UPWELLING IN THE BENGUELA CURRENT

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THE Benguela Current is one of the major features of the circulation of the South Atlantic Ocean. Extending northwards along the African coast from the neighbourhood of Cape Town to about lat. 15° S., the current is a region of upwelling of relatively cold water rich in nutrient. The resultant high fertility of the surface waters gives rise to great production of planktonic plants and animals, while the presence of the cool water has extensive climatic effects. In such features the Benguela Current has much in common with the Peru Current, which was surveyed by the R.R.S. *William Scoresby* under the Discovery Committee in 1931. When this ship visited South African waters in 1950, two surveys of the Benguela Current were carried out, first in March and again in September–October. The programme for the voyage was planned by Dr. N. A. Mackintosh, and it included these surveys not only to allow a comparison to be made with conditions in the Peru Current but also because such regions are specially favourable to investigations on the production of life in the sea.

The German Atlantic Expedition (in the *Meteor*) was the first to study the current extensively, and it enabled Defant[1] to produce the most comprehensive account of it so far. The *Meteor* observations, however, were relatively widely scattered in space and time; they provide a broad picture of the current and its effects in relation to the South Atlantic as a whole, but leave much to be learnt of the fluctuations of the current and the mechanism of upwelling. Hence the *William Scoresby*'s work included lines of closely spaced 'stations' off the South West African coast (Fig. 1). Limited time restricted them to the coastal region, but these intensive observations covered the area which, in view of Defant's findings, was most likely to be of interest.

As the surface currents of the eastern side of the South Atlantic are principally wind-driven systems, to understand them one must have a knowledge of the prevailing winds. Over the South Atlantic the surface winds blow out anticyclonically from a large region of persistent high pressure, and the component blowing over the eastern part of the ocean is the South-East Trade Wind. Near land, however, the trade wind develops a landward component which varies with the fluctuations of pressure over the continent, this in turn resulting from the great heating and cooling which the land mass undergoes. This landward wind or sea breeze thus shows a marked diurnal variation, and frequently attains considerable force, blowing from almost due south in lat. 30° S., and veering to south-west northwards along the coast.

It is not surprising, therefore, that the sea surface currents should show considerable irregularity in the coastal region. Defant, from an analysis of the Dutch current observations, found that inside the relatively constant drift current produced by the South-East Trade, the coastal currents were extremely irregular, and were separated from the drift current by a "one-sided line of divergence". Further, Defant showed that the region of strong negative temperature anomaly was confined to the coastal current.

Distribution of temperature and salinity. The accompanying charts (Fig. 1) show the distribution of surface temperature, compiled from the 'station' observations and supplemented by the data from a distant-reading thermograph with which the ship was equipped. On both surveys, the most outstanding feature of the distribution was the pronounced irregularity of the isotherms. Whereas the isotherms of the open ocean run more or less latitudinally, in the

