THE STRATOSPHERE AND THE TROPOSPHERE OF THE ATLANTIC OCEAN

by

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Within the last two years the schematic representation of the Atlantic Ocean Bottom Water by G. WÜST (1933) *, representation concerning which G. CASTENS (1934) contributed a report to this Review, has been followed by a very detailed study of the Stratosphere by G. WÜST (1935) and of the Troposphere by A. DEFANT (1936). This compilation is issued in two volumes, with numerous illustrations in colours and accompanied by a very fine Atlas (1936) of charts and sections in colours, the execution of which, in common with that of the two volumes of text and illustrations, is worth special consideration owing to the collaboration of the authors, of the publisher and of the *Notgemeinschaft*. From this it has become possible to form some idea of the solution of the most important problem confronting the *Meteor* Expedition, that of the circulation of the waters in the Atlantic Ocean; which question will now be discussed.

A. *THE STRATOSPHERE.*

(Treatise by G. WÜST; also contributions by A. DEFANT, O. v. SCHUBERT and others).

1. *Concept of Stratosphere and Troposphere.* — The terms "Stratosphere" and "Troposphere" as coined by A. DEFANT (1928) are, in reality, borrowed from meteorology, but do not convey exactly the same meaning as in that science. In the ocean, not only does the *troposphere,* warm and rich in salt, 300 to 800 metres in depth, lie *above* while the *stratosphere,* cold, lower in salinity and much deeper, lies *below,* i.e. exactly opposite to atmospheric conditions; but in the North and South, beyond the "polar front" which lies between the 40th and 60th degrees of latitude, the cold surface water in sinking forms a mixture with the stratosphere which thus reaches the surface and there, in contact with the atmosphere, becomes exposed to greater radiation, evaporation, precipitation, congealing, etc. This circumstance (DEFANT 1930) is decisive for the stratospherical circulation, which would almost completely cease if the stratosphere were covered in all latitudes by the troposphere. Owing to the fact that the sinking liquid masses seek their level in accordance with their specific gravities, the stratosphere assumes a stratified structure; the individual layers, however, do not lie everywhere at the same depth and that is why a chart of the temperature, salinity and density at a given level for instance, does not always allow the correlation of the different strata to be clearly recognised. For this reason WÜST places the examination of the charts (also given in the Atlas) at the end, and not at the beginning. He also renounces for the moment the dynamic method of BJERKNES, doubtless because the forces are often too small in relation to the frictional disturbance. He elaborates rather a new method, which will be discussed, the *Kernschichtmethode,* (method of liquid control strata or core layers), which takes the properties of one kind of water as being distinctive of its origin and which, neglecting less important constituents, enables him to distinguish in the Atlantic stratosphere, five layers, namely:

1. — the intermediate subantarctic water (Zs), 2. — the upper North-Atlantic deep water (To), 3. — The middle North Atlantic deep water (Tm), 4. — The lower North Atlantic deep water (Tu) and 5. — antarctic bottom water (Bs).

2. *Intermediate Subantarctic Water, Zs :* Its principal characteristics are its low temperature (2.2°) and low salinity (33.80 ‰). The method of liquid control layers traces,

a) Its extent, by determining everywhere in the ocean the places occupied by a layer showing minimum salinity, and its depth (Fig. 1, Pl. 24). From the Southern "polar front", the line of convergence of the surface water which G.E.R. DEACON for instance, has reported

* *Year-dates refer to the bibliographical list given at the end of this article.*

on (Cf. this Review 1934a), the plane of minimum saline content falls rather rapidly in latitude 50° S. (approx.), to 900 metres, reascends towards the Equator to 800 metres, sometimes to 700 metres and less, and in the Northern hemisphere falls anew to more than 900 metres, finally to disappear about latitude 20° N.

b) Wüst analyses the change in the intermediate subantarctic water during its propagation, by investigating whether any relation exists between the temperature and the salinity along the liquid control layer. In fact, the temperature-salinity diagram, aside from slight discrepancies, plots as a straight line (Fig. 2, Pl. 25), and this indicates that during the process of circulation the liquid control layer mixes to an appreciable extent with only one other kind of water, which is denoted by the other extremity of the line (S = 34.95‰; T = 6.6°). Dividing this straight line into 100 equal parts (by the method of J.P. Jacobsen or others), we obtain for each point of the liquid control layer the composition in percentage of intermediate subantarctic water and its counterpart, whence we derive the chart of the composition (in percentages) of the Atlantic Ocean liquid control layer (Fig. 3, Pl. 24). It may be seen that the intermediate subantarctic water does not spread with any degree of regularity; it tends to the west side of the Ocean, one might almost say it favours the American coast.

c) To form an opinion regarding the mass of the intermediate subantarctic water, the latter must be sharply defined with relation to the layers lying above and below, an operation which offers great difficulty because of the continuous mixing with the two other layers, particularly since the phenomenon of mixing is continued in intensified form to within the liquid control layer itself. For this reason Wüst returns once more to the oxygen content as criterium. If at a certain depth this content shows a minimum, this fact indicates that there the renewing of the water by other waters coming almost directly from the surface and therefore enriched by the oxygen of the atmosphere, is progressing less actively than in the layers immediately above and below. Up to a certain point therefore, these almost stagnant waters may be considered as the boundary of the contrary circulations. Considered from this point of view, the longitudinal sections of salinity (Fig. 4, Pl. 26) and of oxygen (Fig. 5, Pl. 26) as well as of temperature and density, teach us how the intermediate subantarctic water (Zs) is propagated from its point of origin, constantly diminishing its wedge-like shape. Its upper surface in particular is clearly defined; this also represents the surface of separation with respect to the troposphere. The mass of the intermediate subantarctic water naturally varies more towards the sides, as shown in the central and eastern sections given beside the principal section, and in numerous transverse profiles by Wüst; it is impossible, however, to enter into these details here. With regard to the origin of the intermediate subantarctic water which predominates over such a great expanse of the ocean, this non-stratospherical phenomenon has no place in the work in question; it suffices to refer the reader to the discussion in this Review (1934) between H. U. Sverdrup and G. E. R. Deacon from which it is clear that the question cannot yet be definitely settled. Double determinations of the density by means of titration and with the interferometer (L. Möller - 1935) indicate in its composition a considerable proportion of antarctic fusion waters and, if the study were pursued still farther, it might reveal other refinements.

3. *Upper North Atlantic Deep Water (To).* In the liquid masses lying below the intermediate subantarctic water, which formerly were usually considered homogeneous, Wüst, basing his deductions on the results of the *Meteor* Expedition, distinguishes three different strata, the upper of which (upper North Atlantic deep water) is characterized by its richness in salinity as opposed to the intermediate subantarctic water. Its liquid control layer, the plane of salinity maximum, lies in the North Atlantic Ocean, over a considerable area, at about, 1,000 to 1,250 metres' depth; towards the Equator it sinks, reaching a depth of 2,000 m. in latitude 10° to 20° S., and on the Capetown-Buenos-Aires line a depth greater than 2,750 m., thereafter reascending rather rapidly to 500 m., beyond the polar front, as may be seen from the principal section (Fig. 4-5, Pl. 26). A glance at the salinity chart in this liquid control stratum (Fig. 6, Pl. 24) indicates that the spacial migration proceeds almost entirely from Spanish waters which, in consequence of the flow of Mediterranean water through the Straits of Gibraltar, show a high saline content of 36.40 ‰ and more; thence it branches out on all sides through the ocean, as far as the North American coast. According to Wüst, the final traces of the T_0 should be found in the warmer layer of the Weddell Sea determined by Brennecke, which was formerly attributed to an intrusion of water from the Indian Ocean. Meanwhile H. Mosby (1934) put forward the theory that it owed its origin to a dextral cyclonic eddy in the Atlantic part of the Antarctic Ocean,

and that consequently it should contain abyssal waters from all the oceans, but principally from the Atlantic Ocean. WÜST, designating by the abridged form "Mittelmeerwasser" (Mediterranean Water) the water of 11.9° and 36.5‰ salinity found at 600 to 700 metres' depth to the westward of the Straits of Gibraltar, (which water contains according to his calculation about 50% unadulterated Mediterranean water of 13.0° and 38.40‰) and adopting as counterpart the water of 0.6° and 34.68‰ (Weddell Sea), plots the temperature-salinity correlation for the liquid control layer shown in Fig. 3, Pl. 24. This, by its form, which is almost that of a straight line, indicates that in its main essentials the liquid control layer is a mixture of two kinds of water, even though certain anomalies give rise to a slight curvature in the line.

According to this concept the "Mediterranean water" may be observed, at least in minimal traces, up to the very edge of the Weddell Sea. In view of the narrowness of the opening of the Strait of Gibraltar, this idea seems rather bold : but even a summary estimate of the order of magnitude shows that Wüst's theory should not be rejected offhand: about 52,000 km³ of Mediterranean water (M) (Cf. SCHOTT 1915, p. 77) flows annually through the Straits of Gibraltar; taking a velocity of 4cm/sec., which certainly exceeds the true velocity, a liquid particle would cover the distance of 5,700 miles up to the 60th degree of latitude S. in 8 1/3 years. During this time, therefore, there would pour into the Atlantic Ocean, in round figures, 433,000 cub. km. of Mediterranean water. Even if this volume were uniformly distributed amongst all the layers between 1,000 and 3,000 metres' depth, there still remains a figure of 2.3%; it follows that the contribution of the Mediterranean in regard to the stratospheric circulation must be attributed greater importance than heretofore. Further, DEFANT (1930 a) had already directed attention to the importance of the secondary seas in this connection. C. O'D. ISELIN (1936) starts from a somewhat divergent point of view. Taking as basis the *Atlantis* observations he draws a compensatory temperature-salinity line for the Sargasso Sea (Fig. 3, Pl. 24), adopts the B. HELLAND-HANSEN method of examining the divergences of the different observations referred to his normal curve (salinity anomaly) thus obtained, and actually finds surpluses at about 1,200 m. depth up to the North Equatorial current (latitude 20° N.); subsequently, however, negative anomalies are manifest arising from the intermediate subantarctic water, and he deduces therefrom, as opposed to Wüst, that there is no intrusion of Mediterranean water to the Southward beyond latitude 20° N. As may easily be gathered from the temperature-salinity curves, this difference of opinion arises from a difference in definition : according to ISELIN's concept only that is Mediterranean water which, having a temperature of even 4° C. only, yields at least 35‰ salinity, while Wüst, because he starts from the phenomenon of the maximum, includes also the South Atlantic Ocean (See limit on Fig. 3) with its feeble salinity. Certainly the ⊂~⊃ shaped deviation in the line is striking, lending weight perhaps to a theory of variations in the mixing process (possible influence of the middle North Atlantic deep (T_m) water ?).

