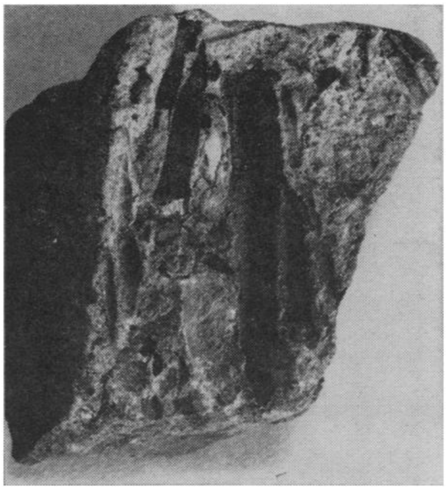

Fig. 2. *Belemnoid* fossil casts from Johnson Nunatak (0.6 times natural size).

collected. A Cretaceous age for this bed was based on the following assemblage:

Rotularia callosa (Stoliczka), a serpulid worm species (Fig. 1).
Belemnoid (Fig. 2).
Synclyclonema sp., a pelecypod.
Variamusium? sp., a pelecypod.

Rotularia callosa occurs frequently in Cretaceous rocks of the Southern Hemisphere, having previously been described from the Aptian of Patagonia and the Campanian of New Zealand as well as from the Cenomanian of India (*3*).

In Antarctica this species has been reported from beds of Aptian age on Alexander I Island (71°21′S, 68°21′W) and from beds of Campanian age on James Ross and Snow Hill islands (64°S, 58°W) (*3*). No fossils present at Johnson Nunatak allow a more precise age than that from Aptian to Campanian indicated by *R. callosa.*

The collection was examined by N. F. Sohl (*4*) who corroborated the identifications and Cretaceous age.

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18 November 1963

Equatorial Undercurrent of the Indian Ocean

Abstract. *Measurements of currents at the equator in the Indian Ocean indicate the presence of an equatorial undercurrent. This current is similar in many respects to the undercurrent in the Pacific and Atlantic oceans. The undercurrent in the Indian Ocean is located in the thermocline and is of low magnitude, unsteady, and more strongly developed on the eastern side of the ocean.*

During the past year the equatorial circulation of the Indian Ocean has been studied in two 3-month cruises carried out from the research vessel, *Argo*, of the Scripps Institution of Oceanography of the University of California. These studies are a United States contribution to the scientific program of the International Indian Ocean Expedition (*1*).

The main objective of these studies was to determine whether the Indian Ocean possesses a current structure similar to that found near the equator in the Atlantic and Pacific oceans (*2*). Measurements at the equator in these oceans have revealed high-speed, subsurface, eastward flows centered at the equator. The Equatorial Undercurrent in the Pacific (Cromwell Current) has been shown to have a maximum speed of 100 to 150 cm/sec at a depth of 50 to 100 m. The current is about 4° wide, symmetrical about the equator, and relatively steady in time. The Equatorial Undercurrent in the Atlantic, although less well documented, appears to be analogous to its counterpart in the Pacific (*3*).

It is generally believed that the Equatorial Undercurrent is in some way driven by the surface winds (*4*). If so, one might expect to find a difference in the equatorial current structure with different wind systems. For this reason, observations were made during the two phases of the Indian Ocean monsoon.

The first cruise, 28 June to 24 September 1962, was during the period of the southwest monsoon. The second cruise, 16 February to 15 May 1963, began at the end of the northeast monsoon period and concluded during the beginning of the southwest monsoon period. The results of a preliminary analysis of the data from the first cruise have already been reported (*5*). Some of the conclusions presented in that paper have now been modified upon further analysis of the data. In particular, an equatorial undercurrent structure, although somewhat different from that observed to be characteristic for the Pacific and Atlantic oceans, was measured on the eastern meridional sections of this first cruise and our conclusion that no undercurrent was present now applies only to the western sections. This report is based on the data from both cruises and is focused on the question of the existence of the Equatorial Undercurrent in the Indian Ocean. The station pattern on the two cruises was nearly identical with four north-south sections across the equator and a zonal section along the equator occupied during both periods (Fig. 1). Current measurements were made from the surface down to 400 m on each meridional section at 1° intervals from 2°N to 2°S. The measurements were made with a telemetering current meter from a drifting ship by a technique previously described by Knauss (*3*).

