Note on plankton and cold-core rings in the Gulf of Mexico

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Data from ship and aircraft hydrographic surveys, supplemented with data from current meter moorings and drifters, have demonstrated that one or more cyclonic circulation features, 100–200 km in diameter, are often present in the Gulf of Mexico. In the eastern Gulf, these cold-core rings (CCR's) occur in close association with the Loop Current (LC) (Lee et al., 1994), and in the central and western Gulf, they are companions of the anticyclonic eddies that are shed during northern excursions of the LC (Hamilton, 1992). Cyclone-anticyclone dipoles and cyclone-anticyclone-cyclone triads have been described (Lewis and Kirwan, 1985; Rouse et al., 1994; Vidal et al., 1994). Temperature-salinity relationships document that cyclones and anticyclones in the Gulf of Mexico form from the same water types, but convergence flow within the anticyclones causes the surface waters of these gyres to be regions of low production. The upper 100 m are depleted in nitrate and chlorophyll concentrations, primary productivity, and zooplankton biomass are generally extremely low (Biggs, 1992). In contrast, the companion cyclones are mesoscale regions of divergence flow. From nutrient-chlorophyll data collected during several cruises when Gulf of Mexico CCR's were tracked, Biggs et al. (1988) hypothesized that cyclones were regions of locally high primary productivity which could support elevated stocks of zooplankton.

In March 1993, a CCR was detected by remote sensing of the western central Gulf of Mexico, and the opportunity arose to study its hydrographic and biological signature as RV *Gyre* transited this feature while proceeding along a TOPEX ground track. This mesoscale cyclonic circulation was visible in remote sensing data as a region of surface temperatures 1–2°C cooler than the adjacent oceanic surface waters (Fig. 1; Table 1) and as an elliptical local depression in sea surface height (SSH) (–15 to –20 dyn cm of SSH anomaly; see Table 1). Expendable bathythermographs (XBT's), dropped to profile isotherm depths in the upper 760 m, resolved strong doming of subsurface isotherms within this CCR (Fig. 2), and Gyre's hull-mounted 153 kHz acoustic Doppler current profiler (ADCP) confirmed that cyclonic near-surface currents were associated with this feature. Both the amplitude and direction of these ADCP-measured currents were found to be in close agreement with those computed from the along-track horizontal geopotential gradient in relation to a reference level of 800 db: a low of 88 dyn cm in the interior of the CCR, versus ≥102 dyn cm to the north and south (Table 1). This –14 cm SSH gradient between interior and periphery of the CCR over a distance of 100 km should have driven a cyclonic transport (relative to 800 db) of 6–7 Sverdrup, with mixed-layer velocities of 40–60 cm/s (see p. 165–166 in Texas A&M[1]). Altimeter-derived dynamic height anomalies from TOPEX Cycle 18, which flew over the ship's track just as *Gyre* completed the XBT survey, showed agreement with the hydrographic estimates to better than 2 cm residual mean squares difference with respect to a corrected along-track mean surface, which is within the generally accepted error range for altimeter measurements (Leben et al, 1993). A comparison with TOPEX Cycle 17 data from 10 days earlier also demonstrates the presence of this cylone (see Fig. 2 in Leben et al, 1993).

Time constraints did not allow us to divert the ship to make a more detailed hydrographic survey of the CCR or to stop to make time-series measurements. However, we were

[1] Texas A&M University. 1993. Ship-of-opportunity hydrographic data from R/V Gyre cruise 93G-03. Tech. Rep. 93-04-T, Dep. Oceanography, TAMU, College Station, TX, 216 p. Available from NTIS, Springfield, VA: PB94-123957.

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able to slow the vessel eight times for 15–20 min periods for net tows in order to collect zooplankton at three stations within and five outside the CCR for comparison with ADCP acoustic backscatter intensity data logged while these tows were made. The ADCP acoustic backscatter intensity data were collected according to the methods described by Flagg and Smith (1989) and Zhou et al. (1994).