The principal section (Fig. 4, 5, Pl. 26) shows that the upper boundary between the North Atlantic upper water and the intermediate subantarctic water is clearly defined by the oxygen minimum, as far as the intermediate subantarctic water extends; where the latter is absent in the Northern Atlantic Ocean, the oxygen minimum divides the upper North Atlantic deep water from the troposphere, to which belongs all the accumulation of warm water, rich in salinity, from the Sargasso Sea. Thus the distribution of oxygen leads us to the concept that the water of the Sargasso Sea is not, as previously assumed, the principal source of North Atlantic deep water, but contributes only an insignificant proportion.

4. *Middle and Lower North Atlantic Deep Water, T_m and T_u and Antarctic Bottom Water, Bs.* — The lower boundary of the upper North Atlantic deep water (T_o) is, according to Wüst's investigations less clearly defined. The middle North Atlantic deep water, (T_m) below, and the still deeper North Atlantic lower deep water (T_u), are not characterized by salinity but by an oxygen maximum for each. From this fact, as has been stated by *Wattenberg*, they draw their waters from the colder subpolar and polar areas, i.e. from the Western area of the North Atlantic Ocean, the former from the zone lying North-east of Newfoundland and Labrador. Its liquid control layer (oxygen maximum) quickly falls to the 2,000 m. level, and with a few variations keeps this level to latitude 25° S. (approx.), whence it sinks gradually to 3,000 m., afterwards rising towards the South. The lower North Atlantic deep water, identical in the North with polar bottom water, moves between 3,000 and 4,000 m. as shown by the section; observations are too far apart, however, to enable any precise statement to be made. It is interesting to note

that the temperature-salinity curve of the middle North Atlantic deep water coincides with the South part of the upper North Atlantic deep water curve, which is a sign of intensive internal mixing (See preceding), and explains why the investigation of the oxygen content alone makes it possible to differentiate between the North Atlantic upper and middle deep water.

With reference to the antarctic bottom water, which must be considered as the lowest waterbed of the Atlantic Ocean this may be distinguished from the lower North Atlantic deep water by its temperature discontinuity, and partly also by an oxygen minimum (Fig. 4, 5, Pl. 26), see the Report by CASTENS (1934) already mentioned. Among the complementary results which WÜST has added to his previous work, the two following should be emphasized: First, a chart showing the percentage composition of antarctic bottom water with respect to bottom water as far as latitude 50° N.; second, a resumption of the question of its origin, subsequent to the fact that H. MOSBY (1934, pp. 80-92), on the strength of new observations and after mature consideration of the reasons for and against, had in the meantime announced the improbability (as NANSEN had previously assumed for the Greenland Seas), that at the limit of the packice the winter-cold water sinks from the surface to the bottom. WÜST thereupon seemed inclined to favour the point of view of BRENNECKE and MOSBY, but up to the present there has been no means of reaching a definite decision on the question.

5. *Complementary Investigations.* The schematic representation of the stratification of the Atlantic Ocean proposed by Wüst gives rise to the question : up to what point have the concepts of the circulation made at the time by BRENNECKE, MERZ and WÜST, and so clearly stated by MERZ as a working hypothesis for the *Meteor* Expedition, been confirmed ? It is not by chance that the old designations *Zwischenstrom* (Intermediate current) and *Tiefenstrom* (Deep Current) have disappeared from the new concept and been replaced by *Zwischenwasser* (Intermediate water) and *Tiefenwasser* (Deep water). The theory of liquid control layers certainly explains the origin and the distribution of the various kinds of water; but it also throws new light on the fact that, side by side with the current, mixing and exchange processes determine the circulation to a much greater extent than was formerly admitted and would be vigorous enough to change the entire structural scheme very quickly and completely, if a continuous compensatory intrusion did not occur. In general the mind will have to picture the movements as a confused backwards and forwards swaying motion, with frequent cyclonic mixation with other waters coming from above, below, the sides, without any definite direction of flow being perceptible. Only on the American side, along which also the principal section (Fig. 1, 4, 5, Pl. 24 & 25) is laid, does the circulation manifest itself so clearly along the coast that Wüst speaks of it as a current. He sees one of the causes for the favouring of the Western side in the deflecting force due to the Earth's rotation; it must be, however, that other causes enter in, in view of the fact that both the intermediate subantarctic water and the North Atlantic upper deep water (See Fig.) flow to the West coast, after having crossed the Equator. By the fact that it seeks to determine the place occupied by the waters to an extent not hitherto possible, and throws light on their distribution resulting from the interplay of current and mixing, the method of liquid control layers according to Wüst has fulfilled its mission and its possibilities. The question which then presents itself is whether there exists some means of learning something of each of the two causes.

It was believed that the velocity of the current might be deduced by following the patches of liquid masses with excess oxygen content, for instance the North Atlantic middle deep water (Fig. 5, Pl. 26). These were considered as liquid masses which sank during the cold season, during which they could absorb more oxygen than during the warm season; in this case the intervals between these maxima would indicate the distance covered during a year and, consequently, the speed. Wüst, however, shows by a far-reaching critical examination that in this way only an upper limit of the speed would be obtained and that for a more reliable estimate it would be necessary to occupy stations at shorter distances from each other and, above all, along the "axis of the current", which is not known.

A. DEFANT (1936a) has made a mathematical study of the ratio between the mixing factor A and the speed u. Certainly here also it is necessary to establish some working hypothesis for tracing the current lines; but, in the region of the antarctic bottom current on the American side, for instance, the assumption is restricted by the forms of bottom relief to which the current must adapt itself, and thus, after a somewhat lengthy computation, above ocean-sills values between 2 and 3 and in depressions values between 5 and

6 cgs. are obtained for the ratio A/u (called the *Vermischungsgrösse* — factor of mixation); these numbers best indicate the extraordinary importance of the mixing-process. If the very rough estimate of A = 4 cgs., which is quite plausible, but naturally altogether arbitrary, were everywhere applied, the speed on the sills would be 1.5 to 2 cm/sec., in the depressions 0.5 to 1 cm/sec. and, in the North Atlantic lower deep water, 0,3 to 0.8 cm/sec. For the intermediate subantarctic water off the American coast, we obtain, with admissible assumption, in the liquid control layer, A/u = 0.82, in the upper and lower boundary strata, 2.64 and 3.18, which corresponds to the lesser speed in these strata and leads to mixing paths (in the PRANDTL sense of the term) of 1 to 1 1/2 m.: the intermediate subantarctic water (Zs) propagates itself similar to the wake stream. As has been theoretically shown by DEFANT, the temperature-salinity curve may also be utilised for the computations of A/u, leading to results of the same order of magnitude. For A = 5 cgs, 5-10 cm/sec. would be found. According to theory one may even follow a non-periodical perturbation of the intermediate subantarctic water off Cape St. Roque, and the theory, also elaborated by DEFANT, of seasonal fluctuations in the region of origin of this water, lends support to the adverse comments of Wüst mentioned above, on the determination of speed based on patches of oxygen maxima. Unfortunately lack of space prevents us from dealing further wtih these interesting questions.

Quite another question is whether the results obtained for the circulation of the water are confirmed and improved upon by still another method. Writers in this connection have drawn attention to the importance of the stability (CASTENS - 1927). As a stable stratification obstructs the rising and falling movement of the liquid particles, and may even prevent it entirely (see further on), one might expect to discover new horizons by a study of the stability, which according to the theory of HESSELBERG and SVERDRUP (1914/15), HESSELBERG (1918, cf. B. SCHULTZ (1917)) is measured by the change in density (ρ) with the increase in depth (z), $E = d\rho / \rho dz$.

A detailed critical analysis by v. SCHUBERT (1935) shows, however, that the differences in density in the stratosphere are so small that even with modern precision methods the inevitable infinitesmal errors in the determination of density still in many cases falsify too much the density differences, so that one cannot draw reliable conclusions. To that must be added the fact that only the mean stability of a water column several hundreds of metres high can be determined by series of measurements, so that the expectations attached to a study of stability are not realisable. However, along the principal section of Wüst, v. SCHUBERT has been able to draw a longitudinal section in which two maxima may be distinguished. The first lies above the antarctic bottom water and thereby corroborates the results deduced from the oxygen minimum regarding the slight extent of the mixing. The other begins at a depth of 1,000 metres, but has no definite cause; it manifests itself in the intermediate subantarctic water as a result of variations in salinity, but might also be produced in the mid-depths of all the oceans by the mean temperature distribution.

Compared with the stratosphere the stability of the troposphere, which we will now discuss, is greater by several tenthpowers, but sharply diminishes from the middle latitudes towards the pole, so that a sinking appears possible here; it is impossible, however, to offer more than a conjecture. In any case H. MOSBY (1934, p. 60) has often found an unstable stratification in antarctic waters which, however, he considers as of a temporary nature and attributes to the melting of ice in the depths. On the other hand, v. SCHUBERT has found between latitudes 20° and 30° S. vast areas (cf. Fig. 7 further on) in which stratification is unstable, not only at the surface and for a brief moment, but for long periods and at times extending as far as to a depth of 100 metres. These are those regions in which, according to Wüst, evaporation exceeds precipitation. A more accurate means for distinguishing the liquid strata of various origin will perhaps be available in future in the differences manifested when the density is measured, on the one hand by the chlorine content and on the other hand by observations with the interferometer. [BEIN - HIRSEKORN - MÖLLER (1935); see, in particular, L. MÖLLER p. 194 *et seq.*]; see preceding.

