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Variations of the vertical stability in the Northern Baltic

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The deep basins of the Baltic are characterized mainly by three different layers. The less saline water extends from the surface to a depth of about 50 to 70 metres. Below this layer there is a sharp discontinuity in the density gradient, which exists all the year round and is called the permanent or primary halocline. At greater depth, varying, say, between 110 and 130 metres, there is a less pronounced layer of discontinuity, the secondary halocline.

Vertical variations of salinity in the layer above the primary halocline are not great enough to prevent the thermal convection. Therefore, the upper layer can be considered homogeneous during the autumn convection period, and deviations from homogenity caused by the influence of runoff and heat, are small even in the summer period.

When the salinity data are plotted against the logarithm of the depth, the curve obtained is linear down to the depth of the primary halocline, as was shown by Hela (1966). If the depth at lower layers is given as the vertical distance calculated from the preceeding halocline downwards, new linear graphs are obtained for the relation between the salinity and the logarithm of the depth. The depths of the primary and the secondary haloclines can be estimated graphically from the intersections of the first mentioned plots.

As might be expected, when salinity is replaced by density, all the three layers display linear correlations between density and the logarithm of depth (Fig. 1.) This relation can be expressed as follows:

(1) $$\sigma_z = \sigma_i^0 + k_i \ln z$$

where σ_z is the value of σ_t at the depth z measured from the surface (or from the preceeding halocline) and σ_i^o that at the surface (or at the halocline), respectively. k_i is the characteristic constant of stratification and we call it the stratification coefficient.

While the logarithmic function is found to be valid for each layer found in the Northern Baltic Sea, we must keep in mind, that the density gradient cannot be strictly discontinuous. The relatively independent dynamics prevailing in the different layers cause at the boundary layers, i.e. at haloclines, a stress which results in diffusion through the halocline. Therefore the perfect discontinuity at the halocline and the properties of the above equation become somewhat indefinite.

When we determined the values of σ_i from a graph representing the data for the layer between the primary and the secondary halocline and used the values obtained for the parameters k_i and σ_i^o for the calculation of the value of sigma-t at the depth of the primary halocline, z'+1, the latter value was sometimes slightly smaller and sometimes slightly greater than the former value. Therefore, it is necessary to introduce in the equation (1) an additional parameter, $z^{x}_{i-1,i}$, which indicates the limits of the validity of the equation, which then reads as follows:

$$\sigma_z = \sigma_i^o + k_i \ln \frac{z}{z^*_{i-1,i}}$$

The values of z^{x} have been determined in the following way (for the primary halocline): The extrapolated value for σ_t is, when calculated from the parameters of the layer 1

$$\sigma_{z'+1} = \sigma_1^o + k_1 \ln (z'+1)$$

while the corresponding value at the same depth (one metre below the halocline) using the parameters for the layer 2 will be

$$\sigma_1 = \sigma_2^o - k_2 \ln z^*_{1,2}$$

Since the left sides of these two equations are equal, the value of z^* determines the differences in the observed values. The procedure is presented graphically in Fig. 2. As can be seen in the graph, there is an uncertainty in the determination of $k_2 \ln z^*_{1,2}$ because of the use of $z = z'+1$. In the case of the permanent halocline this error is much smaller than that caused by inaccuracies in the determination of salinity and depth because of the low stability just above the halocline (see eq.(3)). In addition, close to the secondary halocline the number of depths used for the determination of z^* was limited to the standard depths only. As the discrepancy arises in third or fourth significant number of sigma-t this uncertainty has been ignored.

The derivation of eq. (1) with respect of depth yields, as z^* is constant,

$$\frac{d\sigma_t}{dz} = \frac{k_i}{z} \tag{2}$$

Since the quantity used in oceanography for stability has been defined as follows:

$$E = \frac{1}{\rho} \cdot \frac{d\sigma_t}{dz} \simeq \frac{d\sigma_t}{dz}$$

we may simply connect the above equations and obtain for stability a simple relation

$$E = \frac{k_i}{z} \tag{3}$$

where again z is calculated from the surface or from the preceding halocline. On the basis of the above relation the stratification coefficient, k_1, and the vertical distance from the surface (or from a halocline) determine the stability within the layer, but values at the boundaries between the different layers remain undetermined. We may consider the distance from halocline z' to z^*, a thickness parameter of the transition layer.

The calculated values of the parameters z^*_i and k_i are given in the Table 1. It can be seen from Fig. 3, that the parameter $z^*_{1,2}$ is dependent on k_2. A clear positive correlation with the correlation coefficient r = 0.746 was obtained. On the other hand, when k_3 and $z^x_{2,3}$ are plotted analogously, no clear correlation can be found (Fig.4), which might be explained in two ways: first, no real correlation exists; the high random correlation depends on errors in the determination of halocline depths, secondly there is a real correlation, which can be seen only when the boundary between the two layers is distinct enough. The reason for the latter assumption can be easily understood when looking for example at the curve in a year when the boundary is very diffuse.

