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Equatorial Currents in the Western Indian Ocean

Abstract. *Measurements were made in the equatorial Indian Ocean during spring and summer 1979 from the Somali coast to 62°E in the interior of the western basin. The detailed vertical profiles of horizontal current show that the energetic dominance throughout the region of variability was on vertical scales of several hundreds of meters, confined to within a few degrees of the equator, as observed in 1976. The near-surface equatorial circulation responded directly to variations in the wind field, and satellite-tracked drifter buoys showed the equatorial surface jet extending across the width of the ocean. This eastward flow is generated by the eastward winds that appear in the interval between the northeast and southwest monsoons. The zonal velocity fluctuations extended in a consistent pattern over the observation region. The time and meridional scales of the variability were similar to those observed in 1976, suggesting that the velocity field is dominated by long-term, equatorially trapped motions with long zonal scales.*

During spring and summer 1979, observations were made in the equatorial western Indian Ocean between the African coast and 62°E as a component of the Indian Ocean Experiment (INDEX). The focus of the equatorial observations was the oceanic response to the greatly varying winds associated with the monsoons. Pilot observations in 1976 (*1*, *2*) and earlier suggested that the velocity field in the equatorial Indian Ocean is dominated by a variety of equatorially confined motions. The observational program consisted of compiling vertical profiles of horizontal currents, tracking drifter buoys by satellite, and deploying an array of moored current meters. We report here preliminary results from the first two components.

The first set of vertical profiles of horizontal velocity was made from the *Columbus Iselin* in early April 1979, well before the onset of the southwest monsoon. The second set was made during the period spanning May and June and involved two ships: the French vessel *Marion Dufresne*, which was stationed in the vicinity of 62°E and made vertical profiles of relative current (shear) and deployed the drifter buoys; and the *Columbus Iselin*, which reoccupied the sites at which profiles were made during her first cruise. The profiles were obtained with the White Horse, an acoustically tracked, freely falling instrument. The horizontal velocity profile is inferred from the observed lateral displacement of the instrument as it falls to the ocean bottom and then rises to the surface (*1*, *2*).

The deep equatorial jets in the Indian Ocean (*1*, *2*) were a focus for the INDEX equatorial program. Subsequent observations in the western (*3*) and eastern (*4*) Pacific Ocean have confirmed their existence as a general feature of the equatorial velocity structure in the Indian and Pacific oceans. The observations in 1976 indicated that the zonal component of flow has a time scale on the order of 1 month or longer, whereas the meridional component is variable over periods of 1 week. These motions are confined to within a few degrees of the equator. The most energetic of the zonal jets in the Indian Ocean flowed toward the west, so it was desirable to learn their extension into the interior of the Indian Ocean and, at the western boundary, their interaction with the Somali Current system.

The equatorial profiling program began in early April with the *Columbus Iselin*. A total of 17 velocity and conductivity, temperature, and depth profiles were made at 13 locations between 50° and 59°E. Most of the equatorial profiles away from the coast show eastward flow extending to the thermocline. Below this region there was westward flow, concentrated in structures of relatively short vertical extent, typically 100 to 200 m. The second cruise, in June, extended the spatial coverage from 47° to 62°E, and the 18 profiles made show similar characteristics.

In the latter case, there was eastward flow in the upper layers only to the east of 52°E, and the region of westward flow, extending to 2500 m, intensified. Figure 1 shows the contours of horizontal velocity obtained by the second *Iselin* cruise. The zonal jets are evident in horizontal bands of westward velocity in excess of 20 to 25 cm/sec in the upper 2000 m. The meridional component of flow is smaller in amplitude and generally more spatially and temporally variable. The meridional structure of the flow is similar to that observed in 1976 (*2*). The region of energetic small-scale variability is confined to within 3° of the equator. At 4° from the equator, north and south, the dominance of the large vertical scales typical of mid-latitudes is present. The profile observations from the *Marion Dufresne* confirm this general structure in the upper 500 m at 62°E, although only relative current profiles were made.