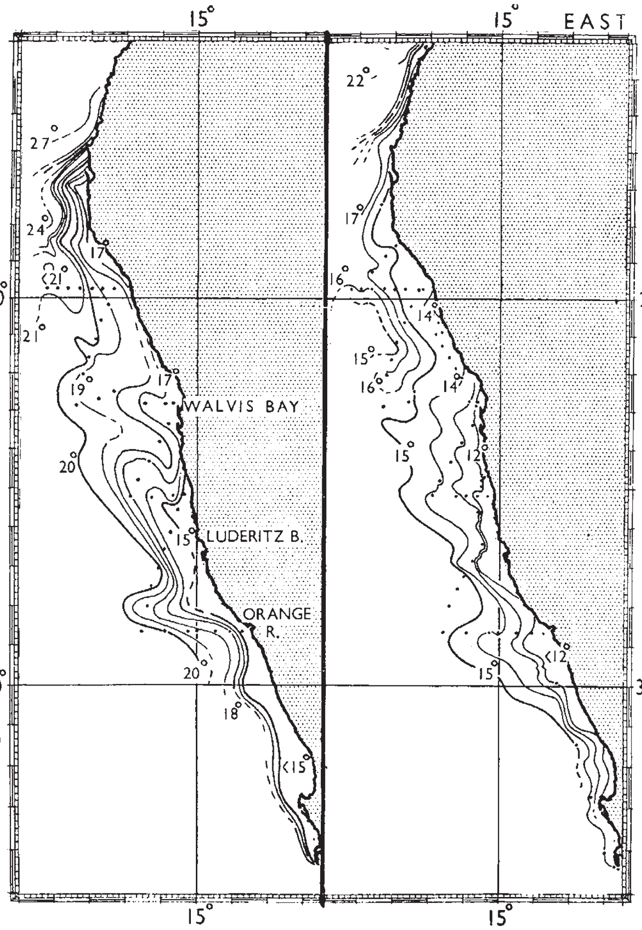

Fig. 1. Sea surface isotherms (*a*) during March, (*b*) during September–October 1950. Isotherms are drawn for each whole degree C. Stations are shown by dots

Benguela Current they run approximately parallel to the coast. The existence of the interlocking tongues of relatively cool and warm water suggests that the upwelling of cool water to the surface occurs not everywhere, but at separated points along the coast. The distribution of salinity follows a pattern similar to that of temperature, the lower salinities occurring in the cool water against the coast. Offshore, one finds that, while the temperature rises relatively steadily, there is a sharp contrast between the salinity of the inshore waters (*c.* 35·00‰ or less) and that of the offshore waters (*c.* 35·20‰). It appears, therefore, that there are two distinct surface waters, generally with a fairly sharp boundary between them, although in places mixtures occur. The inshore water generally has similar properties to the water at sub-surface depths farther offshore.

Examination of the vertical distributions of temperature and salinity shows that on both surveys a well-developed homogeneous surface layer was present offshore. This was separated from the underlying water layers by a strong temperature discontinuity. Inshore, however, there was evidence of considerable variation: during the first survey no such homogeneous layer was detected, and strong heating had apparently taken place on the surface; but during the second survey, there was a thin homogeneous surface layer overlying a weak discontinuity. This difference indicates the contrasting effects of the calm conditions during March and the strong winds during September–October.

Below the upper water layers, both temperature and salinity fell steadily to the salinity minimum of the Antarctic Intermediate Current. Fig. 2 shows the dispersion of all the temperature and salinity observations made in 1950 by the *William Scoresby*, between a depth of 100 metres and the Antarctic intermediate salinity minimum. It can be seen that all lie within narrow limits of the characteristic temperature – salinity curve of the South Atlantic Central Water[2]. As the Antarctic Intermediate Water moves north, it mixes vertically with the overlying and underlying more saline waters. Consequently, the salinity minimum becomes less pronounced towards the north until, finally, it becomes obliterated completely. Using Wüst's 'Kernschichte Methode'[3] —the heavy line in Fig. 2—one finds that in the core of the Antarctic Intermediate layer off South-West Africa only 50 per cent of the original water type remains and this at a depth of more than 600 metres. Since our data indicate that the upwelling does not extend much below 300 metres, it is only a relatively small proportion of Antarctic intermediate water which is subject to upwelling.

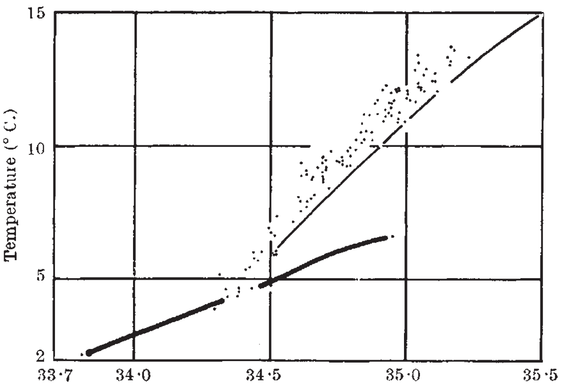

Fig. 2. Temperature – salinity relationships of the water layers between 100 metres and the salinity minimum of the Antarctic Intermediate Water. The heavy line shows the relationship of the core of the Antarctic Intermediate Water from the source (left) to the northern limit (right) after Wüst (ref. 3). The thin line is the line characteristic of South Atlantic Central Water (Sverdrup, ref. 2)

The strong indications of active offshore transport of surface water during September–October, compared with the more quiescent conditions found in March, demonstrate the difference between active upwelling and the more advanced stage of mixing of previously upwelled water. The dynamical principles of the movement of a northward-flowing current in the southern hemisphere require that the more dense water should lie in the east side of the current, and upwelling may purely be a lifting effect within the current.