B. *THE TROPOSPHERE*

(Treatise by A. DEFANT)

It is self-evident that the troposphere, in contact with the air over a large surface, is exposed to greater and more rapid variations than the stratosphere. The questions which arise in connection with it are therefore of another nature, and other means must be taken to answer them. Also seasonal and non-periodical fluctuations, to which we must add internal waves, render investigation more difficult. In spite of that the author has made no transformations in the mean values (which Wüst also avoided as far as possible), but has preferred to take into account the inevitable discrepancies present in the observations; particularly since owing to the great number of observations analysed (717 stations — 1/3 of which are *Meteor*), the principal features still show up quite clearly. Consequently most of the results will be restricted to an area lying between latitude 30° N. and S. — if not to a still narrower belt — in which the seasonal changes lose in importance.

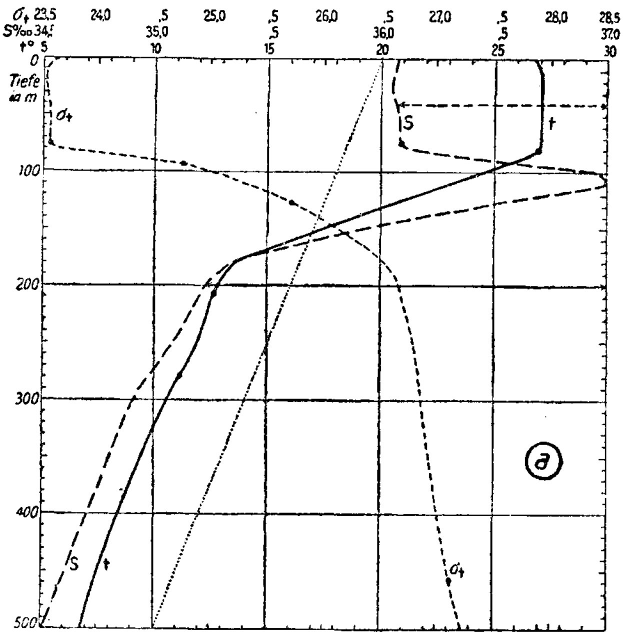
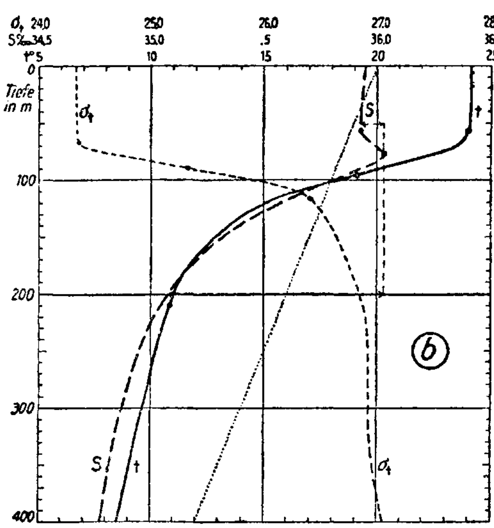


Abb. 7.



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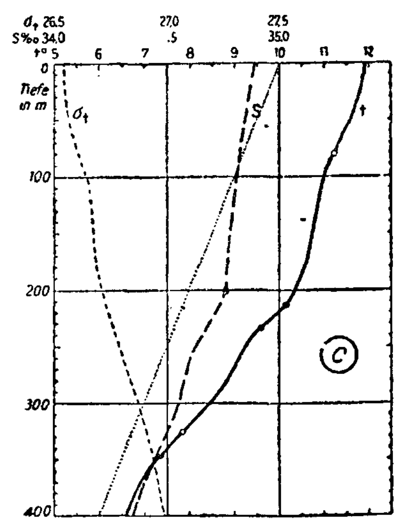


Abb. 9.

State of the Troposphere at the Meteor Stations.

(*a*) 256 (2.1° S. 39.3° W.), (*b*) 195 (8.7° S. 12.5° W.) & (*c*) 68 (41.3° S. 17.4° W.)

The dotted straight line indicates the minimum temperature gradient which may be spoken of as a discontinuity layer.

———— Temperature — — — — — Salinity (‰) - - - - - - Density (σ_t)

6. *Structure of the Troposphere.* The essential characteristic feature of the troposphere is a clearly defined temperature discontinuity layer and, at the same time, a density discontinuity layer, above all in the tropics; it frequently recurs in the distribution of the oxygen and, to a greater degree, of the salinity which, besides, often shows a maximum at temperature discontinuity depths (Fig. 7 & 8). At higher latitudes it gradually disappears (Fig. 9). In order to have a numerical expression DEFANT speaks of a discontinuity layer only when the vertical gradient in temperature is greater than 0.02° per metre (See auxiliary upright in Fig. 7 to 9). Higher up is a covering layer, quite uniform in part, and underneath lies the relatively homogeneous subtroposphere distinguished from the stratosphere by a second but smaller drop in temperature, but better characterized by an oxygen minimum.

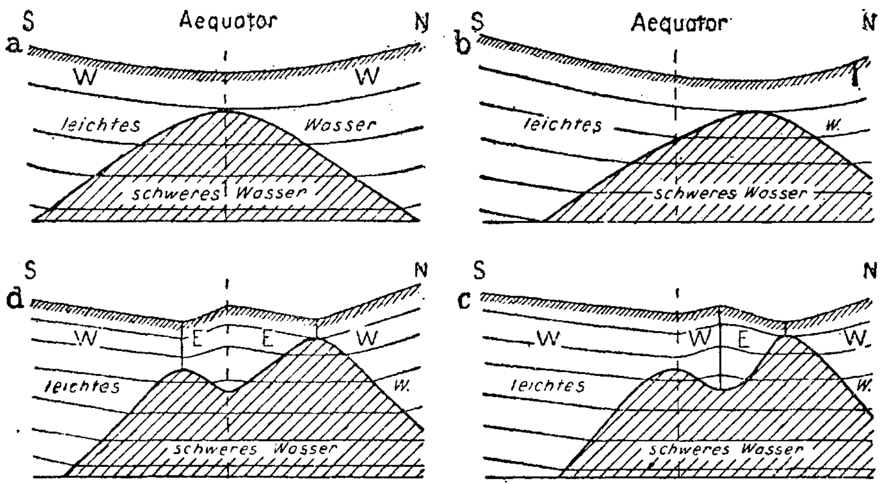
The first question examined by DEFANT is that of the origin of the discontinuity layer. He demonstrates that it cannot be explained solely by radiation and absorption; to this must be added the temperature exchanges provoked by the wind. These cause, for instance, the solar heat contributed to the upper layers to penetrate to deeper and deeper layers by admixture — as a result of which eventual differences that may exist in the covering layer are continually being obliterated. This gives rise to temperature differences, and consequently also to density differences, with respect to the deeper underlying layers, which are condensed within a constantly thinning layer until finally the density gradient becomes so great that the resultant buoyant forces inhibit all further vertical convection of the liquid particles. If A_B is the exchange figure for the movement factor, A_T that for the temperature, if E designates the stability, α the (vertical) gradient of the current velocity, g the acceleration of gravity, then, according to G.J. TAYLOR (1931) we have :—

$$\frac{\alpha^2}{g\,E} > \frac{A_T}{A_B}$$

in order that stratification may not inhibit exchange. Only a few determinations exist for the ratio of the two exchange figures : J.P. JACOBSEN found in the Kattegat (1913-1918) values varying from 1 : 8 to 1 : 48, in the Randersfjord values from 1 : 5 to 1 : 6.5. However that may be, it is evident that the discontinuity layer must be more clearly manifest in the tropics where the differences in density are great, whereas in the high latitudes it is " uncertain ".

7. *The Discontinuity Layer of the Troposphere.* Among the 17 numerical values by which DEFANT characterizes the temperature, the salinity and the density of the troposphere, the most important here is the depth of the discontinuity layer, or, to be more precise, of the layer of maximum temperature gradient or, what amounts to the same thing, of the greatest density gradient (Fig. 10, Pl. 27). The unevenness in the surface thus obtained is but little greater than that in Wüst's liquid control strata. Starting from a depth of 200 to 300 metres in the subtropics (horse latitudes), the discontinuity layer rises towards the equator to less than 100 metres and lies much higher off the African than off the American coast; it even reaches the surface off the S. W. coast of Africa, as is elsewhere explained by DEFANT for instance (1936, p. 60). One striking fact is that the rise on the two sides towards the equator is interrupted by a *saddle* stretching across the ocean from latitudes 2.5° to 5° N. (approx.). The gradient also shows three corresponding maxima and, finally, the whole discontinuity layer, i. e. the layer showing a temperature gradient of at least 0.02° per metre, has almost everywhere the same thickness, so that its upper and lower boundaries show clearly the two ridges and the intervening depression.

To interpret the form of the surface, DEFANT, borrowing an idea of H.U. SVERDRUP for the Pacific Ocean, calls to his aid the counter current and the Guinea Current intruding between the North and South Equatorial Currents. This current is not, as has been thought, an intermediary compensating for the water carried towards the West, but owes its origin precisely to the circumstance that the calm belt, with which it coincides, does not lie on the Equator but rather to the Northward, i. e. asymmetrically, corresponding to the thermal equator (cf. the detailed study by DEFANT - 1935). On the other hand, the deflecting force due to the earth's rotation acts symmetrically. If the two trade winds gradually merged into each other as far as the Equator without leaving a calm belt, the deflecting force would, in the Southern hemisphere, force the water towards the left, i. e. the South and, in the Northern hemisphere, towards the right, i. e. the North (Fig. 11a), and the Equator would be characterized by a depression at the surface. The interplay of forces would then necessitate the discontinuity surface showing a ridge at the same place. Now, if the belt of calm moves towards the Northern hemisphere, the depression cannot simply move there as in Fig. 11b, since the water level must rise from the Equator northward. Surfaces of the form shown in figures 11c and 11d are possible; each, as a consequence of its stable position, implies a corresponding configuration of the discontinuity surface which is, in a certain respect, its negative. Consequently, in the Atlantic Ocean calm belt, the two surfaces set up a current towards the East which is, therefore, essentially a gradient current! On the basis of this theory of stable stratification, Defant calculates for the covering layer (above the discontinuity layer) rather large mean velocities (20 to 30 cm/sec.). Looked at in this way, the compensation for the two equatorial currents comes principally on the surface from North and South; only under the Guinea current are indications found at several hundreds of metres' depth, of a counter current, which moreover corresponds to the current measurements at two anchor stations.



