Geology. — *Influence of the earth's rotation on ventilation currents of the Moluccan deep-sea basins.* By PH. H. KUENEN.

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Abstract.

It is shown that, judging from the oxygen content of the bottom water, the currents ventilating the deep-sea basins in the Moluccas appear to be deflected by Coriolis' force. It is assumed that VAN RIEL's chart of the oxygen distribution gives the best generalization of the available data. In two (three ?) cases north of the equator the currents are forced to the right and in five (six ?) cases south of the equator to the left.

Centrifugal force must add to the deflection in some cases and might even be the sole agent where the shapes of the basins cause the water to flow along a curved course. Examples are available, however, in which no centrifugal force plays a part, only Coriolis' force. The importance to geology and biology lies in the possibility of estimating velocities from the mass distribution, provided the deflecting forces are taken into account. Final judgment must be suspended until these calculations have been carried out.

Most of the deep-sea basins of the Moluccas are connected with the Pacific or Indian Oceans or with other basins by more than one entrance. The superficial strata of water communicate through these straits with the surroundings. Besides strong reversing tidal currents, constant flow in one direction, or flow reversing with the monsoonal winds take care of renewal of these superficial layers. The currents at different levels may flow in opposite directions or at different velocities.

In the oceans the densities of sub-surface waters are determined almost entirely by temperature, salinity being far less variable. Moreover, the stratification of the oceanic water is stable, the density increasing (as the temperature drops) with increasing depths. Hence the greater the sill-depth of an entrance is, the denser the water that can enter through it.

As the various sills of each basin lie at different depths, the deeper layers inside find fewer straits through which to interchange their waters with the surroundings. Finally the deepest entrance determines the greatest depth at which water from outside can enter the basin. This water fills the entire basin below sill depths, because it is more dense than any other water which can find its way into the basin. In the following communication only this flow of deep water will be considered.

In two Reports of the Snellius Expedition VAN RIEL has dealt with the flow of bottom water into the deep-sea basins of the Moluccas. In the first he showed from temperature data and bathymetrical charts through which entrance each basin receives its homothermal deep water. He found that all deeps are ventilated by water deriving from the Pacific, except for the Sulu Sea, communicating with the South China Sea, and the Timor-Aroe Trough renewed by water from the Indian Ocean.

In the second paper VAN RIEL traced the distribution of oxygen in the bottom water. During the leisurely flow from the ocean through one basin to the next the original supply of oxygen is gradually consumed. Respiration of animals and decomposition of organic matter must be responsible for a slow conversion of O_2 to H_2O, CO_2, etc. The bottom water entering the basins from the oceans contains 3.1 cc/l. The tongue passing from the Indian Ocean finally reaches 2.25 cc/l in the Aroe Basin. In the Sulu Sea the lowest values are below 0.6 cc/l because of very slow ventilation. The water in the entrance to the Celebes Sea contains 2.5 cc/l and sinks to 2.1 cc/l in the Makassar Strait and to 1.7 cc/l at the southern end, while a region of less than 1.7 cc/l is also found in the southern part of the Celebes Sea itself. In Lifomatola Strait, north of Buru the oxygen content has sunk to 2.5 cc/l. In the Banda Basins 2.4 cc/l is reached. In the Sawu Sea 1.7 cc/l is the lowest limit and in the Flores Trough 2.1 cc/l.

There are only a few isolated areas where a slight increase occurs along the bottom without it being obvious where the supply comes from. To the south of Ambon, in the central parts of the Makassar Strait, and east of Saleyer such areas are found.

The distribution of the oxygen in the bottom water thus amply confirms the earlier deductions as to the paths followed from the oceans by the ventilation currents of the deeps. The only minor misfits concern the supply of the Weber Trough, first given as coming south of Banda, now apparently north of Banda and west of Damar. For the Sawu Basin the source is not evident from the oxygen chart.

However, there is yet another aspect of the problems involved in this slow convection which is clearly demonstrated by VAN RIEL's chart of the oxygen content. We are now able, not only to verify through which entrances the water is drawn from the surroundings, but also to trace its path along the bottom and across each basin from the intake to the overflow into the next deep.