The wind records for the periods preceding the two surveys leave no doubt, however, that the great difference between the surveys was a direct result of the prevailing wind conditions. No detailed observations of the wind over the sea are available; but it is known that the trade winds were much stronger during September–October than during March. In addition, wind records from three South-West African shore stations show that whereas the sea-breeze was light and variable during February and March, it would have been conducive to a longshore transport of surface water during September–October.

Since there are no direct observations of current, the anomalies of dynamic depth of the isobaric surfaces have been calculated, with reference to the 600-decibar surface. Although in a region where vertical movements are important this method must be used with much caution, the inferences appear reasonable, and show similar features to findings in other regions[4,5]. During March, the computed currents show a general movement to the north with a rather weak southerly movement inshore, reaching to about Luderitz Bay. During September October, a series of horizontal eddies was present inside a much stronger northerly flow. Vertical sections through the eddies indicate that the sea surface slopes upward from the coast to a line of convergence, and then falls into a trough, and farther offshore slopes upwards again. On some of the sections the observations did not extend far enough seawards to show this trough, although the line of convergence was always well marked. Since the sea surface must eventually rise towards the open ocean, however, it is probable that such a trough was there. An example of this distribution is given in Fig. 3. Sverdrup[4] has pointed out that in a region such as this (Sverdrup deals with the Californian coast), strong convection will develop between the more dense water upwelling and being transported offshore and the light offshore water, sufficiently well defined to be regarded as a boundary. Seawards of this boundary there is a tendency for divergence within the offshore water due to the increasing effect of the wind on the surface. A circulation of two vertical cells would thus be formed, separated by a strong convection current. As the boundary moves offshore, there must be a compensation flow into the inner cell, and this Sverdrup defines as the upwelling movement, the upward movement above being part of the cellular circulation. Superimposed upon this vertical circulation must be a horizontal eddy formation.

It appears, therefore, that the circulation is somewhat more complex than Defant could deduce from the data at his disposal, and the 'one-sided divergence'

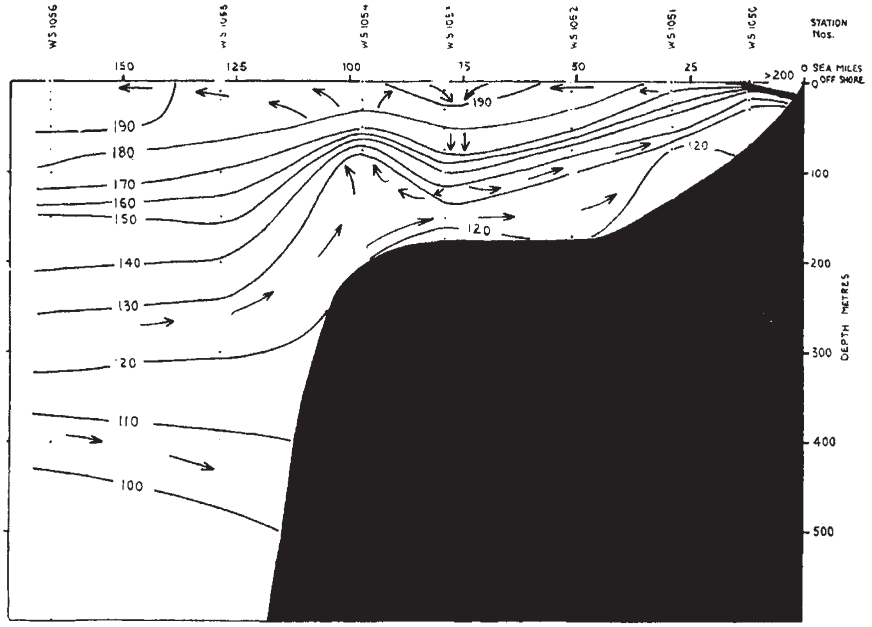

Fig. 3. Vertical section normal to coast in lat. 28° 40′ S. showing isosteres and probable direction of water movement in the vertical plane. (Isosteres are the lines of equal specific volume expressed as the difference × 10^5 from the specific volume of sea water of 35 parts per 1,000 salinity and 0° C. at the same pressure)

seems to be an eddy-like system rather than one long continuous divergence line. The size and stability of these eddies must depend upon the intensity of the forces which produce the upwelling, and about which there is still little precise information. The distance to which they persist must be variable and governed by the variability of the external forces. Whether the eddies are consistently formed in any particular regions is difficult to say without more intensive observations, although the continuous low temperatures and high productivity of the region around Luderitz Bay (*c.* lat. 26° S.) suggest that this may be one region where eddies often form.