Various positions of the discontinuity surface and correlative current systems, according to Sverdrup. Capital letters indicate the direction of the Current.

(*a*) Symmetrical distribution (possible but non-existent); (*b*) dynamically impossible; (*c*) & (*d*) dynamically possible; (*c*) Atlantic and Pacific Oceans, (*d*) Indian Ocean.

8. *Maximum of Salinity and Circulation.* It appears that a dynamic calculation alone, based on the discontinuity surface, can only yield mean values. Defant obtains more corroborative evidence of the circulation by a study of the salinity maximum, which, as previously stated, coincides with the discontinuity layer. This maximum is distributed over the greater part of the tropical zone; in particular, two characteristic exceptions are two bands which practically coincide with the saddle-like elevations of the discontinuity layer (Fig. 12, Pl. 27). In view of the fairly uniform covering layer, such a maximum is explained by the intrusion from beneath of accumulations of water rich in salinity in the subtropics, in the core of which a similar maximum is lacking. Fig. 12, Pl. 27 shows the propagation of the waters in certain favoured directions, for instance along the Brazilian coast where A. Merz (1925) had already suspected anomalies. One section (Fig. 13, Pl. 28) shows that there a liquid layer of only 20 to 30 metres' thickness scarcely alters its saline content over a stretch of 2,500 miles. Certain theories lead Defant to the concept that there the density discontinuity is quite large enough (Cf. preceding) practically to inhibit the vertical mixing process. The same is true for three other sections made by Defant along lower tropical currents.

Conversely, Defant sees in the two bands without salinity maximum, convergence areas of the under current, in which the water is turned towards the surface. Based on this explanation and the chart of computed mean currents, he constructs a chart of the under-currents lying above the discontinuity layer (Fig. 14, Pl. 28), which he compares with another chart of surface currents deduced from Dutch calculations of the drift of ships. (Fig. 15, Pl. 28). In this latter chart the convergences of the undercurrent appear as divergences of the upper current and conversely. Thus there is obtained a homogeneous scheme of the East-West current system. Superposed, however, are feeble circulatory movements in the sense of the Fig. 16, Pl. 29, as a comprehensive whole, although these may often be only the result of irregular mixing processes .

It is not possible in a report like the present to do more than touch upon the newly acquired knowledge, and the reader is invited to consult the works themselves; these offer a profusion of information in their appended detailed tabulations and in the atlas. In the circumstances there are naturally very many details which do not adapt themselves exactly to the points of view developed (for instance the resurgence of the lines of salinity in longitude 35° W., Fig. 13, Pl. 28), and which must be accepted as perturbations which can in part be explained but which in part are inexplicable. Such details cannot, however, weaken the fundamental features of the circulation structure just elaborated — whose comprehensiveness speaks for itself.

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H. Thorade: Die Stratosphäre und die Troposphäre des Atlantischen Ozeans

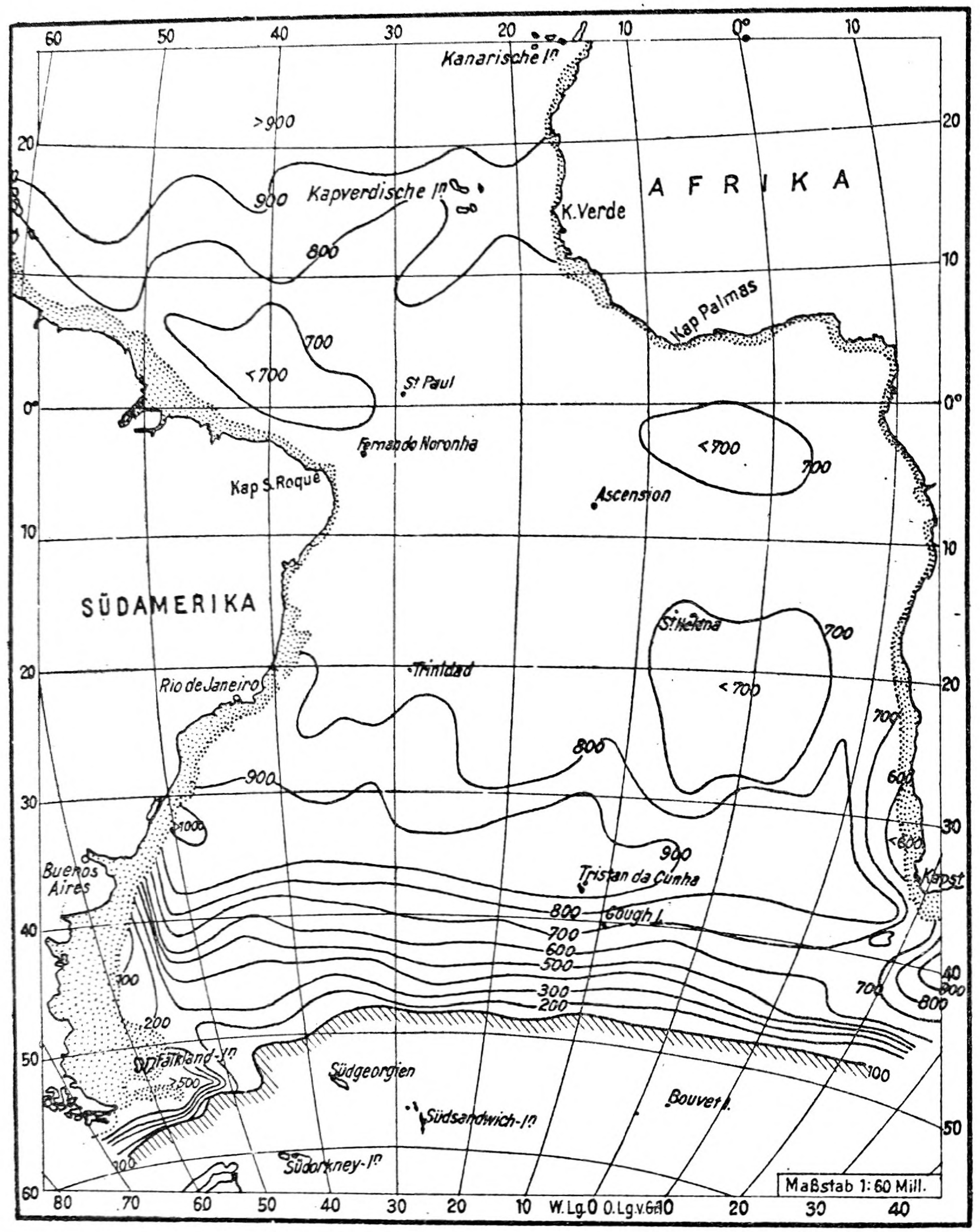


Abb. 1

Tiefenlage der Kernschicht (intermediäres Salzgehaltsminimum) des subantarktischen Zwischenwassers (n. Wüst)

Depths of the liquid control layer (intermediate salinity minimum) of the intermediate subantarctic water (according to Wüst).

Situation en profondeur de la strate liquide maîtresse (salinité minima intermédiaire) de l'eau intermédiaire subantarctique (d'après Wüst).

