In the central Pacific, atolls are indeed situated on subsiding foundations, as has been demonstrated by drilling on Funafuti, Bikini and Eniwetok. Oceanographic work carried on by the Scripps Institution and the Navy Electronics Laboratory has also shown evidence of subsidence on a comparable scale over vast areas in the central Pacific. The Mid-Pacific Mountains, for example, a range that is similar in size and gross morphology to the Hawaiian chain, has subsided some 4000 ft since the Cretaceous (HAMILTON, 1956, pp. 43-48; 1957, p. 5). The isostatic subsidence of individual volcanoes as postulated long ago by MOLENGRAFF may be, locally, a controlling factor but regional changes of level over large parts of the Pacific basin are indicated. These changes may be due to isostasy or crustal movements of other sorts, redistribution of ocean waters caused by shifting of the poles or to a combination of these and perhaps other causes. The Pacific Basin that is bounded by the Andesite Line shows evidence of submergence that contrasts with evidence of elevation beyond that line (summarized by EMERY *et al*, 1954, pp. 152-154). The widespread submergence of the basin does not appear to have been uniform and almost certainly was not continuous. Our note did not mention all possibilities or combinations of them because we were concerned primarily with evidence of emergence that interruped prolonged subsidence.

It is difficult to estimate the amount and the duration of the indicated older periods of emergence. We feel that several hundreds of feet were probably involved – more, in any event, than " small eustatic movements." The emergent periods last long enough to permit the development of a dense tropical deciduous forest and the establishment of land snails of the high island type. Additional data supporting the postulated periods of emergence and the ways in which emergent atolls could have aided in the distribution of life in the Pacific are discussed in a paper by LADD scheduled for publication in the January 1958 number of the *Journal of Paleontology.*

*U.S. Geological Survey,**
Washington 25, *D.C.*

H. S. LADD and J. I. TRACEY, JR.

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The abyssal circulation

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IN my survey of the theories of ocean currents (*Deep-Sea Res.*, 1957, **4**, 149-184) several schematic interpretations of ocean circulatory patterns are presented. In this letter I wish to show how, using the same principles, it is possible to sketch in broad outline the flow pattern for the abyssal circulation of the world ocean.

It seems likely that the low temperature of deep waters in the world ocean is maintained in the face of downward diffusion of heat from the warm surface layers by a very slow upward component of velocity in the deep water. An adequate theory of the thermocline would, presumably, deduce this upward velocity as a function of surface heating, turbulence parameters, etc. We might regard the thermocline as a " pumping mechanism " which slowly draws up deep water and hence actually determines the rate of flow of the abyssal circulation. An estimate of the maximum upward component of velocity under the thermocline, w_{max}, is given in terms of the depth of the thermocline, z_t, by the equation.

$$w_{max} = \frac{\sqrt{2}}{4} \frac{\beta g \alpha l}{f^2} z^2{}_t \, \theta_0.$$

This equation is obtained from a very primitive model* of convection on a beta-plane and contains neither the turbulence parameter nor the artificial basic stability explicity. Both enter implicitly, of course, through the very structure of the model ; both are basically objectionable, are introduced to circumvent our lack of physical knowledge about turbulence and our inability to handle the non-linearity of the energy equation respectively. Consequently our conclusions are limited, at best, to order of magnitude considerations. If we take as representative oceanic averages

$$\beta = 2 \times 10^{-13}\ \mathrm{cm^{-1}\ sec^{-1}}$$
$$g = 10^3\ \mathrm{cm\ sec^{-2}}$$
$$\alpha = 2 \times 10^{-4}\ {}^\circ\mathrm{C}^{-1}$$
$$\theta_0 = 10^\circ\mathrm{C}$$
$$f = 10^{-4}\ \mathrm{sec^{-1}}$$
$$l = 5 \times 10^{-9}\ \mathrm{cm^{-1}}$$
$$z_t = 2 \cdot 10^4\ \mathrm{cm}$$

we find that w_{max} is of the order of 3×10^{-5} cm sec^{-1}. Since the area of the ocean at 2000 m is about 3×10^{14} m^2, the total upward flux of water across the 2,000 m level over the entire world ocean is