Although no significant temperature – salinity differences occur in the underlying water layers (Fig. 2), there is a great depletion of dissolved oxygen and enrichment of phosphate close to the continental slope. This layer of oxygen minimum and phosphate maximum is similar to that found extensively over the equatorial regions of the ocean. It probably results from a balance between the rates of decomposition of organic matter, and the turbidity and diffusion rates between those layers and the neighbouring water masses. Upwelling brings some of this poorly oxygenated, highly nutrient water into the euphotic zone. Although this will favour great phytoplankton production in the surface layer, the low oxygen content will help the effects of local decomposition of organic matter to maintain almost anaerobic conditions in the shallow reaches of the continental shelf.

The inorganic phosphate content of the upwelled water is very high (> 2·0 mgm. atoms phosphorus/$m.^3$, about four or five times the present normal winter maximum of the English Channel[6]), in contrast to the almost complete absence of phosphate in the offshore surface waters. Local maxima and minima occur, as the oxygen shows varying degrees of saturation with the varying abundance of the phytoplankton populations. It was found that the phosphate content on the shelf was often greater than that in the upwelling water. This may be due to intense local regeneration from decaying plankton.

During the second survey an attempt was made to measure the extent of the 'azoic zone', a region of reducing mud[7], and this was found to cover a larger area than was previously supposed. A series of Baillie rod soundings revealed that it extended, at least in patches, between depths of 50 and 150 metres, for about 400 miles north of lat. 25° S. The sediment, a dark green diatom mud, is populated with sulphate-reducing bacteria ; their production of hydrogen sulphide must further reduce the oxygen content of the local shelf waters. The oxygen depletion was most marked near Walvis Bay: during March the water with less than 1·0 c.c. oxygen per litre extended to the sea surface; during September–October, however, these low concentrations were confined to the lower third of the water column. In the determination of the oxygen, steps were taken to eliminate the effect of large quantities of reducing substances and organic matter.

At times, the concentration of hydrogen sulphide becomes so high that the gas is actively evolved from the sea surface. As this frequently occurs at the same time as mass mortalities of marine organisms, some authorities have attributed the mortality primarily to an oxygen deficiency. Brongersma-Sanders[8] has, however, preferred to consider the effects of toxins released from mass outbursts of certain dinoflagellates as being the primary cause, principally on evidence from other similar regions.

Dr. T. J. Hart has found 3,000–5,000 cells/ml. of small dinoflagellates in samples collected from discoloured water patches during these surveys. They have not been finally identified, but probably belong to one of the several genera known to include species capable of producing toxic effects. Small mortalities actually occurred during March 1950, but there is insufficient evidence to show which factor was the more important. The effect may well be due to several unfavourable factors acting together.

A paper on preliminary results of analyses of the other plankton samples by Dr. Hart will appear shortly. This shows that good agreement between the plant and animal distributions and the physical and chemical data is often apparent. Thus all the very heavy diatom populations occurred in the upwelled water ; and they coincided with the highest supersaturation values of the surface water with oxygen. At times, dense concentrations of Chætocerids imparted an olivaceous colour to the upwelled water, in contrast to the transparent blue offshore water. The scanty phytoplankton of the latter included a relatively high proportion of the diatom *Planktoniella sol*, which seems a useful indicator of intrusions of offshore water towards the coast, as

Gunther and Rayner[9] had found previously, off Peru.

The physical and chemical results will be published shortly by the National Institute of Oceanography in the 'Discovery' Reports, and further studies are being made of some of the problems which have been mentioned with the particular object of obtaining evidence about the factors which affect oceanic productivity.