The oxygen content of deep water is supplied by two factors: convection from above and ventilation by currents. Convection due to tidal currents is evidently small, otherwise there could not exist areas with very poor ventilation, such as the Sawu Basin, southern Makassar Strait, Sulu Basin, etc.

Convection due to the ventilation flow itself is probably also slight. In the first place former estimates by the present author gave low velocities for these currents *in* the basins, of the order of 0.5 to 0.1 cm per second, or one hundredth part of the velocity of the tidal currents. In the second place turbulence carrying down oxygen would also raise the temperature, because the water above the homothermal deeps is warmer. However, the rise in temperature as the water flows across the floor of a basin is almost imperceptible.

We will return to the heat budget of the deeps presently. It appears safe to estimate the downward transport of oxygen at a few percent, or less, of the original content at the intake.

From the above it follows that there are no local sources of oxygen worth speaking of, while on the contrary consumption takes place all the while. The observed oxygen content must therefore be supplied by renewal of the deep water through the intake.

Hence, of two bodies of water in a single basin which are being supplied by the same intake the one showing the higher oxygen content must necessarily undergo the higher percentage of renewal per unit of time.

This conclusion is of considerable importance, because it now appears a legitimate procedure to ascertain the course of the bottom flow by connecting the points with the highest oxygen content in successive sections

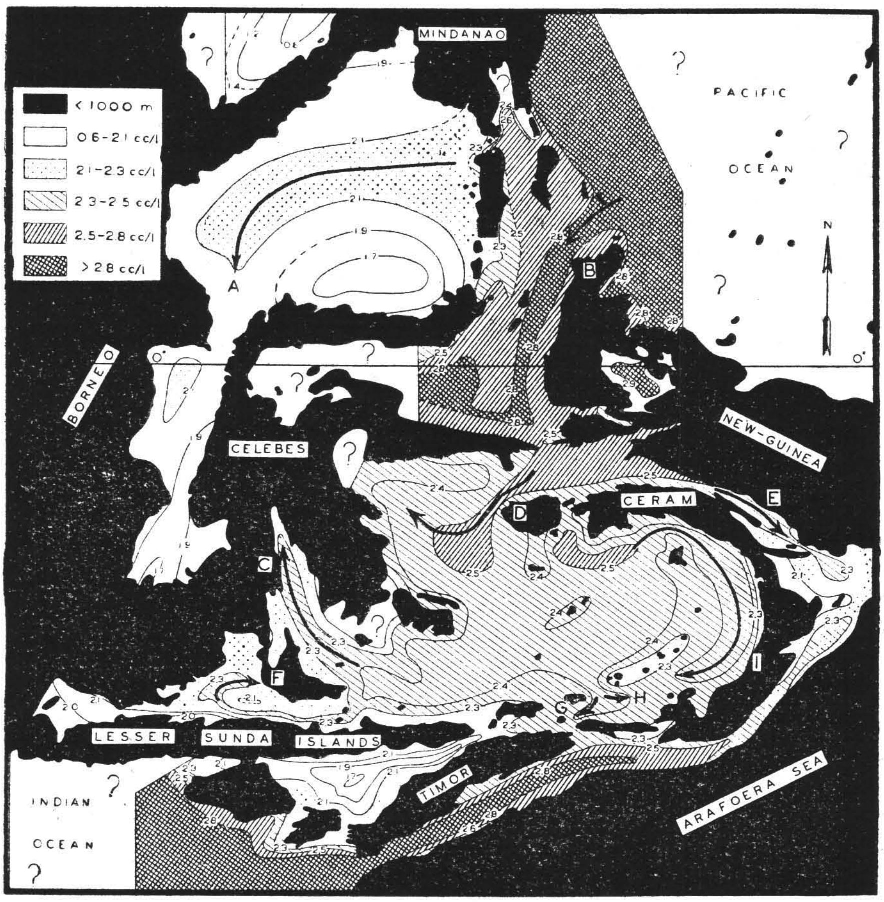

Fig. 1. Distribution of oxygen in bottom water of the Moluccan deep-sea basins, simplified after VAN RIEL. The arrows show the deduced currents.

away from the intake. The areas with lower oxygen content parallel to the line of flow must show a lower rate of ventilation.