The presence of equatorially trapped structures with vertical scales of several hundred meters is consistent with the kinematics of vertically propagating equatorial waves of planetary scale—the equatorial Kelvin and Rossby waves (*2*, *5*). Wunsch (*6*) suggested that monsoonal variations in wind stress can generate a downward-propagating equatorial Rossby wave of annual period whose vertical scale is a few hundred meters. The vertical-phase speed of such a wave is so low that dissipation, together with scattering from the bottom topography, can prevent the formation of standing vertical modes. Cane (*7*) and Philander and Pacanowski (*8*) argued that the response in the upper equatorial ocean rapidly becomes nonlinear, so that the linear radiation mechanism proposed by Wunsch applies only beneath the thermocline. An analysis of the combined moored current meter and velocity profile data in terms of the vertically propagating equatorial wave models is desirable.

During the transition periods between the two phases of the monsoon, there is an interval of eastward wind along the equatorial region of the Indian Ocean. These winds apparently drive the eastward surface jet discovered by Wyrtki (*9*) and documented by Knox (*10*) near Gan Island (70°E). During May 1979, four drogued (20 m) drifter buoys were launched from the *Marion Dufresne* at 0°, 62°E and tracked by the Argos system aboard TIROS-N. Also, two drogued buoys were launched from the *Discovery* at 0°, 48°E, and in June two were deployed by the Australian vessel *Diamantina* near 0°, 90°E (*11*). The trajectories of these buoys are shown in Fig. 2. With the exception of one of the *Discovery* buoys (it became trapped in the circulation system of the Somali Current), the buoys stayed in the vicinity of the equator and showed periods of strong flow to the east, followed by less energetic flow toward the west and then intervals of rather weak indeterminate flow. The periods of eastward flow coincided with the transition periods between the monsoons—May and October. During these periods of eastward flow, the speed of the buoys often reached 1 m/sec. By the end of November 1979, the five buoys in the western basin had traversed the width of the Indian Ocean, and at present they are near the coast of Sumatra. A similar course was followed by two buoys launched in January 1979 near 50°E (*11*).

Some simple theoretical models have been proposed to explain the development of this equatorial surface jet (*7*, *8*, *12*). The initial response in a resting ocean to an eastward wind along the equator is an accelerating, equatorially confined eastward current, balancing the imposed wind stress. Since this solution cannot satisfy the conditions at the continental boundaries, an equatorially trapped Kelvin wave is generated that propagates into the ocean's interior from the western boundary. As this wave front passes a given location in the interior, a pressure force is established, balancing the wind stress so that the current ceases to accelerate. When the Kelvin wave encounters the eastern boundary, an equatorially trapped Rossby wave is formed that propagates west, raising the thermocline and reducing the eastward flow as it passes.

As this system reaches equilibrium, a westward pressure gradient balances the imposed wind stress so that, in effect, the current runs uphill. When the east-

