: L-125A, L-125G (Kulp et al. 1952), L-175B, L-175C, L-175D, L-175E, L-175F (Broecker et al. 1956), O-7A, O-62, O-64, O-72, O-73, O-86, O-87, O-94, O-99, O-100, O-101, O-107, O-111, O-112, O-114, O-115, O-117, O-119, O-126, O-141 (Brannon et al. 1957), L-291A, L-291B, L-291G, L-291H, L-291K, L-291L, L-291-N, L-291T, L-291U, L-291X (Broecker & Kulp 1957).

The way to calculate the curve is exactly the same as in the previous case; the difference is only in the position of the empirical points. We believe that the best fitting curve for the empirical data is a cubic paraboda (polynomial of the third degree).

The desired curve representing the Holocene and the Late Würm rise of the sealavel is

$$Y = -0.012\,82\,x^3 - 0.499\,30\,x^2 + 0.544\,62\,x. \qquad (2)$$

When values for $x = -1, -2, \ldots, -34$ are substituted in the above equation (2) we obtain the positions of the sealevel 1,000, 2,000, ... , 34,000 years ago (tab. 2).

The enormous thickness of the Quaternary Mississippi deltaic sediments leads us to the conclusion that the tectonic subsidence of the delta is not a temporary but a lasting Quaternary process. In spite of the fact that the sinking of the delta is not so simple as previously believed, we conclude that the Late Würm and the Holocene subsidence is only a continuation of a much older sinking. Since it is not possible to calculate directly the tectonic component from the radiocarbon data, we shall suppose that the tectonic subsidence was a linear process, at least in last 34,000 years. Assuming that this is correct we shall construct the world sealevel positions during the Late Würm solely on the base of the Mississippi delta data. The mathematical way to do this is extremely simple. The eustatic curve representing the positions of the world sealevel has been plotted by the elimination of the subsidence component from the curve representing sealevel positions in the Mississippi gelta. If one compares the Holocene sealevel positions of the world sea with the curve derived by the data from the Mississippi delta (fig. 2) it is clear that the subsidence is responsible for the systematically lower position of the Mississippi curve. In the last 10,000 years the Mississippi delta has sunk 11.57 m. (42.56 — 30.99 = 11.57), or on average 1.157 m. per 1,000 years. Now it is clear that we have been right not to take the Mississippi data for the calculation of the curve representing sealevel positions in the Holocene as some authors did. These values will be used for the extrapolation of the positions of world sealevel in Late Würm by this simple method: the product of multiplication of 1.157 by the number of years one must subtract from the Mississippi data. So we eliminate the subsidence component, and the result is the "pure" glacio-eustatic component (tab. 3).

Tab. 2

The Holocene and the Late Würm positions of the sealevel (in meters) derived by the radiocarbon data from Mississippi delta

Years Before Present	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000
Sealevel Positions	—1,03	—2,98	—5,78	—9,35	—13,60	—18,47	—23,88	—29,75	—35,99
Years Before Present	10,000	11,000	12,000	13,000	14,000	15,000	16,000	17,000	18,000
Sealevel Positions	—42,56	—49,34	—56,28	—63,60	—70,31	—77,24	—84,02	—90,57	—96,81
Years Before Present	19,000	20,000	21,000	22,000	23,000	24,000	25,000	26,000	27,000
Sealevel Positions	—102,66	—108,05	—112,90	—117,14	—120,68	—123,44	—125,37	—126,36	—126,35
Years Before Present	28,000	29,000	30,000	31,000	32,000	33,000	34,000	—	—
Sealevel Positions	—125,28	—123,04	—119,57	—114,79	—108,63	—101,00	—91,83	—	—

Tab. 3

The Late Würm sealevel positions (the continuation of tab. 1)