On the chart, Fig. 1, an attempt has been made to draw the central line of the bottom flow in a number of the basins and entrances on the basis of VAN RIEL's chart of the oxygen distribution. This brings out a highly significant property of these flows, namely that they are strongly deflected from the shortest line connecting intake with outflow (or blind ending) [1].

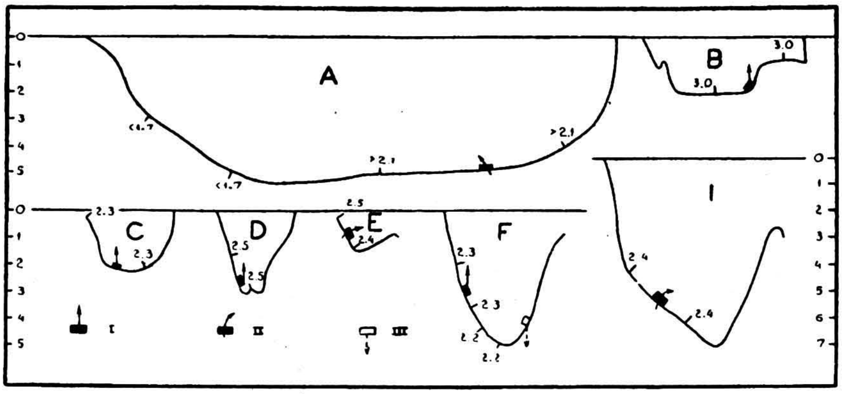

Fig. 2. Sections through Moluccan throughs showing position of iso-oxygen lines and arrows of fig. 1 on the basin floor. (Vertical scale 25 × horizontal, depth in 1000 m.) I and II = currents directed away from the observer, III towards the observer, II additional centrifugal force. A and B north of the equator, C to I south. Section A from middle of northern arm of Celebes to middle of ridge connecting Borneo with Mindanào, B Morotai to eastern point of Snellius Ridge, F Flores due north, the others from corresponding letters on fig. 1.

In fig. 2 a few cross sections are given in which this central line is shown as a block. This demonstrates the degree in which the bottom flow is deflected from the deepest point or the centre of the section.

There are also one or two instances where the central line of the inflow can be ascertained with sufficient accuracy to show that the ventilàting current does not pass through the middle of the entrance but along one of the two sides. The clearest examples occur north of Morotai, where the main flow from the Pacific into the Morotai Basin is evidently deflected against the Snellius Ridge to the north, and Sanana Strait between Buru and Sanana where the current is found well to the south, on the Buru side.

Several factors may be suggested as contributing to this deflection: inaccuracies of the chart, bottom topography, centrifugal force, and finally the earth's rotation (Force of Coriolis).

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[1] To simplify the picture some of the lines of equal oxygen content given by VAN RIEL have been omitted and only those currents have been indicated in which deflection is apparent.

1. *Inaccuracies of the chart.* Large features based on several stations such as the poorly ventilated area in the southern Celebes Sea cannot be the result of poor or insufficient data or either of mistakes in the drawing of the iso-oxygen lines. The consistency of the general picture is so great that even smaller features can hardly be otherwise than real. This will become more evident when treating the other possible factors.

In drawing the iso-lines VAN RIEL had no axe to grind and it may be assumed that his generalization gives the most logical picture that can be based on the data available. For this reason the author has refrained from giving an alternative construction that might be biassed. But it must be admitted that the number of stations where the oxygen content of the bottom water is known amounts only to 200 for all of the area deeper than 1000 m. Several instances are met with in which the iso-lines could be