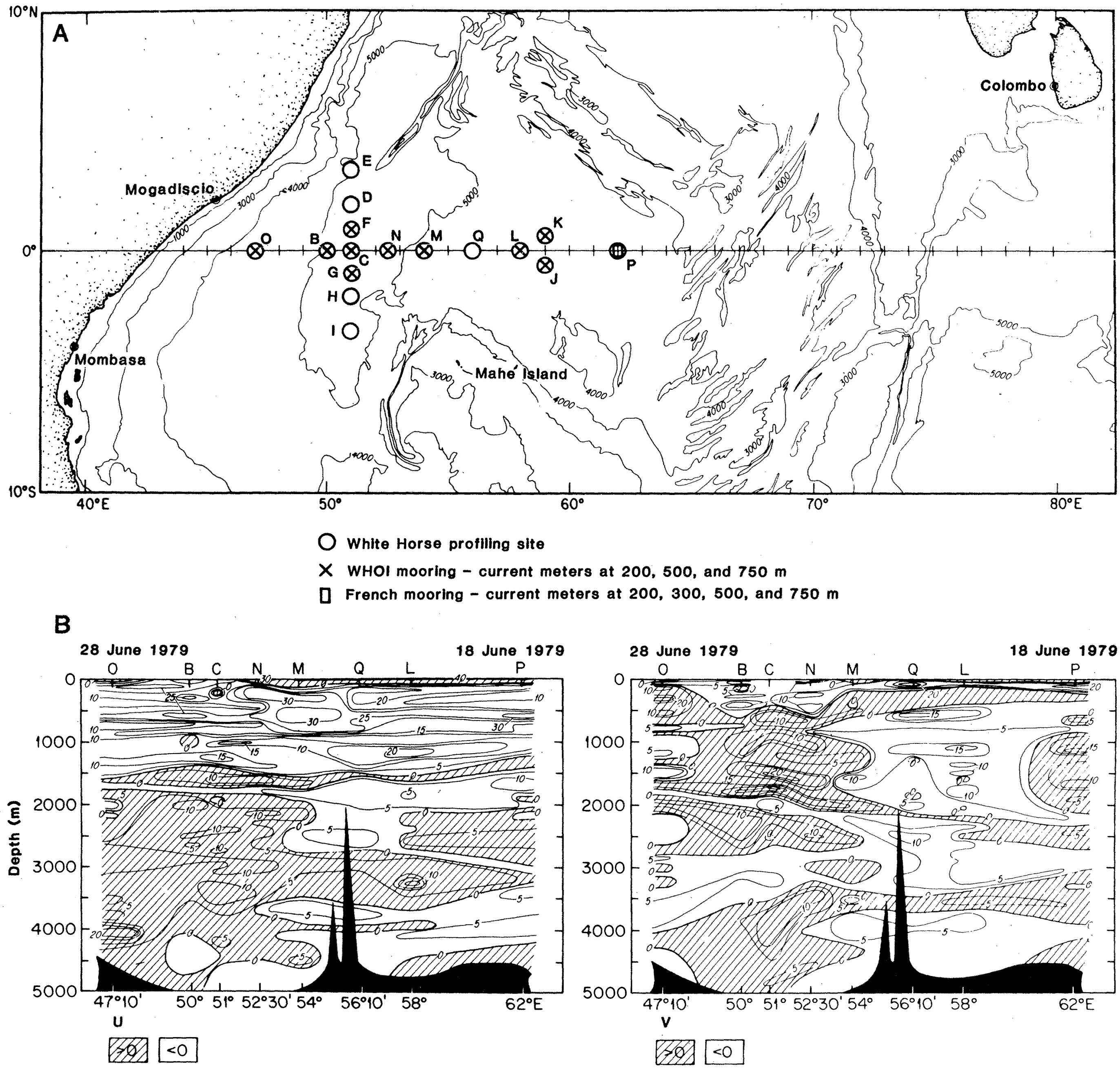

Fig. 1. (A) Spatial distribution of profile observation and mooring sites (*WHOI*, Woods Hole Oceanographic Institution). (B) Contours of zonal (left) and meridional (right) velocity components, in centimeters per second, from equatorial sites.