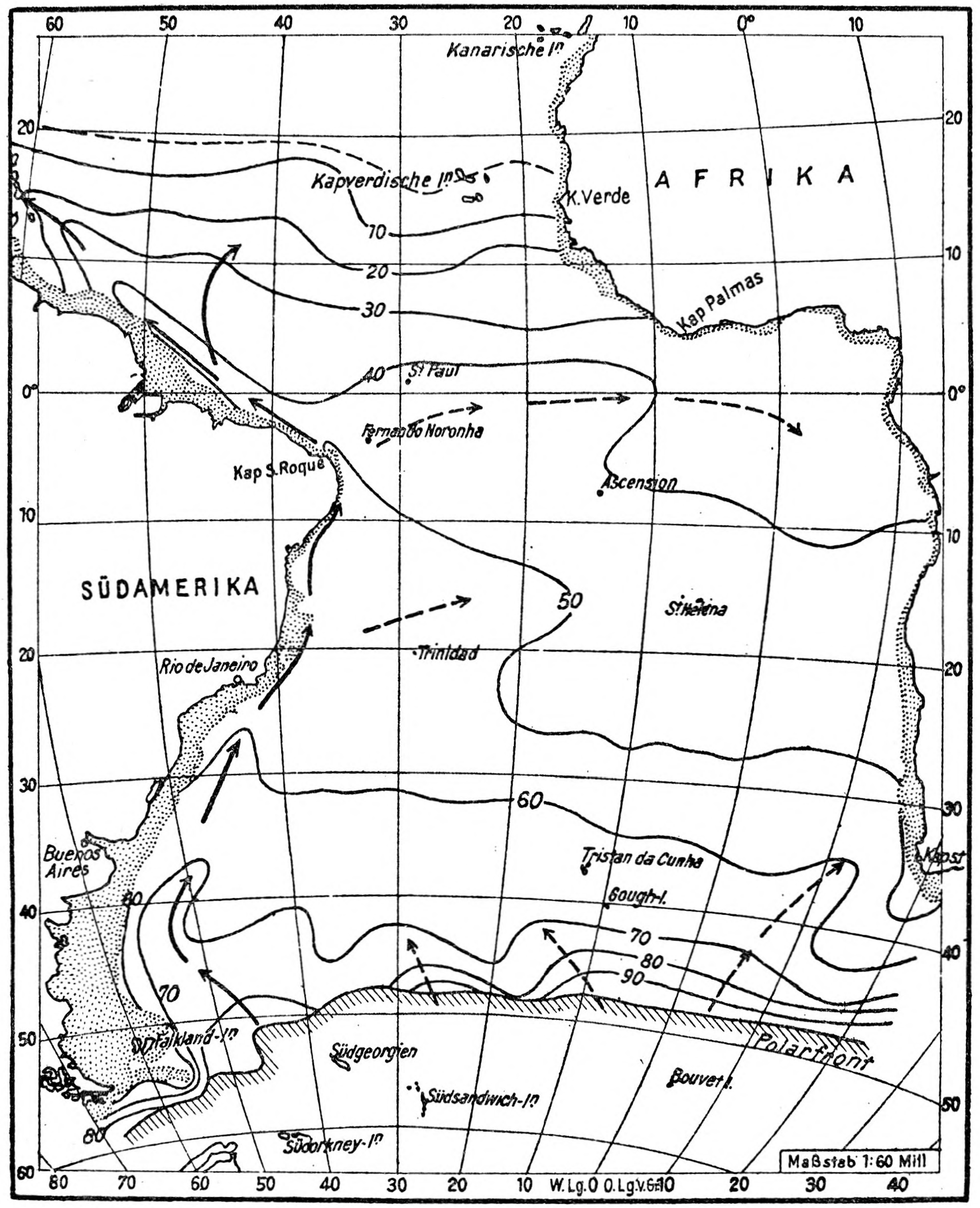


Abb. 3

Ausbreitung des subantarktischen Zwischenwassers in der Kernschicht (intermediäres Salzgehaltsminimum) dargestellt durch den prozentischen Anteil der subantarktischen Komponente (n. Wüst)

Propagation of the intermediate subantarctic water in the control layer (intermediate salinity minimum) represented by the percentage participation of the subantarctic components (according to Wüst).

Propagation de l'eau intermédiaire subantarctique dans la strate liquide maîtresse (salinité minima intermédiaire) représentée par le pourcentage de la composante subantarctique (d'après Wüst).

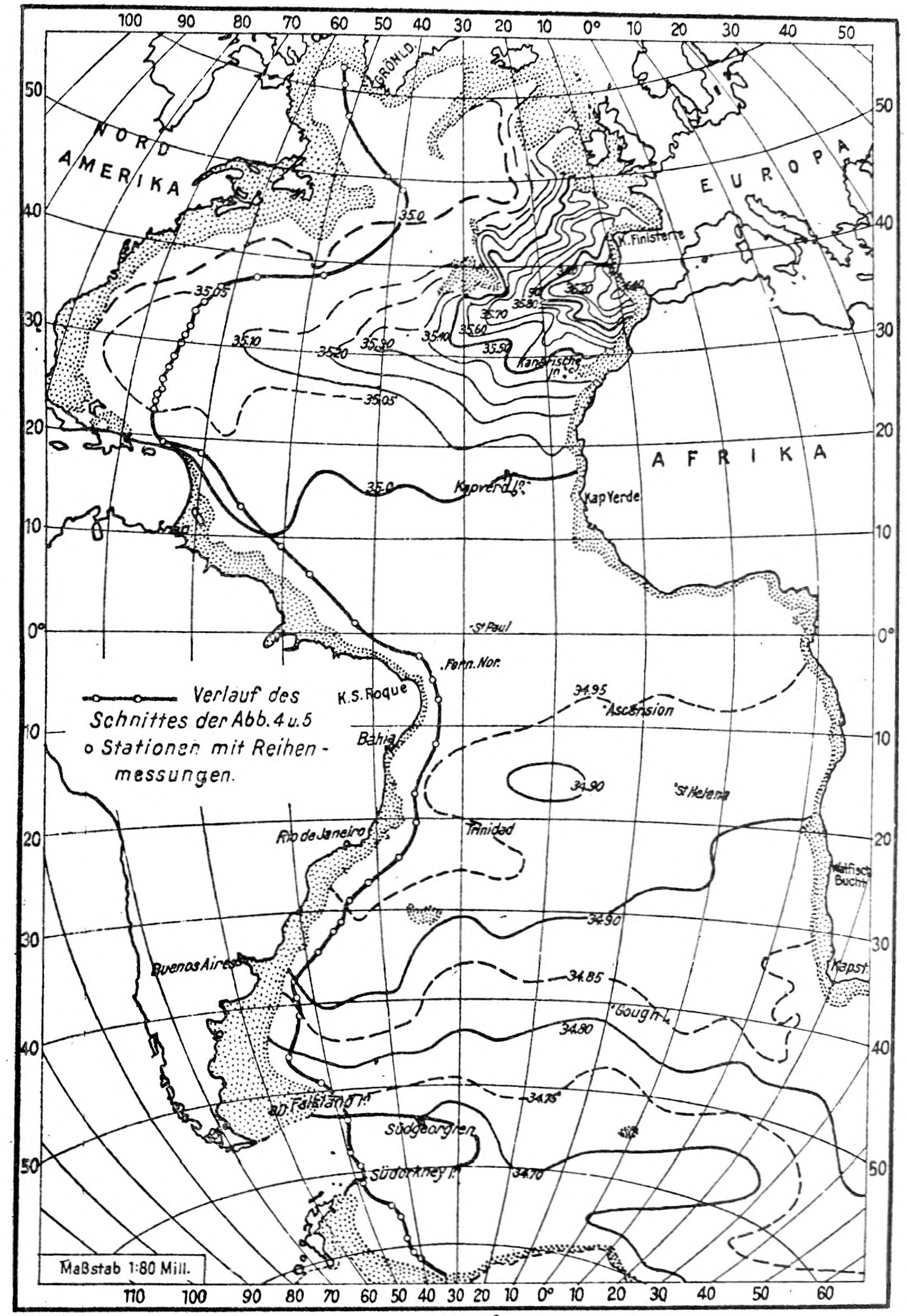


Abb. 6

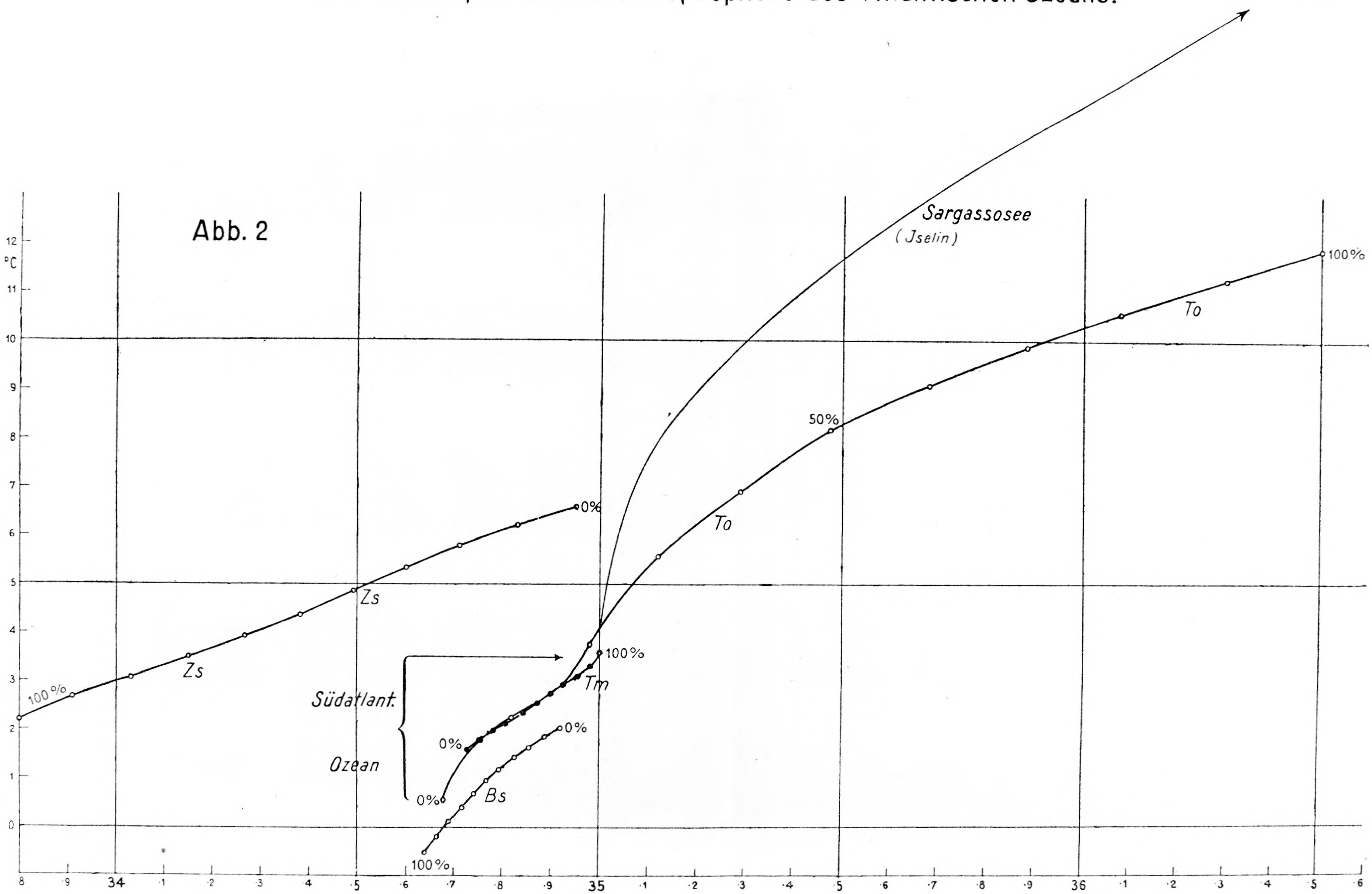
Salzgehalt (‰) der Kernschicht (intermediäres Salzgehaltsmaximum) des oberen nordatlantischen Tiefenwassers (n. Wüst)