On three of the eight sections (79°E, 89°E, and 92°E) the distribution of the zonal component of velocity with depth was similar to that of the Equatorial Undercurrent. The core of these eastward flows was located in the middle thermocline, the maximum eastward speeds were centered at the equator, the associated meridional components were small in comparison to the zonal component, and the current structure in the thermocline was stable over periods of

Table 1. Maximum measured eastward velocity component in thermocline and associated meridional velocity component and depth for equatorial stations where the undercurrent was present. Positive meridional components are northward and negative components are southward.

Date	Zonal component (cm/sec)	Meridional component (cm/sec)	Depth (m)
	61°E		
9 March	27	+13	81
31 March	57	− 5	80
	69°E		
4 March	49	−16	90
	77°E		
1 March	31	+ 2	120
	79°E		
9 July	19	− 7	125
2 Sept.	67	+20	110
8 Sept.	61	−32	100
	85°E		
7 April	60	+23	105
	89°E		
11 Sept.	51	+12	120
17 Sept.	34	+14	140
	92°E		
9 April	81	− 7	100
22 April	76	+19	120

at least a week. The surface current on these sections was eastward at 79°E and 89°E and westward at 92°E. The zonal velocity structure most closely resembled that of the undercurrent on the 92°E section in April where the maximum eastward speeds in the thermocline were observed (Fig. 2). The section at 79°E in September showed a more complicated structure with a peak of westward flow in the lower portion of the surface layer and an eastward flow in the thermocline from 2°N to 2°S with a maximum speed of 60 cm/sec at the equator. The portion of this section from 1°N to 1°S was repeated approximately 1 week after the first run and the core of 60 cm/sec eastward flow in the thermocline was again found to be present. Current measurements at 89°E in September also showed eastward flow in the thermocline from 2.5°N to 1°S with a maximum eastward speed at the equator of 50 cm/sec.

An eastward flow, of lower magnitude, was measured in the thermocline from 2°N to 1°S on the 61°E section in early March. The maximum eastward speed (38 cm/sec) was not located at the equator, and thus the velocity structure departed from that usually associated with the undercurrent. When considered with the evidence from the distributions of properties and the measurements of current at the equator at 61°E 3 weeks after the section was occupied (see below), our interpretation is that these measurements probably represent a weakly developed undercurrent.

On four sections, namely, 53°E in both May and August, 62°E in August, and 85°E in February, an undercurrent was not measured. The measurements on the 85°E section did indicate eastward velocities in the lower thermocline of magnitude 15 cm/sec. Since 15 cm/sec is the order of the uncertainty in the measurements of currents, the reality of this eastward flow cannot be established. On the two sections at 53°E and 62°E the zonal component of velocity in the thermocline was either westward or its magnitude was below the noise level of the measurements. In addition, on the section at 53°E in August and at 62°E the meridional flow was considerably stronger than the zonal flow (*5*).

Further evidence for the presence of the undercurrent comes from measurements of currents at stations on the equator at 61°E, 69°E, 77°E in March and at 85°E and 92°E in April. These observations seem to indicate a continuous undercurrent from 61°E east to 92°E during late March and early April; the magnitude of this undercurrent increases from the west to the east. A strong eastward flow in the thermocline was measured on the equator at 85°E in April where the section during February revealed only a weak eastward flow. The repetition of the equatorial current measurements at 61°E, 79°E, 89°E and 92°E with time differences of 1 to 3 weeks provides evidence for the stability, over periods of weeks, of the eastward flows measured on the meridional sections. However, the sign of the meridional component of velocity associated with the maximum eastward flow was unsteady. Table 1 summarizes the measurements of an eastward undercurrent along the equator during the two cruises.