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MAGNETIC PROPERTIES OF ROCKS

THE significance of the natural remanent magnetism of igneous and sedimentary rocks has not yet been determined. On one hand, there is the hypothesis that the direction of magnetization can be interpreted in terms of a widely varying magnetic field and, on the other, that the adverse polarizations arise from intrinsic properties of the rock assemblage. These aspects formed the main theme of a geophysical discussion at a joint meeting of the Royal Astronomical Society and the Geological Society, held in London on January 23, with Prof. E. C. Tilley (Department of Mineralogy and Petrology, Cambridge) in the chair. Prof. Tilley noted that the magnetic properties of rocks have also been found to be of considerable value to geologists by yielding magnetic anomalies reflecting the distribution of certain rock-types, the measurement of such anomalies culminating in aeromagnetic surveys.

In opening the discussion, Dr. J. M. Bruckshaw stated that the value to the geologist of the results he proposed to discuss would be controlled by their final interpretation. Of recent years the study of permanent rock magnetism has been intensified, and Dr. Bruckshaw's interest was first aroused by the discovery that the tholeiite dykes of northern England are magnetized in a direction opposite to that of the present earth's field. Since these dykes represent the final phase of igneous activity centred upon Mull, it was an obvious step to examine the rocks in the earlier phases of this activity. The earliest phase was the quiet extrusion of a sequence of lava flows followed by the cyclic intrusion of basic and acid ring dykes and cone sheets about a centre which migrated twice towards the north-west. The final phase was the production of the north-west dyke swarms, of which the tholeiite dykes were the last members. Since a known time-sequence of events exists, it is possible to sample rocks of different periods and, in the present case, some of the basalt flows, some early basic intrusions, the ring dykes of Glen More and Loch Bà and some of the north-west dykes were examined. After a rock has been polarized, many factors may tend to modify it, and some influences will result in random magnetization. For example, a partially solidified lava-flow might be broken up by a further supply of lava. Thus a number of specimens from each formation must be examined, and they usually show a scatter of directions. Inspection may be sufficient in some cases to determine if the mean direction has a significance, but the probability that the observed set of directions can be selected from a random distribution is used for indicating what weight can be attached to the mean direction; the smaller the probability the more significant the mean direction.

Using those formations associated with significant directions, the basalt flows proved to be adversely magnetized and also the early basic intrusions. The more acid ring dykes of Glen More and those of Loch Bà were normally magnetized; but a dolerite dyke, earlier than the Loch Bà granophyre, proved adversely magnetized. The dykes of the north-west swarm were normal, and to this must be added the adverse phase of the tholeiite dykes, giving a total of three adverse phases.

The large observed intensities of magnetization in relation to the earth's magnetizing field can only be explained in terms of thermoremanence acquired during the initial cooling, the only occasion when the present rocks were at the necessary high temperature. If this is accepted, the amazing stability of this polarization follows; and laboratory observations support this conclusion, the coercive force of the rocks being comparable with that of modern magnet-steels. In all respects the rocks exhibited ordinary magnetic properties under a variety of conditions and, in particular, acquired normal polarization when cooled in the earth's field. It would thus appear that the simplest explanation of the facts is a number of reversals of the earth's magnetic field in the past, a suggestion to which there are no theoretical objections.

Mr. K. M. Creer pointed out that the main evidence on adverse magnetization comes from igneous rocks, which are magnetized either normally or at 180° to the normal direction. Although there are no theoretical objections to a reversal of the earth's polarity, other explanations of adverse magnetism are possible, such as those suggested by Neel. One of these assumes a constituent having a spinel structure in which two sub-lattices exist, one tetrahedral and the other octahedral. The spontaneous magnetic vectors associated with the sub-lattices have opposite directions and, in suitable conditions, the resultant magnetization would change sign with temperature, thus allowing adverse polarity. This property of imperfect antiferromagnetism is not known. Another process involves two magnetic constituents with widely differing Curie temperatures. On cooling, the constituent of higher Curie point is first magnetized and produces a demagnetizing field. Due to its large negative temperature-coefficient, the initial intensity grows rapidly and the demagnetizing field ultimately exceeds the original field at the Curie point of the second constituent, which becomes adversely magnetized. The ferromagnetic constituents must occur in aggregates of high local concentration.

Mr. Creer recorded that a hypersthene hornblende dacite discovered by Nagata does exhibit adverse magnetization when cooled in a weak field. From it, two magnetic constituents have been separated by Dr. G. D. Nicholls, of the University of Manchester. One (probably magnetite) behaves normally, but the other shows reversed thermoremanent magnetism. He suggested that the normal behaviour of naturally