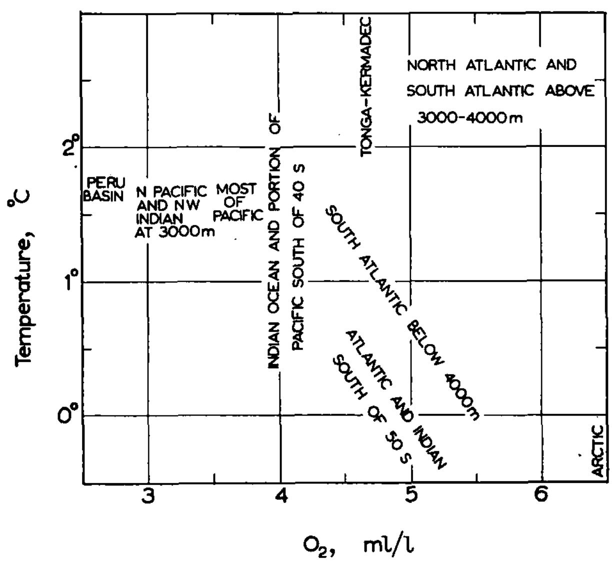

Fig. 1.

of the order 90×10^6 m^3 sec^{-1}, about twice the maximum estimated by analysis of hydrographic data. The slow upward flow over most of the ocean must be compensated for somewhere by downward flowing sources of deep water. I envisage these deep-water sources as occurring in very limited areas of weak gravitational stability where the thermocline " springs a leak." The location of these sources is apparently very sensitive to climatic factors ; we determine it by consideration of the distribution of dissolved oxygen in the ocean below 3,000 m (Fig. 1). Evidently the two sources are in the North Atlantic, and in the Weddell Sea (heavy black circles in Fig. 2); there is no source

*HENRY STOMMEL and GEORGE VERONIS (1957) *Tellus* 9, 401-407, to which the reader is referred for definitions of quantities : the above relation being derived by substituting $Gz_t = 1$ into equation (20).

in the Arctic regions of the Pacific Ocean. The simple beta-plane convective model also assures us that the wind has no effect on the water below 2,000 m. Therefore, we have a distributed " sink " more or less over the entire ocean below 2,000 m acting on the water below ; and two point " sources." To complete the picture of the thermal circulation in the ocean we must connect the distributed sink to the sources in a way consistent with the dynamics of the fluid on a beta-plane or rotating sphere.

The streamlines in Fig. 2 are sketched following the modified form of Goldsbrough's method for the rotating sphere as described in my survey article. Because of the distributed " sink " the

Fig. 2.

flow below 2,000 m is everywhere horizontally convergent, hence the meridional component of velocity below 2,000 m must everywhere in the interior of the ocean be directed away from the equator ($\beta v = -f \operatorname{div}_h \vec{v}$): except at the equator itself where it must vanish. Having fixed the meridional component and vertical component, the zonal component is determined by the continuity equation working westward from the eastern coasts. At the western coasts intense boundary currents are introduced as necessary to connect with the sources. The chief ambiguity is how much water to admit through Drake Passage ; the Antarctic Circumpolar Current Transport is fixed however. Summarizing the features of flow deduced in Fig. 2 : If the two sources each have strength 20 ($\times\ 10^6\ m^3/sec$), then the western boundary currents are : western North Atlantic, 24 southward ; western South Indian, 14 northward ; western South Pacific, 30 northward ; western North Pacific, less than 10, directed toward 30°N. latitude circle. The zonal transport of the Antarctic Circumpolar Current (below 2,000 m) is 50 across 55°S. latitude circle. In the interior of all oceans at mid-latitudes below 2,000 m the mean meridional component of velocity is of the order of 0·03 cm sec^{-1}. The value of w_{max} is $1 \cdot 5 \times 10^{-5}$ cm sec^{-1}.

The above presentation is in the nature of a *tour-de-force*. One cannot pretend that it describes the the abyssal circulation accurately in detail.

Woods Hole, Mass., U.S.A. HENRY STOMMEL

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