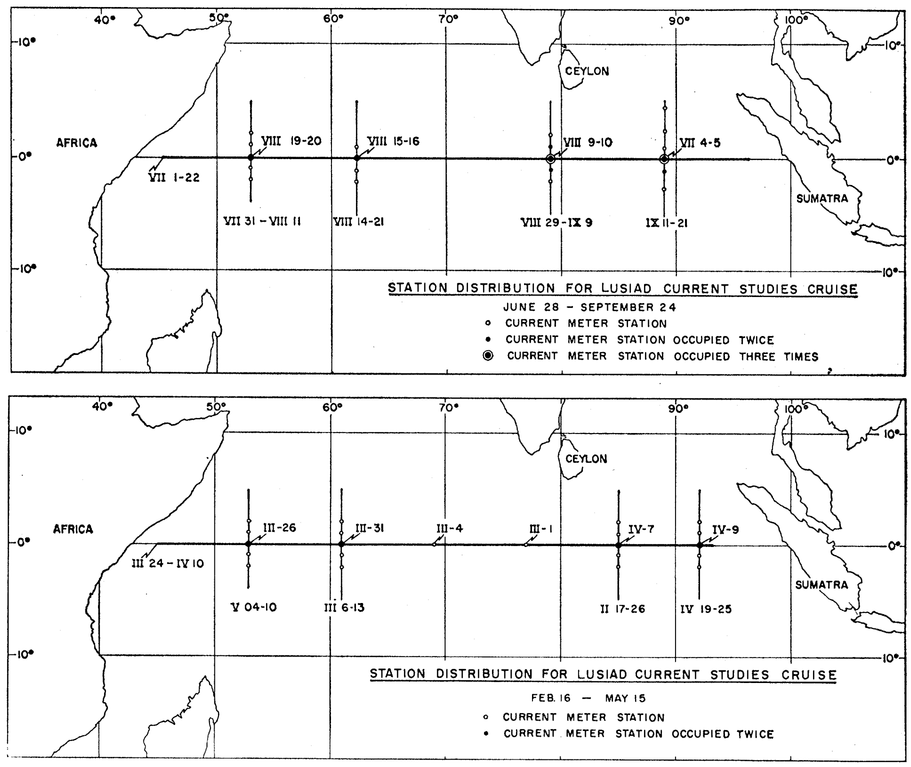

Fig. 1. Locations of stations for the *Lusiad* cruises for studies of currents: (top) 28 June to 24 September 1962; (bottom) 16 February to 15 May 1963. The heavy lines denote sections of hydrographic stations. Current-meter stations are indicated by open circles if occupied once, by filled circles if occupied twice, and by ringed filled circles if occupied three times. At the southern end of each section is shown the period during which the section was made (Roman numerals indicating the months). The dates given for single current-meter stations on the equator are the times of occupancy in addition to that while working the section.

Usually associated with the undercurrent is the spreading of the thermocline at the equator. Montgomery has used thermocline spreading as a criterion for predicting the existence of an undercurrent in the Indian Ocean (*3*). On two of the sections where an undercurrent was clearly developed (79°E and 92°E) the thickness of the thermocline, as measured by the separation of the 15°C and 25°C isotherms, was a maximum at the equator (Fig. 3). The thermocline at 89°E was considerably

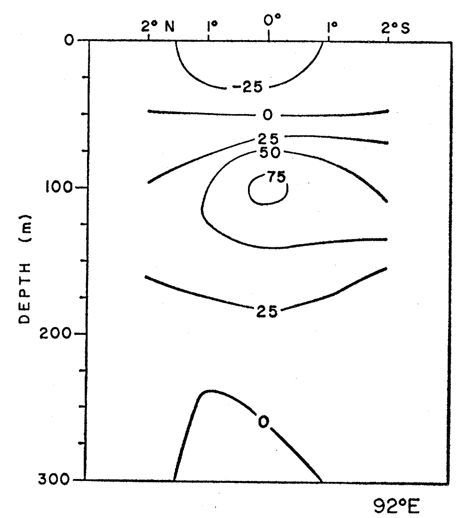

Fig. 2. Vertical section of zonal component of measured current velocity (cm/sec) at 92°E (19–25 April 1963). Eastward current is positive and westward current is negative.

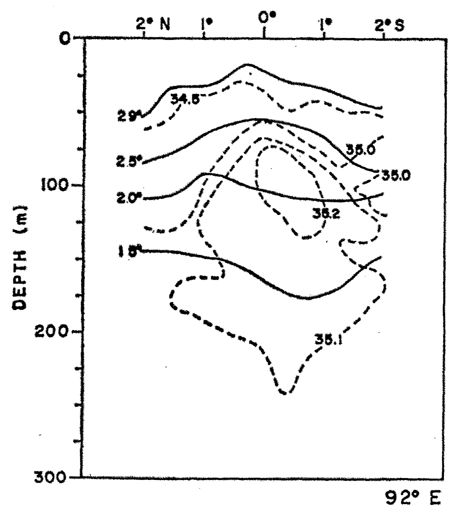

Fig. 3. Vertical section of temperature (solid lines, °C) and salinity (dotted lines, per mille) at 92°E (19–25 April 1963).