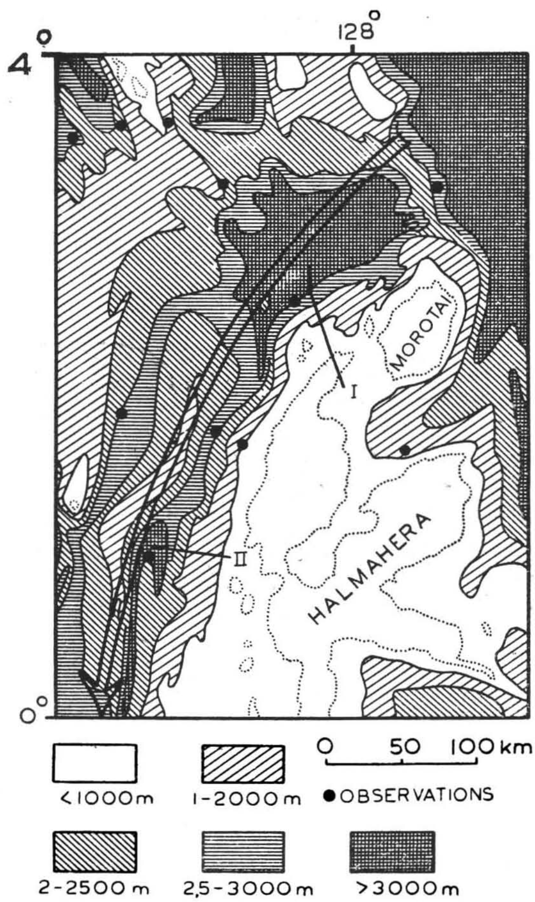

Fig 3. Position of bottom flow as deduced from oxygen content west of Halmahera. I = Morotai Basin, II = Halmahera Trough.

drawn differently with almost equal probability. This is notably the case for the Bali Basin, Aroe Basin, parts of the Timor Trough and the entrance to the Morotai Basin north of Morotai [2]). In fact the central lines given in fig. 1 and 2 must be taken cum grano salis. Nevertheless examination of the oxygen values as given in table form by VAN RIEL has convinced the present author that the deflection of the arrows shown in fig. 1 is on the whole well founded.

2. *Bottom topography* does not appear to influence the flow across the basins. It should be borne in mind that the bottom of the basins is not flat and generally lies several thousands of meters below both intake and outflow. The chart takes no account of this relief and covers all of the bottom below the 1000 meter depth contour. While the topography determines the position and depth of the intake, the shapes of the basin floor within and below this level have remarkably small influence on the flow across the basins. Following the flow on the oxygen chart one can find no indication of the position or depth of the successive homothermal deeps it crosses. The impression is given of a perfectly level floor, even where the depth chart shows the occurrence of great variations in depth. A few examples are the following: the Morotai, Ternate, and Batjan Troughs west of Halmahera (fig. 3); the ridges and troughs between Buru and Celebes; the Buru, Ceram, Bali, and Flores Troughs north of these islands (fig. 4); the immense Weber Trough southeast of Ceram.

The bottom water covers these ridges and deeps in a uniform layer and

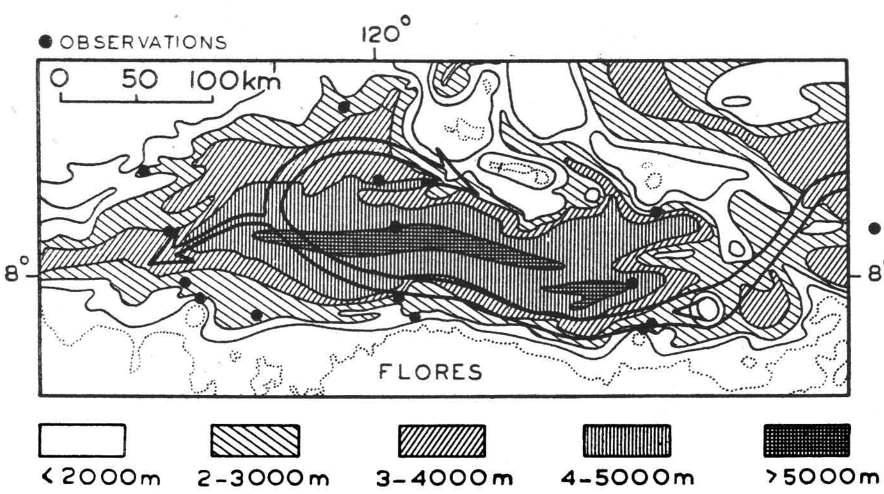

Fig. 4. Position of bottom flow as deduced from oxygen content north of Flores.

their shapes find no expression in the distribution of the property under investigation. It would appear that the variations in density of the almost

[2]) On VAN RIEL's chart the flow through the Lifomatola Strait, 2° south of the equator, is shown as deflected towards the west (right), but the high oxygen content of station 228 forms a strong indication that the centre of the flow runs between stations 224 and 225 well to the east (left) of the deepest part of the sill.

perfectly homothermal water in the deeps is so very slight that the flow does no bypass ridges or deeps, nor stagnate in the latter. It follows its course under the influence of its momentum over elevations and down along depressions irrespective of these undulations of the basin floors.