The fact that in the primary halocline a linear correlation is found between the stratification coefficient and the thickness parameter may indicate, that the limiting value of stability in normal sea conditions remains below a certain critical value. At the station F 81 the maximum stability value $E = k_2/z^x_{1,2}$ varied between 0.83 and $5.2\sigma_t$-units per metre. As the estimates are based on samples taken at 10 m. intervals, a closer study of the limits of this variation must be left aside. It must further be remembered, that most of the observations are made during the summer, when the uppermost layer is more stratified than in autumn and winter.

In the studies of ocean thermocline erosion Grant er al. (2) have obtained similar types of density profiles. Also some temperature profiles in lakes studied by one of us (PM) have the same characteristics: a decreasing stability down to the thermocline, followed by a sharp transition layer and again logarithmic decrease below the transition layer. Throughout the Baltic Sea similar patterns of vertical density are found in records from the southern Gulf of Bothnia through Bornholm Deep, except in coastal regions.

The occurrence of the same density pattern in such different aquatic environments, as lakes, stratified brackish water and open ocean, may reflect a more prevailing feature of the general circulation. The dynamical analysis is at the present time not possible, however, because of the lack of proper observations.

On the other side, the study of the changes of these parameters may give us some information on the details of the circulation in the different layers. For example we consider the changes of k_3 and σ_3^o in time. If both parameters are increasing, it is a clear sign of a total renewal of water in the layer 3. If σ_3^o does not increase with an increasing stratification coefficient, the inflow of new water is limited to the deepest part of the layer 3, and does not reach the secondary halocline. Further, when the stratification coefficient increases with a decreasing σ_3^o, mixing penetrates the secondary halocline. This process probably gains its energy from currents above the secondary halocline. The inflow of new water is not essential.

Considering the cases when the stratification coefficient remains unchanged, we may assume that an unchanged value of σ_3^o corresponds to a "complete" stagnation. A decreasing value of σ_3^o cannot indicate a renewal of water, since the new water mass would be lighter than the old one. This could be a sign of vertical mixing through the halocline.

A decreasing stratification coefficient with an increasing value of σ_3^o points out vertical homogenisation. Finally, a decreasing value of k_3 with a decreasing or unchanged value of σ_3^o is a sign of vertical mixing through the secondary halocline, while it may be destroyed.

The thickness parameter of the halocline may also be used, when analysing the circulation. A decreasing value of z^x points out to strong advective movements, while an increasing value is probably connected with vertical diffusion.

In addition to the above considerations, data from the Finnish cruises of the years 1924-69 are studied. The parameters evaluated on the basis of the data from station F 81, Gotland Deep, are given in Table 1 and plotted in Fig. 5.

The possible mechanisms, which have resulted in the changes of values of these parameters, are shortly discussed below.

1924 - 26 Both haloclines remain practically at constant depths. k_2 decreases and σ_2^0 does not change, while k_3 increases and σ_3^0 decreases. This indicates some exchange of matter through the secondary halocline. However, no detailed conclusions can be made due to missing data for 1925.

1926 - 27 Both haloclines remain practically at constant depths. k_2 increases considerably and σ_2^0 decreases sligthly, while k_3 decreases and σ_3^0 increases. These changes probably indicate an inflow of new water to the lowest part of the intermediate layer, which has induced mixing inside and below the secondary halocline. At the same time the value of $z^{x}_{2,3}$ has increased, i.e. the secondary halocline has become more diffuse.

1927 - 28 k_2, σ_2^0 and k_3 decrease slightly, while σ_3^0 and the depths of both haloclines do not change significantly. A rather quiet period during which slow exchange of matter through both the haloclines have occurred and the energy is perhaps gained from the internal waves (?).

1928 - 29 A great decrease of k_2 without any significant change of σ_2^0. k_3 increases and σ_3^0 decreases. The secondary halocline sinks and both haloclines get sharper. These changes indicate considerable movements in the intermediate layer, which result in some erosion of the upper part of the layer 3. Since the depth of the primary halocline does not change, the increase of σ_1^0 and the decrease of k_1 point out to an exchange of matter through the primary halocline. Therefore it seems possible that the main energy source for the changes in the lower layer has been the kinetic energy of the layer 1. (Winds?).

1929 - 30 All quantities remain practically unchanged in the layer 3. In the intermediate layer, however, considerable changes take place. The primary halocline sinks and gets somewhat more diffused, while k_2 increases without any significant change of σ_2^0. All this indicates the influence of the layer 1 on the intermediate layer. This influence has not reached the lowest layer, as can be confirmed by the small oxygen content of the water near the bottom. The exceptional restlessness of the surface layer is indirectly shown by the minimum ice cover observed during the winter 1929-30 (Jurva, 1944).

1930 - 31. There are no significant changes of the parameters for the intermediate layer, except for a slight sinking of the primary halocline and a considerable rise of the secondary halocline. The latter change is connected with a small increase of k_3 and a small decrease of σ_3^0. All these changes point out to a slow mixing through the secondary halocline without any significant inflow. The recorded existence of hydrogen sulfide in the bottom water agrees with this assumption.

The most pronounced changes in the whole water column take place in the layer 1, as seen from the great increase of σ_1^0 connected with the decrease of k_1. As described by Hela (1944), the maximum changes in the sea level during 1926-35 were observed in the late autumn 1930. Since no significant inflow of new water in the two lower layers can be traced, the main source of energy causing mixing in the whole water column is probably gained from the movements in layer 1.