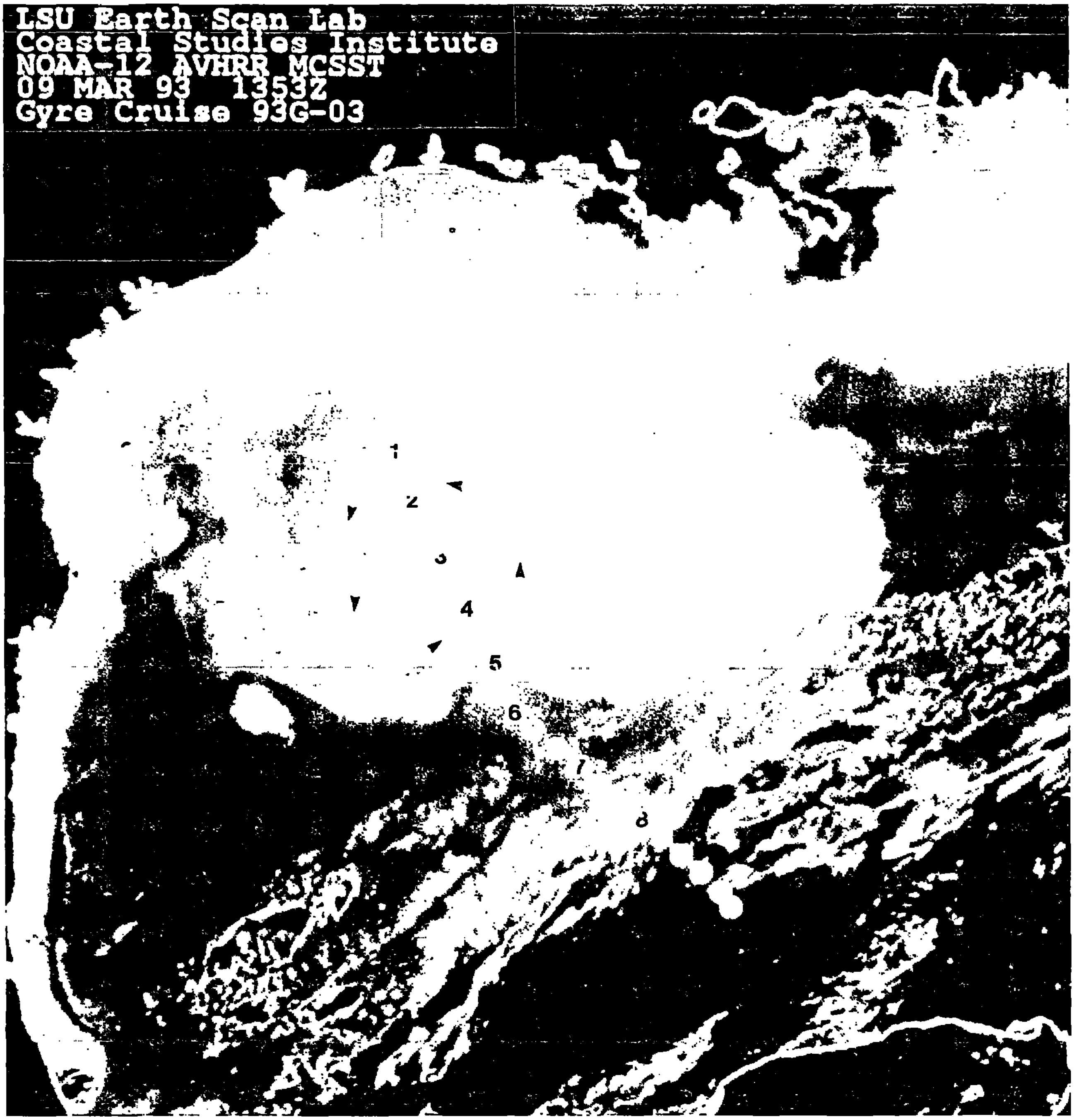

Figure 1

Analysis of NOAA-12 advanced very-high-resolution radiometer satellite imagery of sea surface temperatures (SST) processed by Louisiana State University. Circles give the location of the 33 XBT stations; the numbers inside these circles designate where zooplankton tows 1–8 were made. Lighter grey shades represent lower SST; the CCR is visible as a region of locally cooler surface temperatures encircling XBT's 10–17 (zooplankton tows 2–4). Arrowheads show the expected counter-clockwise circulation in CCR periphery.