3. *Centrifugal force* begins to act on the flow as soon as the course is no longer straight. Several cases are met with in which the shape of the basin is such that the flow cannot pass along a straight line from one end to the other. The Weber Trough and Ceram Trough form the best examples, less obvious is the case of the Gulf between the southern arms of Celebes. The flow passing down these basins has to follow a curved course and centrifugal force will act, carrying the central line towards the outer side. Centrifugal force will also be a contributing factor in cases where Coriolis' force forms the primary cause of the curved course, and topography the secondary cause (e.g. the Celebes Sea).

4. *Coriolis' force* acts on all currents and is even the principal factor determining the course of many oceanic currents. But as the value of this force decreases towards the equator where it reaches zero, oceanographers have expressed doubt whether in the Moluccas any influence could be apparent. The main purpose of this article is to show that the ventilation currents appear to be deflected by the earth's rotation.

As it happens, there are three narrow ventilation currents in which the deflection might be attributed to centrifugal force, as pointed out above. However, there are other instances in which this cannot be the case. The two most obvious of these occur where the water passes through straits and flows in a straight line. No centrifugal action can therefore be invoked to explain the observed deflection. These are the currents already referred to north of Morotai and of Buru (the position of the former is rather doubtful). Cross sections of these straits (fig. 2) show the marked degree in which the central line of the intake is forced sideways up against the lateral slope of the entrance. In spite of this upward deflection the water passing through the entrance originates at sill-level outside. This follows from a comparison of the temperature of the flow and the stratification outside (see VAN RIEL, 1934).

The deflection of the flow to the right between the Talaud Islands and Miangas south of Mindanao is small and requires verification.

Another case in which Coriolis' force must be the primary cause of deflection, but where the effect is enhanced by centrifugal force is met with in the Flores Trough.

The ventilating current passes along the southern slope, far above the level of the centre of the trough and curves back 180° on itself in a finely developed loop (fig. 4). The topography in itself gives no clue to this remarkable behaviour. Hence the earth's rotation must be the sole *primary* cause of the spiral flow.

The flow passing through the Celebes Sea is markedly curved on its way from the entrance in the northeast to the outflow into the Makassar Strait. A large stagnant area to the south is avoided. Here again, the only logical reason the writer can suggest is Coriolis' force, augmented by centrifugal force.

These examples where the earth's rotation evidently acts as an independant cause in deflecting the bottom flow are sufficiently clear to allow invoking the same force as additional cause for explaining the three ambiguous cases cited earlier, where topography is also active.

Summarizing we find 4 examples of the action of Coriolis' force, of which two lie north of the equator with deflection to the right, and two south with deflection to the left. Furthermore three cases in which the force appears to add to centrifugal deflection, all south of the equator with deflection to the left. Finally one doubtful case north of the equator (Miangas), and one south (Lifomatola Strait).

No deflection is shown on VAN RIEL's chart in the flow passing from the Indian Ocean into the Timor Trough and Aroe Basin. The distribution of oxygen in the Bali Trough is even opposite (higher values on the north side) to what should be expected. In the latter instance there are only three stations lying in a straight line along the axis of the trough. Hence no weight can be given to this case. There are more data for the Timor Trough and one would have expected a marked deflection. The writer has no suggestion to offer to account for this apparent absence of deflection.

As VAN RIEL's chart of oxygen distribution appertains only to the bottom, the noted flows form merely the sole of thicker bodies moving through the basins. Only by investigating the whole of the homothermal water body in a basin can information be obtained as to the general shape of the convection and ventilation of the deeps.