Years Before Present	11,000	12,000	13,000	14,000	15,000	16,000	17,000	18,000	19,000
Sealevel Positions	—36,6	—42,4	—48,3	—54,1	—59,8	—65,5	—70,9	—76,0	—80,7
Years Before Present	20,000	21,000	22,000	23,000	24,000	25,000	26,000	27,000	—
Sealevel Positions	—84,9	—88,6	—91,7	—94,1	—95,7	—96,4	—96,3	—96,1	—

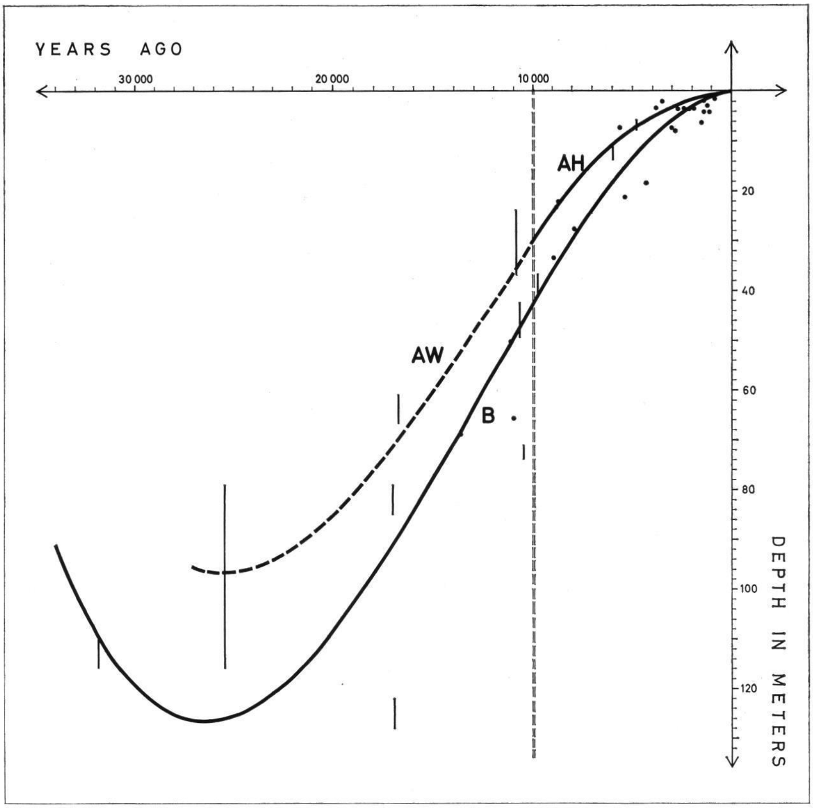

Fig. 2. The positions of 37 radiocarbon samples from the Mississippi delta area. B, the positions of the Holocene and the Late Würm sealevel which were calculated solely by the data from Mississippi delta. AH, the Holocene sealevel positions (see fig. 1). AW, the Late Würm sealevel positions calculated from Mississippi radiocarbon data eliminating the effect of the delta subsidence. AW + AH, the sealavel positions in the last 27,000 years.