The plankton tows were made with an open net of 333-µm mesh and 1 m in diameter, at every 3rd XBT site beginning at 27°00'N. The net was outfitted with an impeller-type flowmeter (General Oceanics) that allowed the volume of water fished to be determined upon recovery of the net. In 15–20 min oblique tows to 100 m depth, volumes of water fished ranged from 450 to 800 m^3. Collections were preserved in a 4% formaldehyde solution buffered with borax, and then bulk sample displacement volume was measured according to the method of Ahlstrom and Thrailkill (1960). Four of the 8 tows were made during daylight hours and the other 4 were made at night. Tow 1 was made in daylight outside and to the northwest of the CCR, whereas tows 2–4 were at night, within the CCR. Tows 5–7 were daylight tows outside and to the southeast of the CCR, and tow 8 the following night was also outside and to the southeast of the CCR. Because only nighttime tows were able to be made in the CCR, we chose to enumerate the taxonomic composition of all eight samples for three groups of macrozooplankton that are well known to exhibit diel vertical migration (Gasca et al., 1995). Each sample was split 1:4 with a Folsom plankton splitter and then euphausiids, thecosome pteropods, and siphonophores were enumerated to species at the Centro de Investigaciones Quintana Roo.

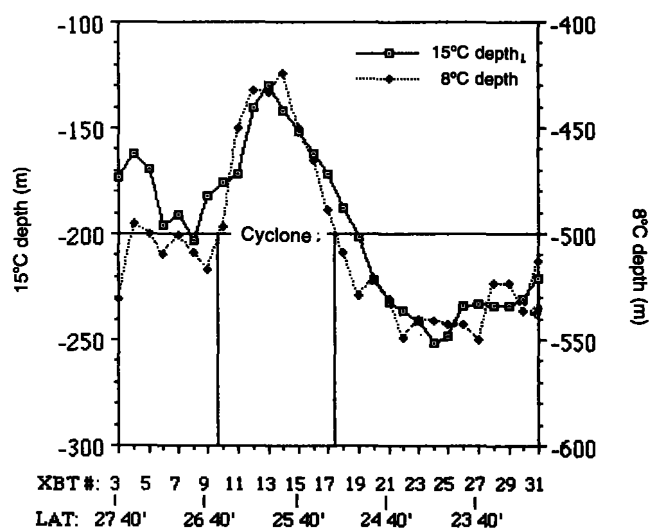

Figure 2
Along-track plot of the doming of 15°C and 8°C isotherms, showing the cyclone as a 150-km wide region where 8°C <500 m.

Results

Zooplankton biovolume averaged 2.4-fold higher in nighttime tows than in daytime tows (90 versus 38 mL/1,000 m^3; see Table 2). This elevation of stock at night reflects greatly increased numbers of euphausiids at night, for most of the euphausiid species present in the western Gulf of Mexico perform vertical migratory patterns during a day-night cycle. During the night hours, these euphausiid species can be collected in the upper 200 m (Mauchline, 1980). However, the numbers and kinds of euphausiids present at night inside versus outside the CCR were quite different: 56% of the number of euphausiids inside the CCR were species of the genus *Euphausia*, whereas 63% of the individuals in the night tow outside the CCR belonged to two species of the smaller-size genus *Stylocheiron*. Moreover, euphausiid species of the genus *Euphausia* at night were, on average, 1.8-fold more abundant within the CCR than outside (321 individuals/1,000 m^3 inside,

Table 1
Surface temperature, mixed layer (ML) depth, temperature at 100 m, and the calculated dynamic height (relative to 800 db) for stations where plankton tows were made.

Plankton Tow	Local Time	XBT station	Temp (°C) at surface	Depth (m) to reach surface temp. minus 1°C (= ML depth)	Temp (°C) at 100 m	Dynamic height (cm)
1	15:52–16:09	7	23.24	54	19.7	102
2	19:23–19:38	10	22.34	72	19.2	97
3	23:11–23:27	13	21.50	75	17.8	88
4	03:08–03:23	16	21.75	71	19.0	94
5	07:08–07:19	19	22.50	99	21.4	106
6	12:11–12:26	22	23.62	98	22.4	115
7	16:08–16:25	25	23.39	112	22.5	113
8	21:17–21:34	28	23.36	95	21.9	111

versus 179 individuals/1,000 m^3 outside), the most abundant being *E. tenera, E. mutica*, and *E. americana*. Species richness of euphausiids was also greater inside the CCR than outside: five species (*Euphausia pseudogibba, E. brevis, Nematoscelis atlantica, Thysanopoda monoacantha*, and *Nematobrachion flexipes*) were found only in collections made inside the CCR. Details are available from the authors in a 3-page table. We speculate that the presense of the later three mesopelagic euphausiid species within the CCR, but not recorded outside the CCR, reflects the extension of their upper vertical distribution limits: where cold water domed shallower than 100 m, these mesopelagic species reached up into the zone where our nets collected samples at night.