1931 - 32 The decrease of σ_3^0, while k_3 remains unchanged, indicates slow mixing through the secondary halocline, which could be caused by an inflow into the layer 2, since k_2 and σ_2^0 increase slightly. However, these increases are perhaps not great enough to be significant. A more detailed analysis of the original hydrographic data and the increase of $z^{*}_{1,2}$ rather point to some vertical exchange. Again the energy source must be sought from the mobility of layer 1.

1932 - 33 The vertical mixing through the secondary halocline continues (k_2 decrease, σ_3^0 and $z^{*}_{2,3}$ do not change, the secondary halocline sinks). No pronounced changes of the parameters for layer 2 are observed. It is difficult to explain why new cold water, rich in oxygen, has appeared in the bottom layer, since the density differences are negligible except for the values in the layer between 70 and 90 metres, where some increases of salinity were found.

1933 - 34 All parameters for layers 2 and 3 increase including the depths of both haloclines, which indicates powerful inflows in both layers mentioned.

1934 - 35 Decrease in all parameters excluding σ_2^0, which increases. The changes of σ_3^0 and σ_2^0 are connected with the rise of secondary halocline and the sinking of the primary halocline, respectively. New water masses have penetrated into the layers 2 and 3, especially at the upper part of the layer 3, as can be seen from the sharpening of the two boundaries ($z^x_{1,2}$ and $z^x_{2,3}$ decrease). A proof for these inflows is found when considering the original data for temperature and salinity.

1938 - 39 All parameters for the layers 2 and 3 increase, while the secondary halocline sinks and the primary halocline remains at a constant depth. This indicates powerful inflows in both lower layers. The increases of salinity both at 100 m. and at 200 m. were some 0.3 o/oo.

1954 - 68 Since 1954 the most pronounced feature was the rapid increase of the stability coefficient to a level, which has never been observed earlier. The subsequent slow decrease (1960-65) created conditions favourable to the intrusion of new water into the bottom layer by the end of that decade. There is also a clear elevation of the level of σ_3^0 indicating the well known increase in the salinity.

1969 - 70 During this period new water with oxygen appeared in the Gotland Deep. The great increase of ${}_3^0$ with decreasing value of k_3 points out, that the major inflow took place in the boundary between layers 2 and 3. In agreement with this assumption the value of $z^x_{2,3}$ is unusually great.

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3. JURVA, Risto 1944: über den Verlauf des Eiswinters in den Meeren Finnlands. Sber. finn. Akad. Wiss. 1941. Helsinki 1944.
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TABLE 1 k is the stability coefficient, σ^o density at the upper boundary z^* thickness parameter of the halocline, z' depth of the halocline. Indices 1,2 and 3 refer to the layers above the primary halocline, between the two haloclines and below the secondary halocline, respectively.

Year	k_1	σ_1^o	k_2	σ_2^o	$z^*_{1,2}$	$z'_{1,2}$	$\Delta z'_2$	k_3	σ_3^o	$z^*_{2,3}$	$z'_{2,3}$	$\Delta z'_3$	$\bar{\sigma}_{o-200}$
1924	0.39	5.37	1.70	6.07	1.35	63		0.64	8.82	1.45	119		8.07
26	0.61	4.92	1.55	6.03	1.30	65	+ 2	0.76	8.50	1.85	115	- 4	7.84
27	0.97	4.21	2.21	5.97	2.35	65	0	0.60	8.95	4.65	118	+ 3	7.80
28	0.82	4.33	2.05	5.81	1.40	63	- 2	0.53	9.05	5.40	115	- 3	7.85
29	0.50	4.85	1.12	5.85	0.25	63	0	0.64	8.47	1.85	120	+ 5	8.20
1930	0.81	4.30	1.63	5.81	1.05	73	+10	0.64	8.54	2.80	122	+ 2	7.55
31	0.21	5.40	1.59	5.80	0.75	77	+ 4	0.78	8.43	5.95	110	-12	7.57
32	0.84	4.31	1.62	5.89	1.95	74	- 3	0.78	8.04	2.10	115	+ 5	7.34
33	0.66	4.61	1.33	5.83	1.20	70	- 4	0.61	8.00	0.85	120	+ 5	7.35
34	0.93	4.19	1.98	5.92	1.90	72	+ 2	0.85	8.88	11.70	130	+10	7.50
35	1.55	3.15	1.06	6.08	0.25	77	+ 5	0.55	8.37	0.80	115	-15	7.51
38	0.09	5.60	1.23	5.76	0.25	64		0.82	8.56	4.25	110		7.85
39	1.60	3.06	2.33	6.04	2.55	71	+ 7	0.90	8.72	5.15	110	0	7.63
1954	0.55	5.22	2.03	6.25	1.05	75		0.66	9.60	3.65	120		8.28
55	0.58	5.39	1.44	6.45	0.35	68	- 7	0.77	9.48	3.00	110	-10	8.60
56	0.63	5.23	1.33	6.34	0.35	72	+ 4	1.15	9.37	7.40	130	+20	8.23
58	0.50	5.31	1.83	6.23	1.70	68	- 4	1.15	8.89	5.15	115	-15	8.10
59	0.71	4.88	1.75	6.21	1.95	75	+ 7	1.03	8.69	2.50	125	+10	7.85
1960	0.85	4.70	2.00	6.24	2.10	64	-11	0.99	9.08	6.70	118	- 7	8.08
61	0.41	5.25	2.11	5.97	1.55	57	- 7	0.90	9.23	6.30	110	- 8	8.29
62	0.65	5.01	1.55	6.24	0.70	76	+19	0.79	8.99	3.20	115	+ 5	8.09
63	0.90	4.77	1.65	6.41	1.70	65	- 9	0.86	8.82	2.20	115	0	8.24
64	0.85	4.73	1.64	6.28	1.10	66	+ 1	0.74	8.91	2.00	110	- 5	8.24
65	0.69	4.90	1.93	6.17	0.75	68	+ 2	0.64	9.18	2.30	110	0	8.36
66	0.64	5.10	2.00	6.29	1.30	72	+ 4	0.61	9.31	4.05	120	+10	8.26
67	0.86	4.77	1.40	6.25	0.50	52	-20	0.64	9.20	2.35	115	- 5	8.54
68	0.62	5.05	1.65	6.18	0.95	65	+13	0.63	9.09	2.55	120	+ 5	8.23
69	0.71	4.95	1.91	6.21	1.90	59	- 6	0.70	9.00	3.00	113	- 7	8.38
70	0.73	5.12	1.72	6.47	0.85	70	+11	0.57	9.67	9.95	130	+27	8.30