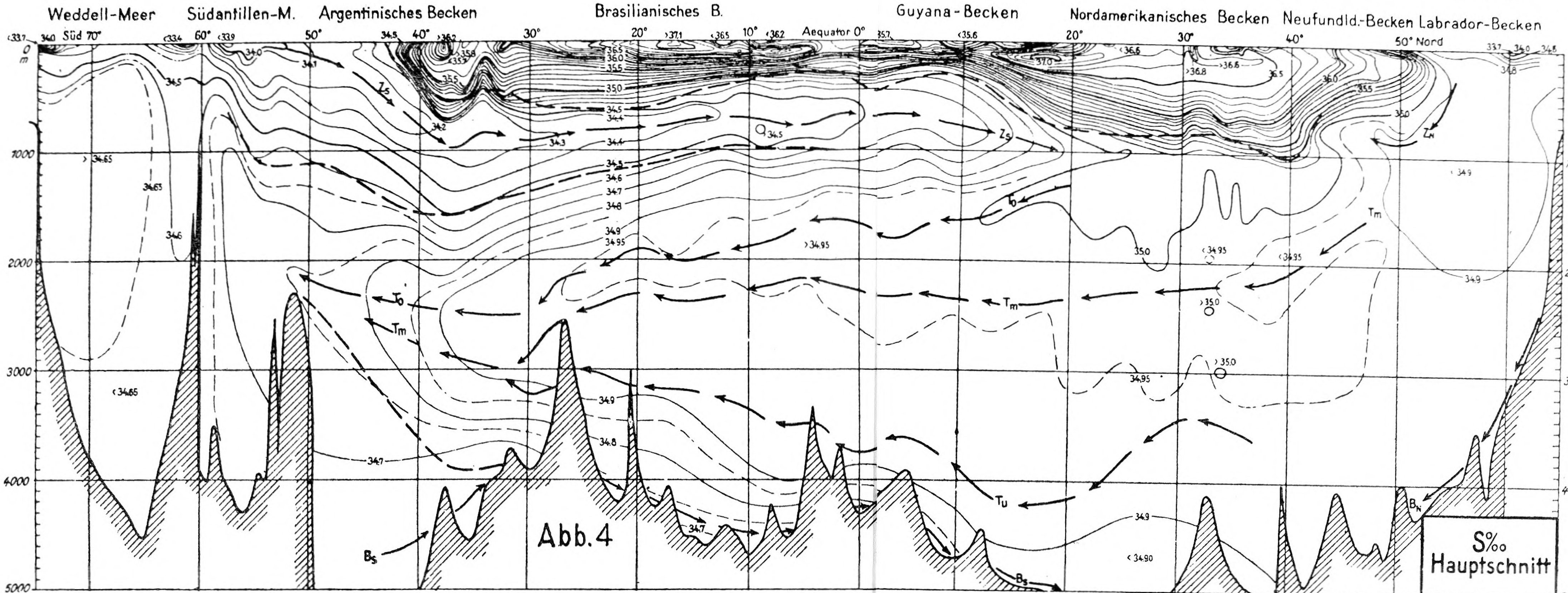
Salinity content (‰) of the control layer (intermediate salinity maximum) of the upper North Atlantic Deep Water (according to Wüst).

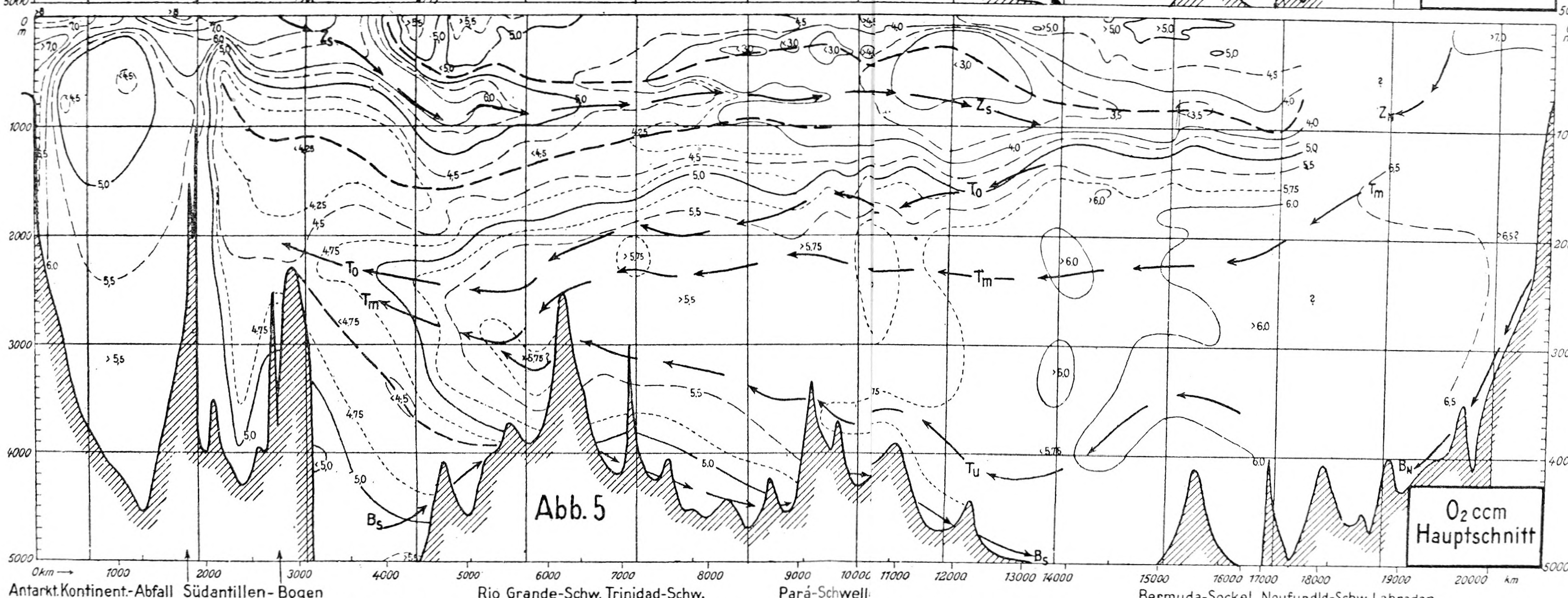
Salinité (‰) de la strate liquide maîtresse (salinité maxima intermédiaire) de l'eau profonde Nord Atlantique supérieure (d'après Wüst).

H. Thorade:

Die Stratosphäre und die Troposphäre des Atlantischen Ozeans.







Die Pfeile bezeichnen die Hauptausbreitung der Kernmassen: Zs = *subantarktisches Zwischenwasser (Salzgehaltsminimum)* Zn = *nordatlantisches Zwischenwasser (Salzgehaltsminimum)* To = *oberes nordatlantisches Tiefenwasser (Salzgehaltsmaximum)*
Tm = *mittleres nordatlantisches Tiefenwasser (1. Sauerstoffmaximum)* Tu = *unteres nordatlantisches Tiefenwasser (2. Sauerstoffmaximum)* Bs = *antarktis Bodenwasser (Minimum d. pot. Temperatur)* Bn = *subarktisches Bodenwasser (Minimum d. pot. Temperatur)*
Die dick-gestrichelten Linien bezeichnen die Wasserartgrenzen auf Grund der intermediären Sauerstoffminima.

H. Thorade:

Die Stratosphäre und die Troposphäre des Atlantischen Ozeans

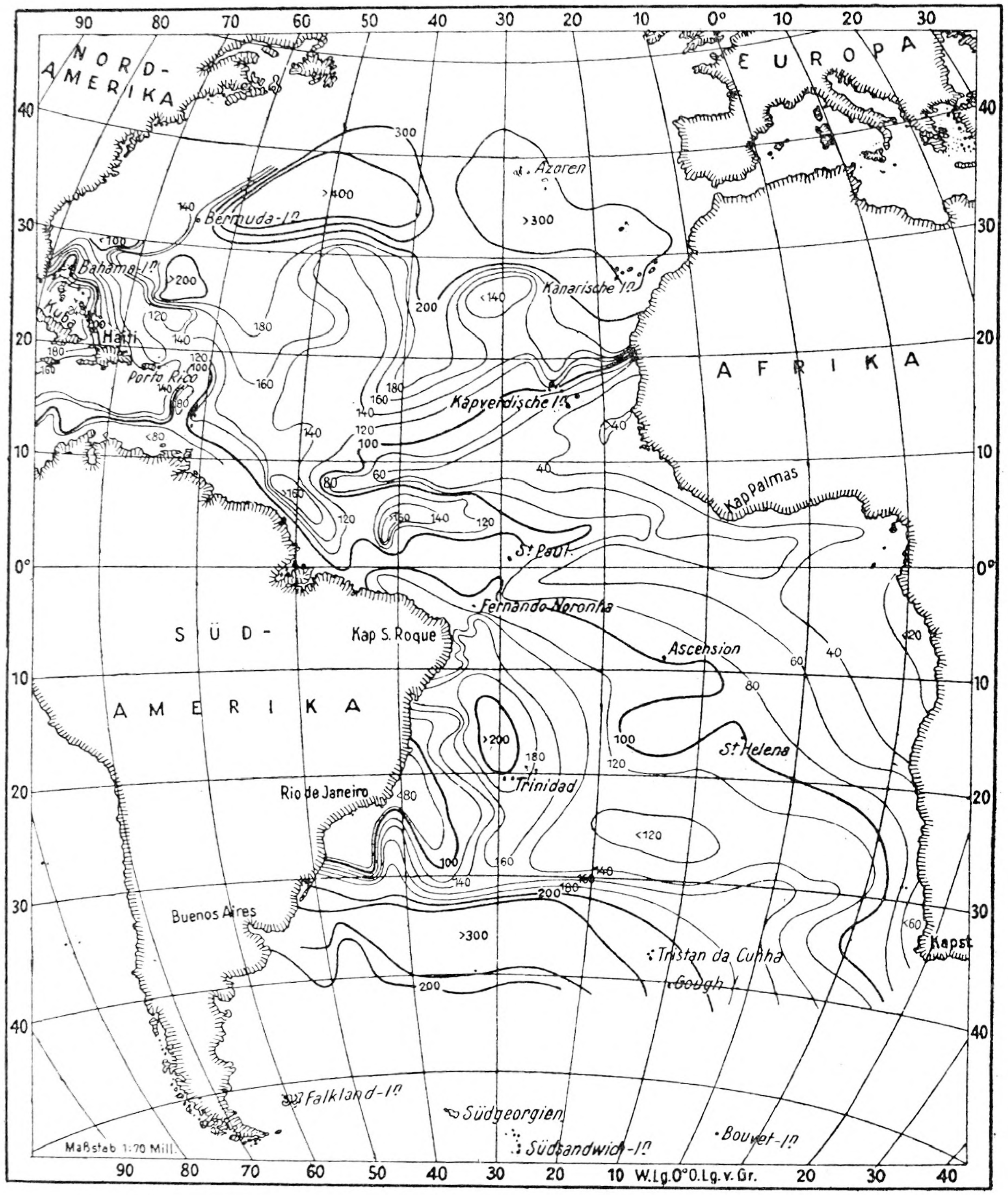


Abb. 10 Tiefenlage des maximalen Temperaturgradienten

Depths of the Maximum Temperature Gradients.