The foregoing discussion has brought out that thanks to the very slight variations in density in the homothermal deeps, the small force of Coriolis near the equator appears to be sufficient to deflect the ventilation flows so as the cause them to rise from the floor of the basin to higher levels along the slope. The importance of this result lies partly in an explanation now being available for the curious pattern of oxygen distribution, and partly in the possibility of calculating the velocity of the ventilation flows when the deflecting forces are taken into account. The distribution of density throughout the homothermal deeps is known from many oceanographical stations with considerable accuracy. Theoretically it should therefore prove possible to calculate the strength of the deflecting force that causes the flow to deviate from the central line of basin or entrance and to rise laterally against the gentle slope of the floor and sides. As the value of Coriolis' force depends only on velocity, besides on factors that can be calculated or estimated for a given case, the velocity should be ascertainable for the Moluccan ventilation flows.

Complications may arise, however, where more than one current occur at different levels. Another difficulty is that the cross-section of a single current may show independent variations in density and velocity. It will evidently be no simple matter to arrive at satisfactory conclusions.

Dr. GROEN, oceanographer of the Koninklijk Nederlands Meteorologisch Instituut in de Bilt, has undertaken the task of attempting this calculation as part of the work he is doing on the Snellius results [3]). If the available data prove sufficient, both biology and geology will gain highly significant foundations for quantitative computations. The total amount of organic matter sinking from above into the homothermal deep could be estimated from the rate of sedimentation and the percentage of decomposable matter in the deposits, when coupled with the amount of O_2 used in metabolism and decomposition. Limiting values for the intensity of animal life in the deeps would also become available. Furthermore the solution of lime and silica are dependent, amongst others, on the rate of renewal of the bottom water. The transport of suspended sediment in the deeps could also be evaluated. Before attempting any of these computations the results of Dr. GROEN should be awaited.

A final point may be shortly touched upon. The deep water flowing from the oceans through the successive basins receives heat from four sources: (1) reaction of oxygen with organic matter, (2) the flow of internal heat from the earth, (3) turbulent mixing with warmer overlying water, (4) friction.

The amount of heat generated by the reactions consuming oxygen can be roughly estimated. The average loss of O_2 between the inflow from the oceans and final removal of the water from the homothermal deeps is of the order of 1 to 2 cm^3 per liter. This should generate about 5 to 10 gr. cal. per liter and raise the temperature by 0.005° to 0.01° C.

The flow of internal heat is of the order of 50 gr. cal. per cm^2 per year. The amount of heat generated by oxygen consumption in the homothermal deeps of 2000 m is 1000 to 2000 gr. cal. per cm^2, or 20 to 40 times as much as the annual flow of internal heat. Hence, if the renewal of the homothermal deep takes 20 to 40 years, both factors would contribute equal amounts.

The turbulent mixing and frictional heat are due to swimming animals, slight turbulence and friction of the flow and tidal currents within the basins, and strong turbulence and friction in the relatively swift currents (also in part tidal) in each passage from one basin to the next. The rise in temperature between the Pacific and the Sawu Basin is about 0.5°—1° C and is due almost entirely to mixing and friction in the narrow straits. Data for judging the horizontal variations have not yet been published. But the contribution from all factors acting on the water in a single basin may be estimated in first approximation from the rise in temperature between the bottom and the upper part of the homothermal deep on the tentative

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[3]) The writer wishes to thank Dr. GROEN for helpful criticism of the present paper.

assumption that the bottom water near the entrance shows the temperature of the intake and the top of the homothermal deep shows the temperature attained when the water leaves the basin. The difference is of the order of 0.10° to 0.15° C in the Celebes Sea.

As the oxygen consumption per basin is less than 1 cc/1 this factor is probably only of small importance. Whether the flow of heat from the earth is found to be quantitatively important, will depend on the time available. If the renewal occupies 200 years it would account for a rise in temperature of 0.05° C. That would leave 0.1° C of the estimated rise of 0.15° C to be caused by turbulence and friction. This could be brought about by the addition of 10 % water of 1° C higher temperature. The author is not able to offer an estimate on the contribution from friction.

Evidently the heat budget of the homothermal deeps is closely related to the velocity of the bottom flow, and must be reconsidered when the latter value is better known.

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