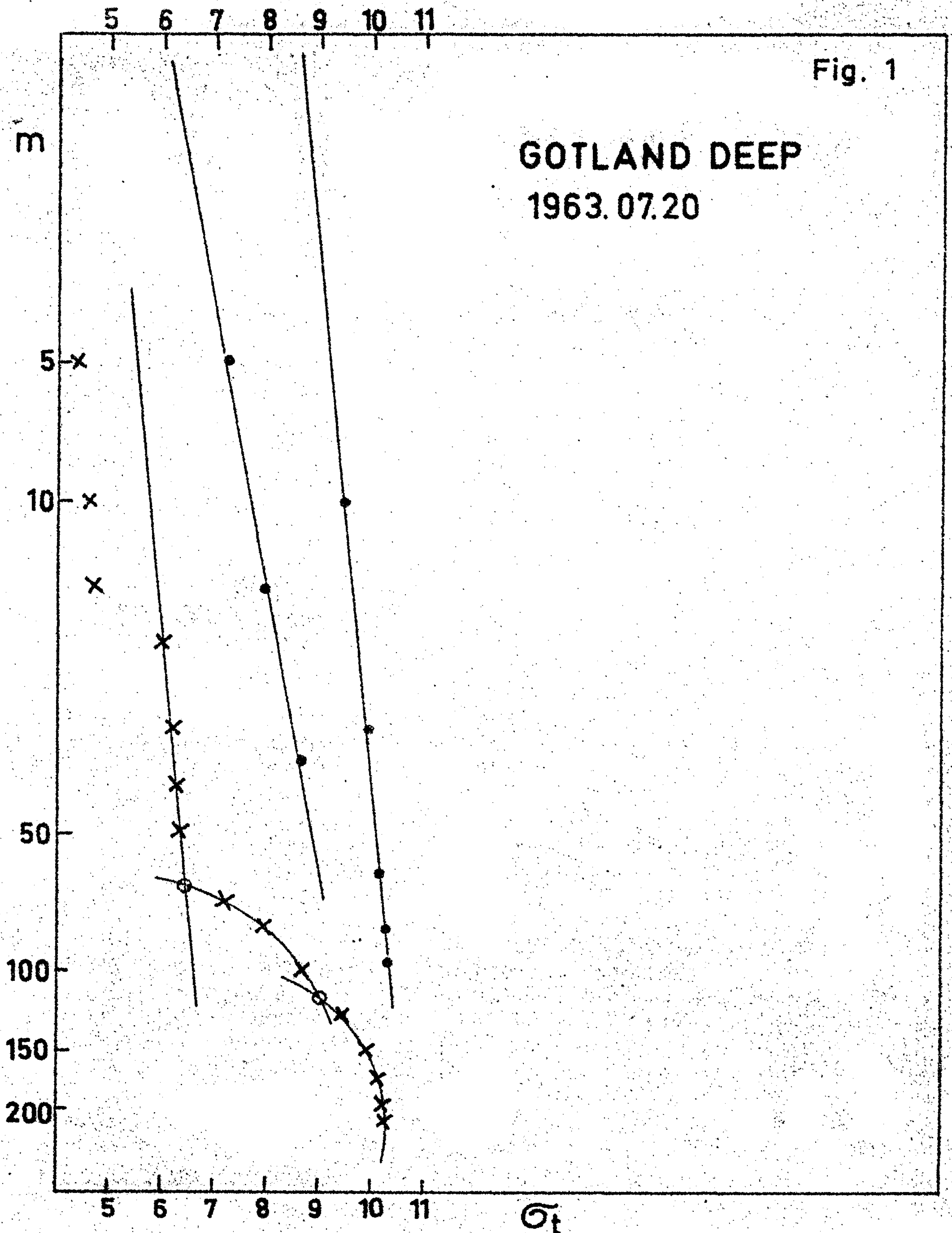


Fig. 1

GOTLAND DEEP
1963.07.20

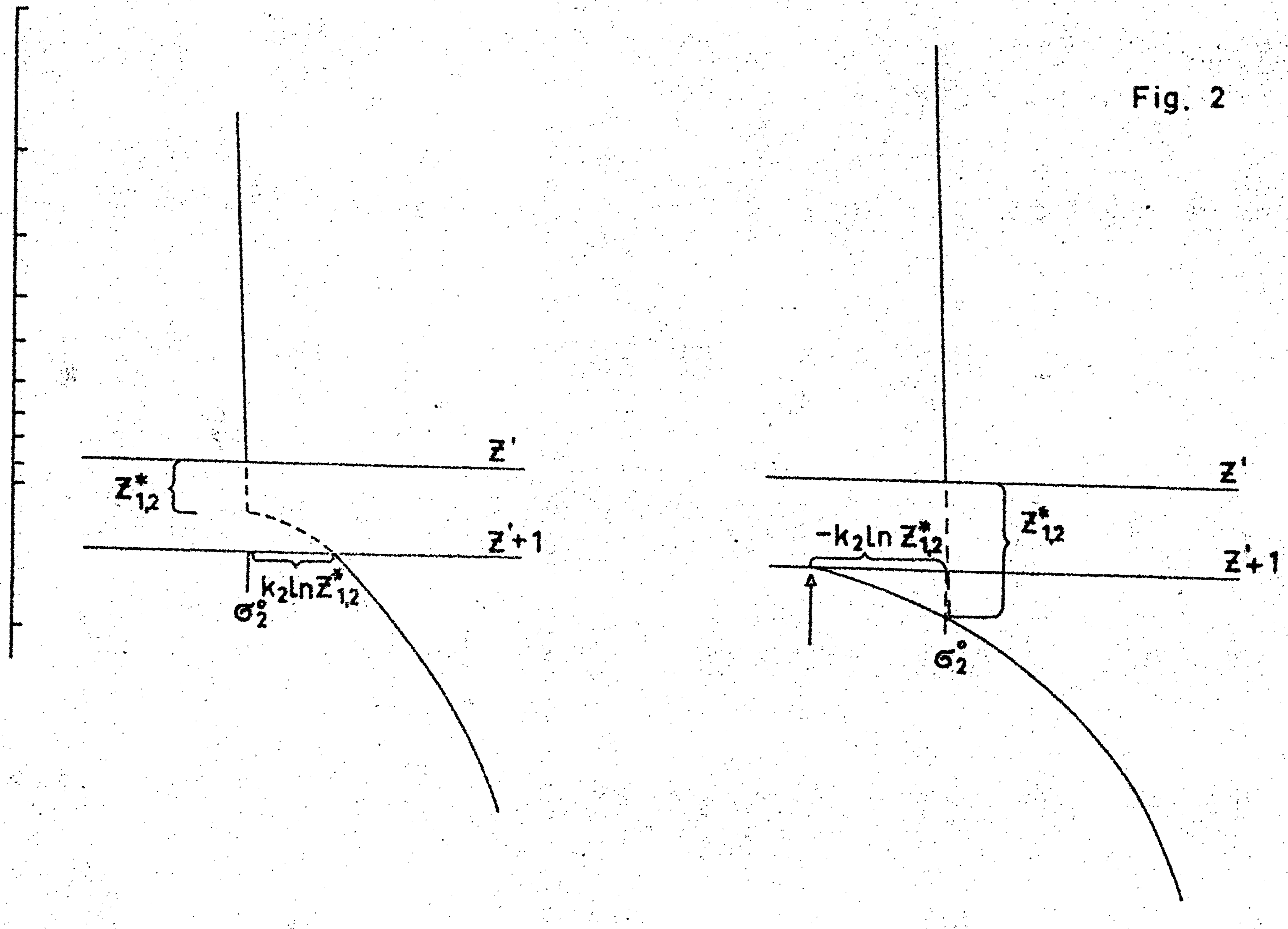