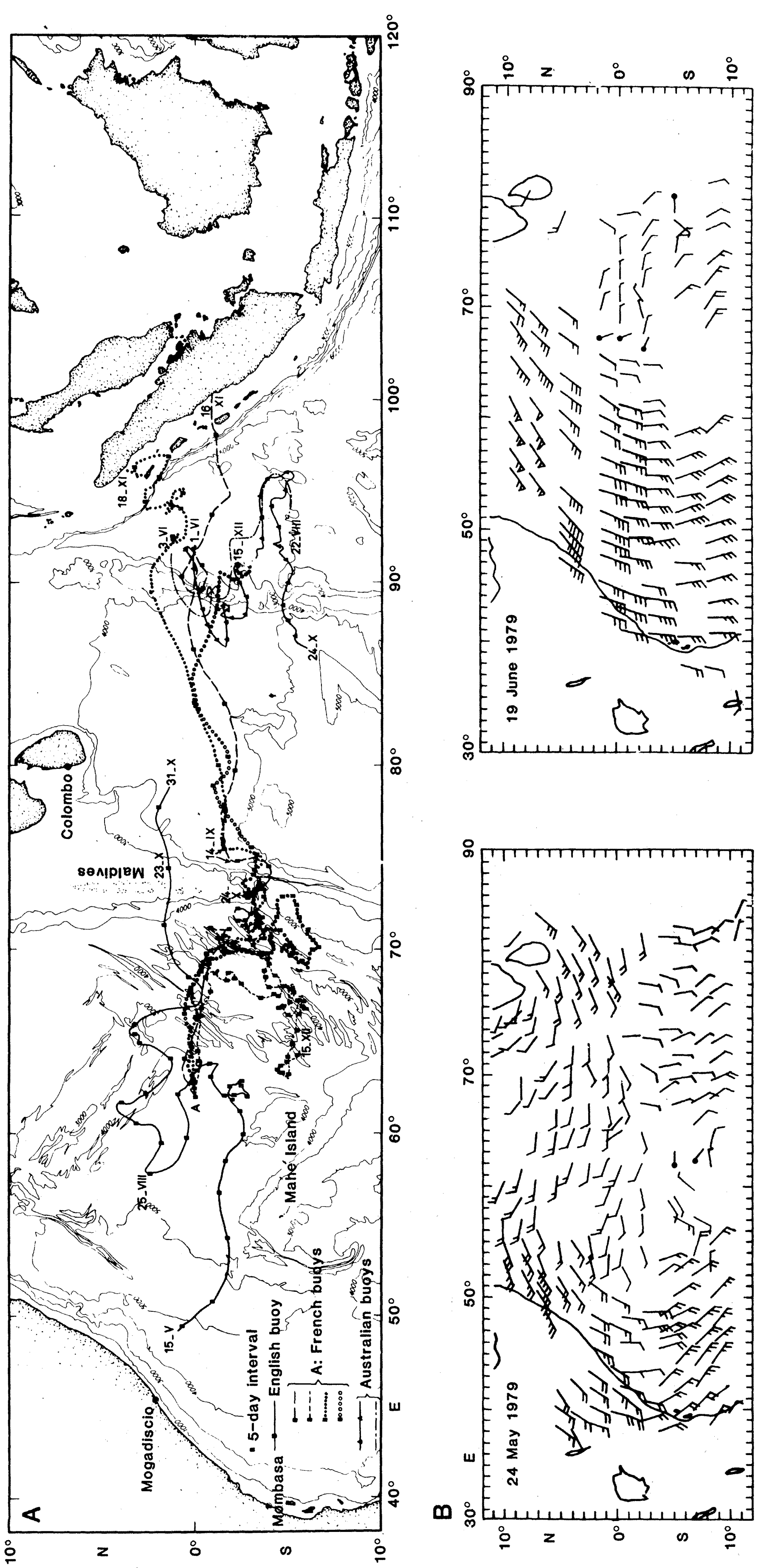

Fig. 2. (A) Trajectories of freely drifting drogued buoys, tracked by satellite. Symbols are spaced at 5-day intervals. (B) Wind vectors, estimated from cloud trajectories on satellite images. The clouds are at approximately the 900-mbar level (*13*).

ward winds relax as the monsoon regimes become established, the flow is rapidly reversed, giving a westward flow followed by an equilibration period in which no additional momentum is supplied.

The trajectories shown in Fig. 2 are consistent with this pattern of strong, accelerating eastward flow followed by a period of less intense westward flow and then a period of nearly stagnant flow. It is interesting to note that during these stagnant periods, the buoys were above regions of complex bathymetry—the Carlsberg Ridge (65° to 70°E) and Ninety-East Ridge (90°E). One might expect that the strong, shallow equatorial thermocline would isolate the near-surface layers from the submarine topography, but apparently it does not.

The equatorial observations made during the INDEX experiment have corroborated and provided a larger context in terms of zonal scale for many of the features observed in previous work. The equatorial surface jet is seen to span the entire Indian Ocean, although it is certainly most vigorous in the central region. The deep equatorial jets are seen to exist in the central region of the western Indian Ocean and are, in some cases, continuous over large zonal separations. They are equatorially confined, and, in vertical and meridional scales, are consistent with the kinematics of equatorially trapped, low-frequency waves of planetary scale.

More will be known about the longer term evolution of these features and the possibility of vertical propagation after recovery of the moored current meter array in June 1980. We look forward to relating changes in the structure of the equatorial flow at the surface and in the deeper layers to the variations in the wind field observed from cloud drift (*13*) and the interaction of the westward flow along the equator with the developing Somali Current system. The entire region shows rich horizontal and vertical variations in the velocity, temperature, and salinity fields.

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Origin of the Warped Heliospheric Current Sheet

Abstract. *The warped heliospheric current sheet for early 1976 is calculated from the observed photospheric magnetic field by a potential field method. Comparisons with measurements of the interplanetary magnetic field polarity for early 1976 obtained at several locations in the heliosphere by Helios 1, Helios 2, Pioneer 11, and at the earth show a rather detailed agreement between the computed current sheet and the observations. It appears that the large-scale structure of the warped heliospheric current sheet is determined by the structure of the photospheric magnetic field and that "ballerina skirt" effects may add small-scale ripples.*

The magnetic field of the sun is extended outward by the solar wind throughout the solar system. The structure of the extended field has been observed only within 16° of latitude of the solar equator, so that its overall form, containing the well-known magnetic sectors near the equatorial plane, has been a matter of conjecture and debate for many years. The Solar Polar Mission, sometime in the next decade, will probably settle the major questions by direct observation in space. This report describes our present view of the extended structure of the solar magnetic field.