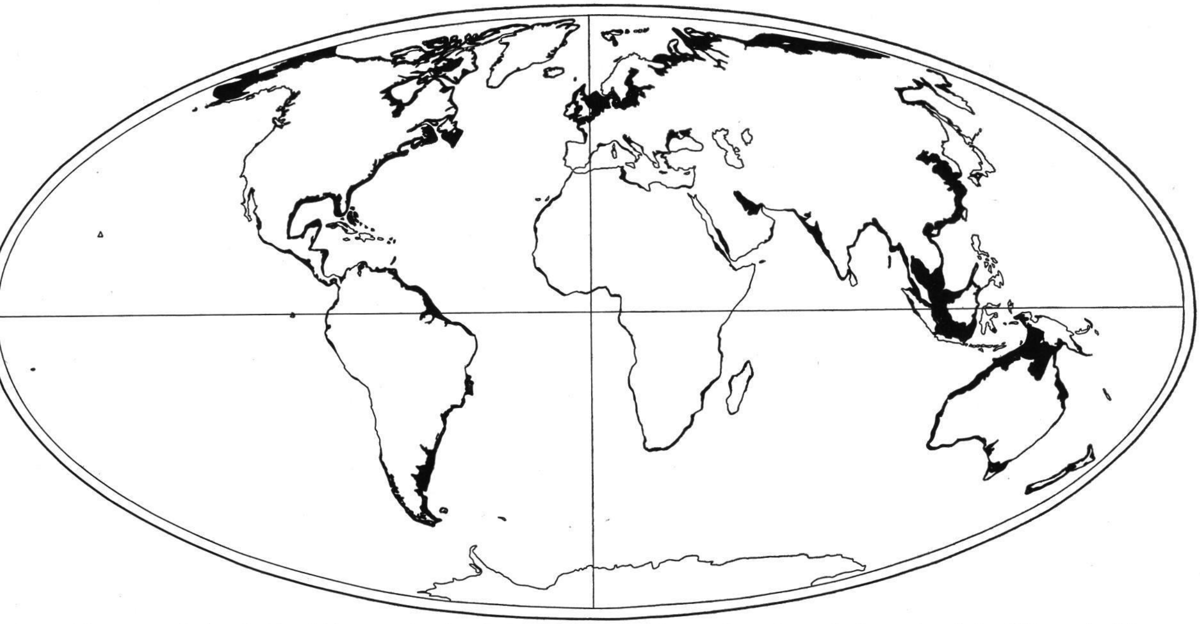

Fig. 3. The part of the shelf which was dry land during the maximum lowering of the sealevel in Würm glacial stage.

In Pleistocene research special attention is paid to the lowest position of the sealevel during the last glacial stage. If our assumptions are correct we arrive at the next conclusion: the lowest position of the sea during the last glacial stage was at —96.4 m. It seems that this result is not in serious conflict with our recent knowledge. The majority of the most reliable data vary between 80 and 120 m.

In spite of the known fact that the coasts in many parts of the world are not stable, we have drawn the map of the world (fig. 3) representing the surface of the shelf which was dry land (or buried by the ice) during the maximum lowering of the sealevel in the last glacial stage. Namely, isostatic uplift as the most important disturbing factor was confined to the areas which were warped by the ice load, i. e. its influence was confined to the glaciated areas. In other parts of the world tectonic instability was the most important disturbing factor but in the majority of cases it was spatialy confined to smaller areas. Finally, it is not possible to show all details on this scale. This map is only the first step in the mapping of this important paleogeographical problem, and — quite naturally — will be corrected in the future in accordance with the progress of research.

At the end, it is important to note one fact which is substantial for the theory of the Quaternary glaciation, but we shall not go deeply into the details. Namely, the lowest position of the sealevel during the Würm glacial stage was attained much earlier that the temperature drop to the lowest point. According to our calculations, the maximum sealevel lowering was attained 25,000 years ago, but the majority of recent data clearly indicate that the maximum cold was attained about 20,000 years ago (systematic review Šegota 1963, p. 96). From this it is clear that the volume of the ice on the Earth was not in a simple relation to the temperature as was previously believed. The maximum volume of the ice on the Earth during the last glacial stage was attained 25,000 years ago. As an automatic response, the sealevel had fallen in the same year to the lowest point (—96.4 m.). This was the turning point in the history of the Würm glacial stage, marking the beginning of the phase of progressive and rapid reduction of the ice on the Earth. The immediate effect was a rise of the sealevel in the last 25,000 years in spite of a temporary continuation and even a worsening of the cold in the next 5,000 years. Accordingly, the greater part (2/3) of the ice which was accumulated on the Earth in the Early and Middle Würm glacial stage (and at the end of Riss/Würm interglacial stage?) was melted away during this same glacial stage, and only 1/3 of the ice returned to the sea in the Holocene. The last glacial stage was at the same time the "deglacial" stage! Having all this in mind, it is not correct to say that the ice was melted away in the postglacial period; this is only partly true.

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Manuscript received on 19. 9. 1968.

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