Fig. 2

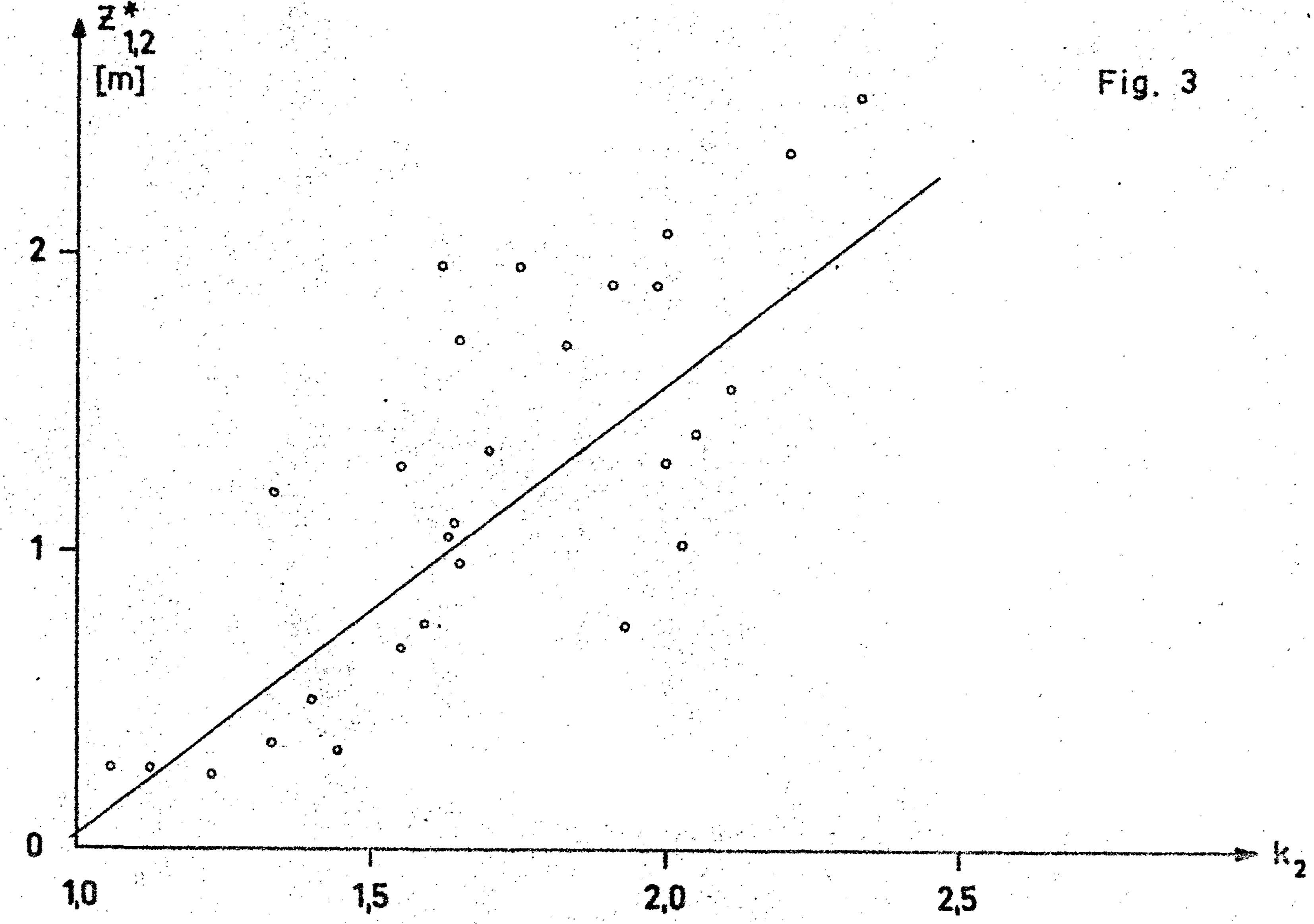


Fig. 3

Fig. 4

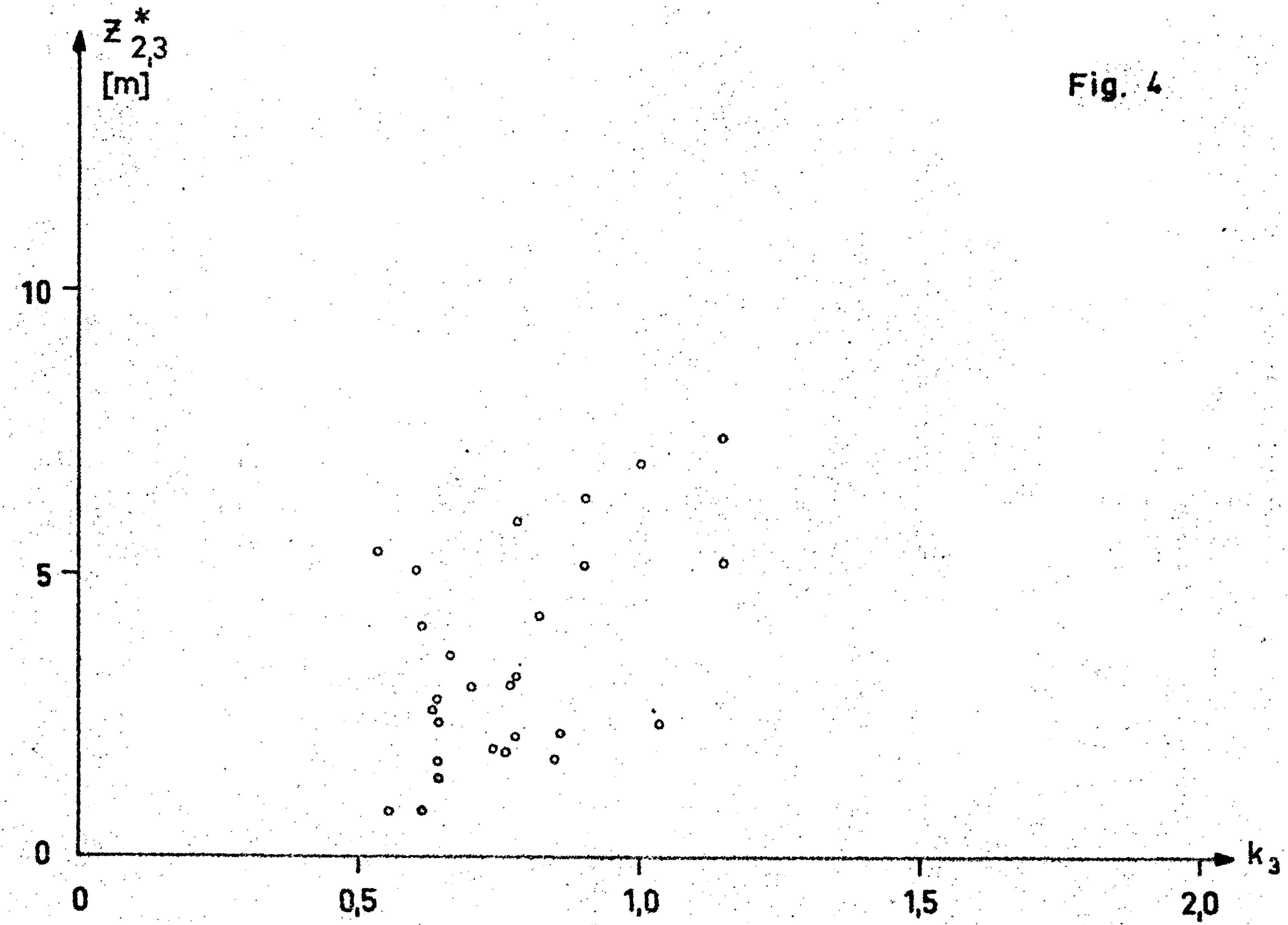