The existence of a warped current sheet in the nonpolar regions of the heliosphere is now generally accepted (*1*-*4*). An artist's impression of an average shape of the current sheet at a time near sunspot minimum (*2*) is shown in Fig. 1. As the current sheet rotates with the sun, the sector structure of the interplanetary magnetic field (IMF) is produced (*5*). At the phase of the sunspot cycle discussed in this report, the large-scale IMF is directed away from the sun northward of the current sheet and is directed toward the sun southward of the sheet. It should be noted that the term "interplanetary sector structure" coined by Wilcox and Ness (*5*) describes the structure in the plane of the ecliptic and does not refer to three-dimensional structures such as the sections of an orange.

There are two points of view regarding the origin of the warped heliospheric current sheet. Svalgaard and Wilcox (*6*) review the computations of the magnetic field at a "source surface," for which the photospheric magnetic field observed by use of the Zeeman effect serves as a boundary condition. Outside the source surface the warped current sheet is assumed to be carried radially outward by the solar wind. In this model, the structure of the current sheet (the location in solar longitude and the extent in solar latitude of the maxima and minima) is a direct consequence of the observed photospheric magnetic field.

Alfven (*4*) [see also (*7*)] has proposed an alternative viewpoint in which the solar origin of the current sheet is a plane similar to the plane in which the skirt of a ballerina originates (the waist). In this model the current sheet waves up and down like the skirt of a spinning ballerina.

It is our purpose in this report to show that the observations of the IMF during the first months of 1976 (that is, near sunspot minimum) at the earth—by Pioneer 11 near a heliospheric latitude of 16°N (*8*) and by Helios 1 and Helios 2 between 0.28 and 1 A.U. within a latitudinal excursion of ±7.23° from the solar equatorial plane (*9*)—are in good agreement with a warped current sheet computed from the observed photospheric magnetic field by the methods reviewed in (*6*). It thus appears that the large-scale structure of the heliospheric current sheet is controlled by the photospheric magnetic field, although small-scale ripples may be added by dynamic solar wind processes (the ballerina effect).

The curved line in Fig. 2 represents the average warped current sheet that separates regions with magnetic field away from the sun (above the line) and toward the sun (below the line), as computed on a source surface at 2.6 solar radii during the interval 20 January through 26 May 1976. The solar wind is assumed to carry the magnetic structure on the source surface radially outward into the heliosphere. In fact, the curved line in Fig. 2 is similar to the bottom panel of figure 4 in (*6*), which was computed as the average of eighteen 27-day solar rotations starting 5 May 1976 and ending 7 August 1977, just after the interval discussed in this report. This similarity is evidence of the long-term stability of the large-scale photospheric and heliospheric magnetic fields.

Such long-term stability would not be expected from the dynamic effects of the ballerina skirt model. Nor would this stability be expected if the predominant warps in the current sheet were caused by coronal holes (*9*), since the lifetime of a coronal hole is typically only several rotations. Because coronal holes appear in the central portion of sectors (*6*), it would be expected that the longitudes of coronal holes would correspond to the

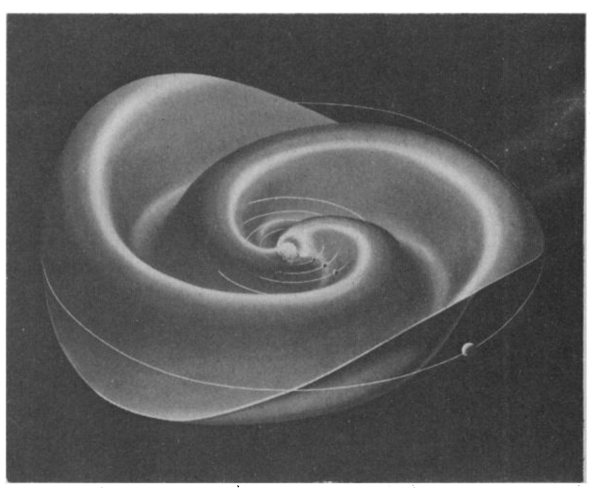

Fig. 1. Artist's impression of the warped heliospheric current sheet. The region above the current sheet has interplanetary magnetic field directed away from the sun and the region below has field directed toward the sun. [Artist: Werner Heil]

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