sharper than on any of the other meridional sections and showed no tendency to spread at the equator. Associated with the thermocline spreading at 92°E were low values of dissolved oxygen and high values of inorganic phosphate in the surface layer. The meridional distributions of temperature, dissolved oxygen, and inorganic phosphate on the 61°E section, where the presence of the undercurrent was suggested but not clearly established, all showed spreading of the isopleths at the equator. The weakening of the thermocline at the equator was not observed on the other sections where the undercurrent was not present. Thus, even in the Indian Ocean, where the undercurrent is not as well developed nor as steady as in the other oceans, these indications of upwelling of water from the thermocline may be found.

Within the thermocline along the equator a salinity maximum is found whose value at the maximum decreases from west to east. On our sections at 85°E, 89°E, and 92°E this maximum was found to be isolated in the meridional plane from water of a comparable salinity (Fig. 3). This salinity maximum is present throughout the year and would require eastward transport of water of high salinity for its maintenance. The eastward undercurrent measured on the sections at 79°E, 89°E, and 92°E provides the required eastward transport. Metcalf *et al.* have described an analogous relationship between the Atlantic Undercurrent and a salinity maximum at the equator (*3*).

The sign of the slope of the sea surface did not change with the phase of the monsoon. The dynamic topography of the sea surface relative to 1000 decibars on the July equatorial section clearly showed a slope up toward the east of 5×10^{-8} (*5*). The three separate determinations of the slope of the sea surface during the February to May cruise indicated on the eastern side of the ocean a slope of half the magnitude but of the same sign. However, on the equatorial sections of both cruises (July and April) the slope of the deeper isobaric surfaces on the eastern side of the ocean changes sign and becomes negative at 100 to 125 decibars. Thus the eastward velocity component in the thermocline is associated with an eastward pressure gradient roughly comparable to that found near the core of the undercurrent in the Pacific.

These studies show that an equatorial undercurrent does exist in the Indian Ocean with many of the properties associated with the undercurrents of the Pacific and Atlantic. There is no evidence that it is restricted to only one phase of the monsoon although its maximum development occurred during the end of the northeast monsoon. The tendency for the undercurrent to develop in the Indian Ocean is more marked on the eastern side of the ocean than on the western side. The undercurrent did not appear on either of our westernmost sections at 53°E. However, the observed current structure is certainly different from that typically observed at the equator in the other ocean. The speed of the eastward flow in the undercurrent of the Indian Ocean is only half that found in the Pacific. Although the eastward velocity component does appear to be steady over periods of weeks when the undercurrent is developed and can be traced over half the width of the ocean, there were times at which the undercurrent was either weakly developed or not present (*6*).

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6. The work reported here was part of the *Lusiad* Expedition, a joint University of California–University of Rhode Island venture, and a United States contribution to the International Indian Ocean Expedition. Support for the work was provided by the Office of Naval Research and the National Science Foundation. This report is a contribution from the Graduate School of Oceanography of the University of Rhode Island and the Scripps Institution of Oceanography of the University of California.

6 November 1963

Marine Sediments: Effects of a Tube-Building Polychaete

Abstract. *The marine tube-building polychaete,* Owenia fusiformis, *selects sand grains of tablet form for its tube. It can concentrate the mineral hornblende at least 25-fold and these concentrations may persist after the death of the worm.* Owenia *and a small anemone,* Zaolutus actius, *can act together to stabilize the sand surface against movement by wave surge. The result is the formation of an area of stabilized substrate, with which characteristic animals and plants are associated, in the midst of a region of shifting granular substrate.*

The tube-building marine polychaete, *Owenia fusiformis* Delle Chiaje, is reported to have a worldwide distribution (*1*). It is usually found in areas where the sediment consists of fine sand or a mixture of fine sand and silt. On the intercanyon shelf in La Jolla Bay, *Owenia* is most abundant at depths of 8 to 12 meters; usually, few individuals are found deeper or shallower than this. Most of the observations reported here were made, and specimens were obtained, while diving with self-contained underwater breathing apparatus.

The newly settled young appeared in large numbers in early April, although a few were observed at other times throughout the year—in July, September, January. Starting in May 1960 and continuing through February 1961, sets of 12 sand-core samples, each sample 35 cm² in area, were taken monthly at three different depths, approximately 9,