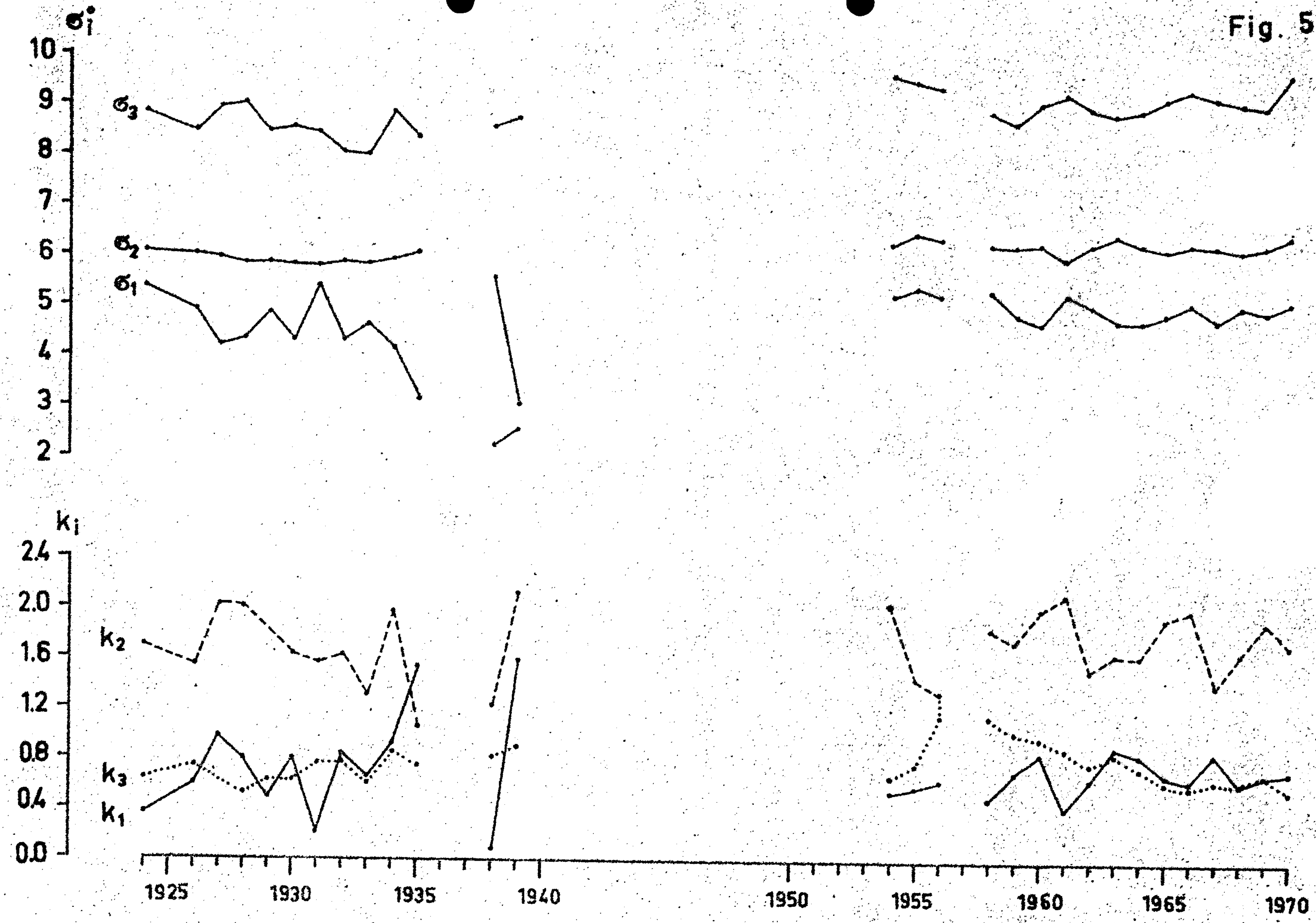
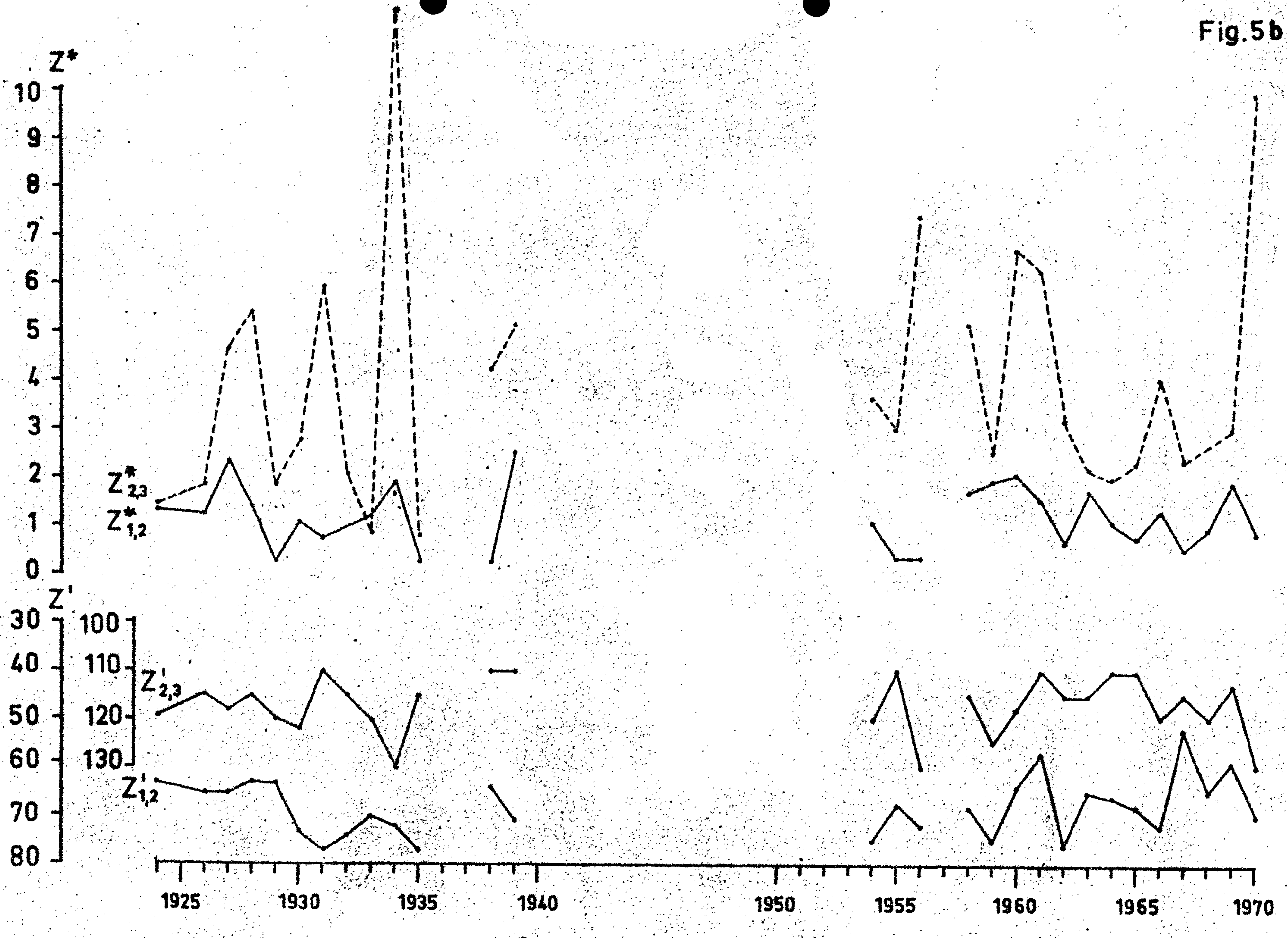


Fig. 5a



σ_i°
10
9
8
7
6
5
4
3
2
σ_3
σ_2
σ_1
k_i
2.4
2.0
1.6
1.2
0.8
0.4
0.0
k_2
k_3
k_1
1925
1930
1935
1940
1950
1955
1960
1965
1970

Fig.5b


Z^*
10
9
8
7
6
5
4
3
2
1
0
$Z^*_{2,3}$
$Z^*_{1,2}$
Z'
30
40
50
60
70
80
100
110
120
130
$Z'_{2,3}$
$Z'_{1,2}$
1925
1930
1935
1940
1950
1955
1960
1965
1970