Situation en profondeur du gradient de température maximum.

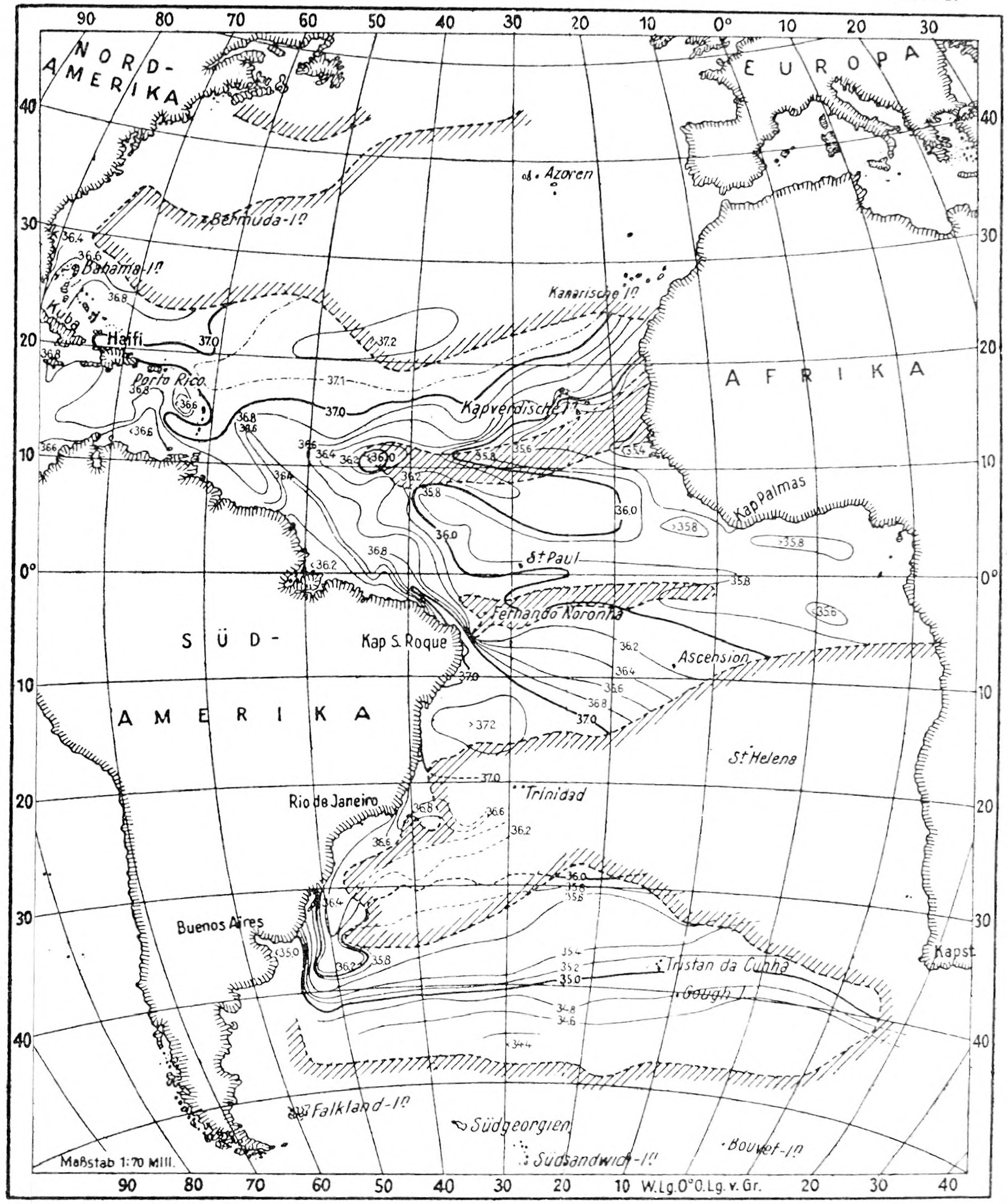


Abb. 12 Maximaler Salzgehalt im subtropischen Salzgehaltsmaximum

Salinity maxima in the Subtropic Salinity Maximum.

Salinité maxima dans le maximum de salinité subtropique.

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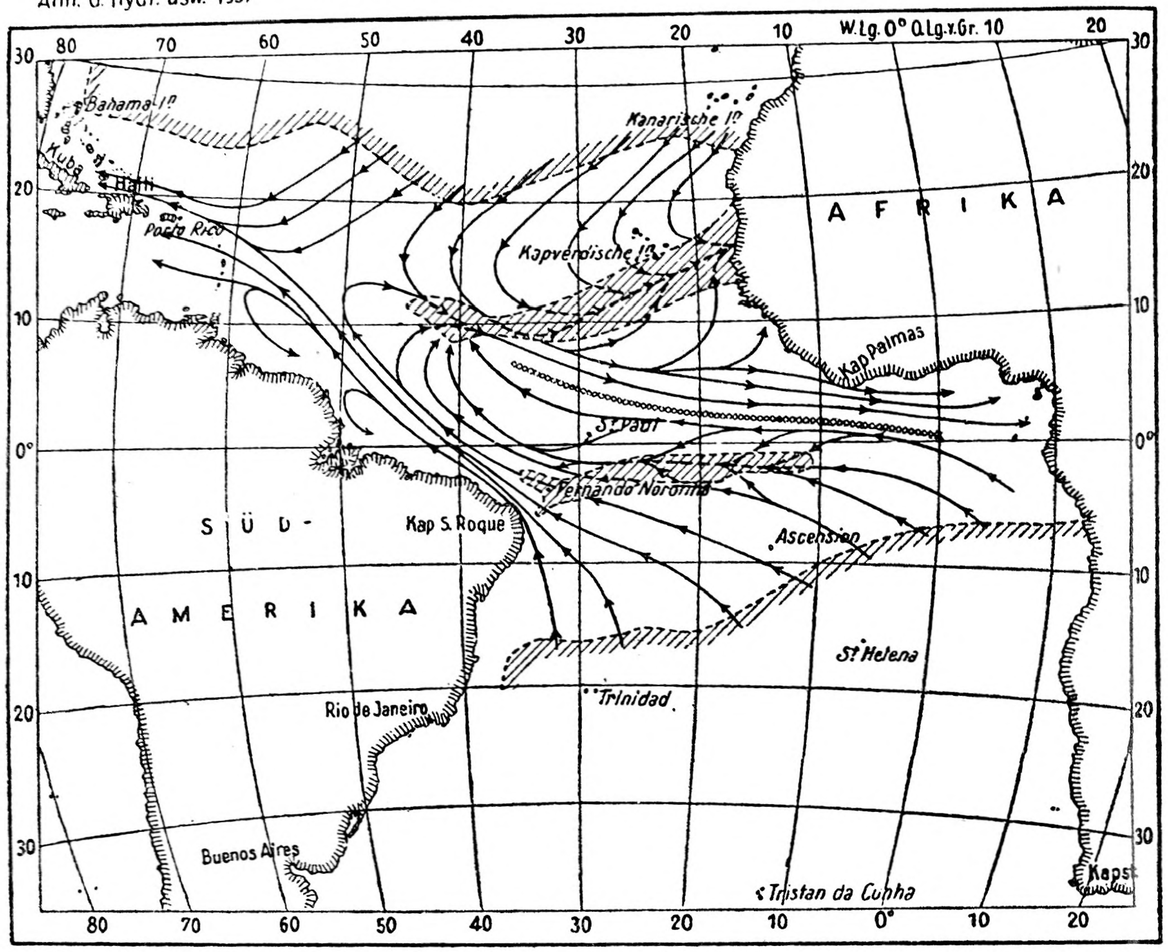

Abb. 14 Die Strömungsverhältnisse in den Unterschichten der Troposphäre, abgeleitet aus der Salzgehaltsverteilung. (n. Defant)

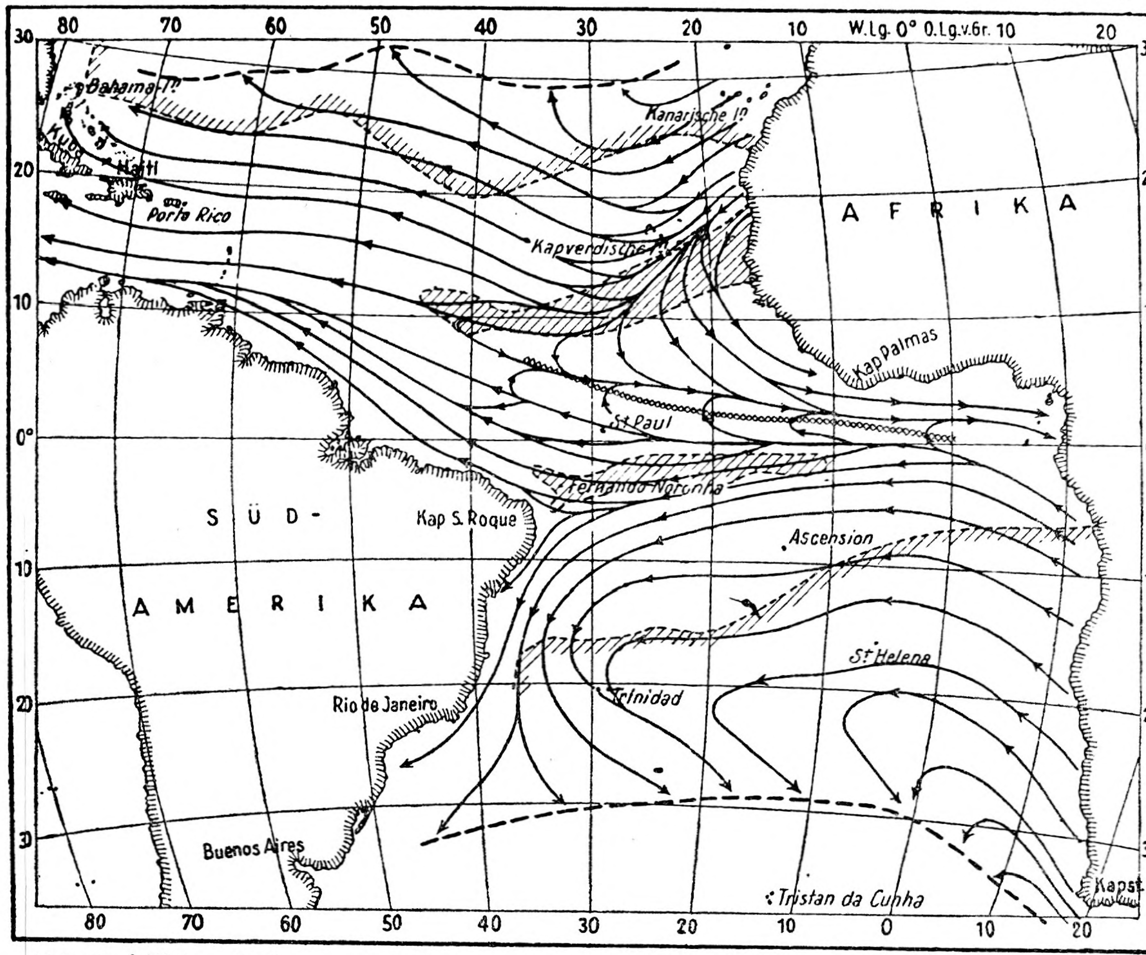

Abb. 15 Mittlere Strömungsverhältnisse an der Oberfläche des Atlantischen Ozeans (bis zu den subtropischen Konvergenzen) (n. Defant)

xxxxxxxxx *Divergenzlinie am südlichen Rand des äquatorialen Gegenstroms (Guineastrom)* ////// *Gebiete ohne subtropisches Salzgehaltsmaximum*

The current relations in the lower layers of the Troposphere deduced from the salinity distribution (according to Defant).

Etat des courants dans les strates inférieures de la Troposphère, déduit de la répartition de la Salinité (d'après Defant).

Mean currents on the surface of the Atlantic Ocean (up to the subtropical convergences) (after Defant).

Etat moyen des courants à la surface de l'Océan Atlantique (jusqu'aux convergences subtropiques) (d'après Defant).

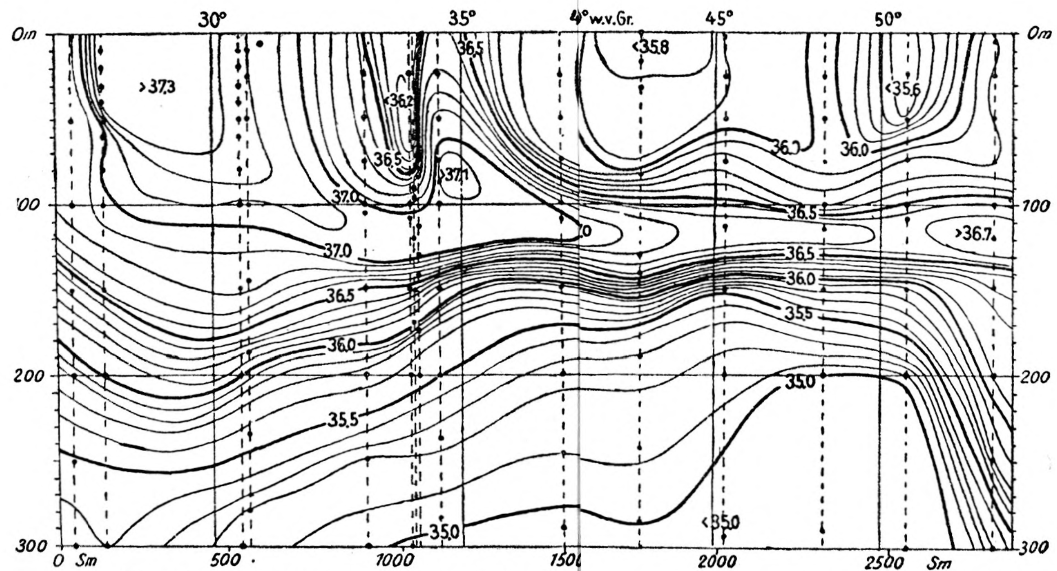

Abb. 13 Längsschnitt des Salzgehalts im Südhemisphärischen Unterstrom. (n. Defant)

Longitudinal section of the salinity content in the undercurrent of the Southern Hemisphere (after Defant).

Coupe longitudinale de la salinité dans le courant inférieur de l'hémisphère sud (d'après Defant).

H. Thorade:

Die Stratosphäre und die Troposphäre des Atlantischen Ozeans

Ann. d. Hydr. usw. 1937

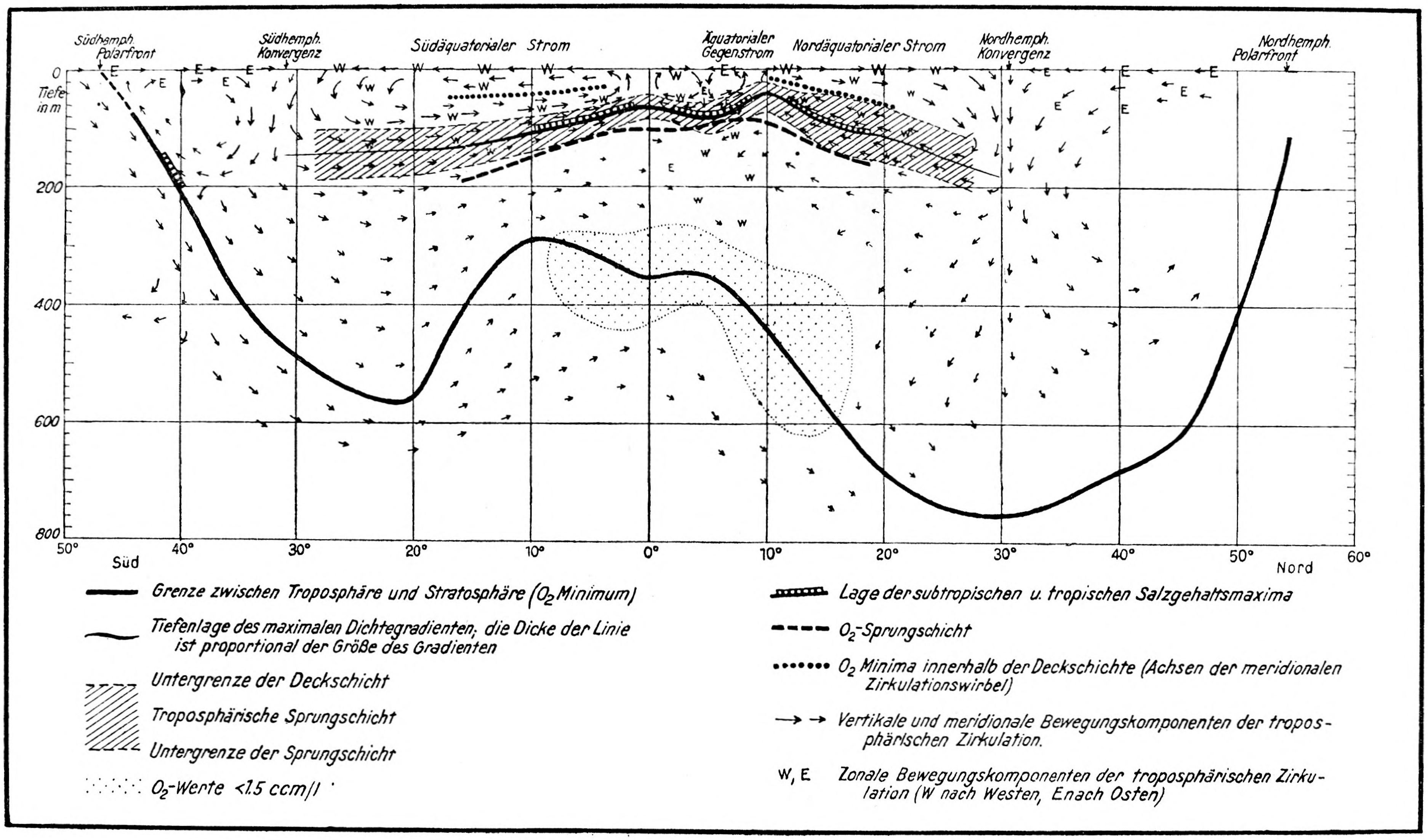

Abb. 16

Schnitt längs der Mittelachse des Atlantischen Ozeans.
Zusammenfassende Darstellung des Aufbaus und der Zirkulation
(nach Defant)

Section along the central axis of the Atlantic Ocean.
General representation of the structure and the circulation (after Defant).

Coupe le long de l'axe médian de l'Océan Atlantique.
Schéma d'ensemble de la structure et de la circulation (d'après Defant).