We have calculated a mean acoustic backscatter intensity (ABI) 0–200 m by time-averaging ADCP data from the 15–20 minute periods when net tows were made. The ADCP was calibrated, as explained by Zimmerman (1993), with mean ABI expressed as dB re$(M\times4\pi)^{-1}$. We also computed the integrated ABI (IABI): the amount of backscatter that was greater than the grand mean of –74 dB for the upper 200 m, bin by bin, from the 8–12 m bin to the 96–100 m bin) to provide a summary number for comparison with wet displacement volume of zooplankton collected from 0 to 100 m in the net tows. Figure 3 summarizes the mean ABI during the ensembles when net collections were being made. These acoustic data have been corrected for sound attenuation with depth, which was modeled from the *T/Z* relationship at each XBT station. Subsurface regions of locally intensified return (locally higher backscatter) are presumed to be local concentrations of biological scatterers. Although these regions of locally enhanced backscatter were concentrated into the vertical range of 60–100 m during the day, they reached closer to the surface and occurred over a greater vertical range of the water column at night. The ABI data, however, are not sufficient to distinguish whether at night euphausiids were more abundant and more species rich within the CCR than without.

Discussion

In the decade since Iles and Sinclair (1982) recognized the existence of larval retention zones caused by oceanographic features, the relations between stocks of phytoplankton, zooplankton, larval nekton, and frontal zones have been an area of intense research. For example, it is now well known that local aggregations of phytoplankton can develop along and within week-long meanders and eddies in the Gulf Stream (Lee et al., 1991) and that elevated fish stocks often co-occur in these frontal disturbances (Atkinson and Targett, 1983). In the Gulf of Mexico, frontal zones at the periphery of meanders and eddies that are seaward of the continental margin are typically expressed as sharp gradients in temperature. These may have secondary expression as gradients in salinity, particularly in local convergences that can entrain low-salinity water and transport it off shelf as plumes or jets. For example, Biggs and Muller-Karger (1994) reported that some cyclone-anticyclone geometries in the Gulf of Mexico create flow confluence zones that can transport high-chlorophyll shelf water seaward several hundreds of kilometers. Sharp frontal zones may also be created during periods of northern extensions of the Loop Current. Lamkin (1997) found a significant positive correlation between the abundance of larval nomeid fish and the location of the northern edge of the Loop Current by analyzing NOAA annual icthyoplankton survey data from 1983 to 1988. Lamkin's data indicate that *Cubiceps pauciradiatus*, in particular, is a species whose adult spawning grounds and larval habitat are tied to sharp temperature gradients. Peak larval abundance was found close to the frontal interface, and peak abundance occurred just above the region of peak sea surface temperature (SST) gradient. Lamkin went on to speculate that the extent of the frontal systems in the Gulf of Mexico would be expected to impact annual recruitment of a species that is tied to a frontal habitat.

Table 2

Comparison of net-collected with acoustic characterization of zooplankton stocks. See text for explanation of how Acoustic Backscatter was calculated. CCR = cold-core ring; IABI = integrated acoustic backscatter intensity.

Plankton Tow (0-100-0 m)	Total wet displaced volume (mL/1,000 m^3 ± SD)	Acoustic Backscatter (db) (IABI, 10–100 m ±SD)	Euphausiids	Pteropods	Siphonophores
			(numbers per 1,000 m^3 ±SD)		
1 (day: NW of CCR)	36	46.3	112	93	212
2–4 (night: inside CCR)	90 ±12	87.7 ±11.5	574 ±138	204 ±19	580 ±78
5–7 (day: SE of CCR)	39 ±6	36.2 ±31.2	154 ±56	104 ±48	453 ±253
8 (night: SE of CCR)	67	82.7	806	198	840

On shorter time scales, the biological implications of thermal fronts in the Gulf of Mexico are widely recognized by fishermen: many of them now direct their boats to selected fishing areas where SST imagery shows sharp temperature gradients over short (<10 km) distances. Skipjack, blackfin tuna, swordfish, and blue marlin have been reported by fishermen to be locally abundant in these frontal zones (Roffer[2]). Also, on seven research cruises of the GulfCet program 1992–94, there were frequent sightings of family groups of sperm whales, *Physeter catodon*, and periodic sightings of pods of killer whales, *Orcinus orca*, in association with thermal fronts over the continental slope of the northern Gulf of Mexico (Davis and Fargion[3]). Clearly, populations of apex predators like these are not likely to be sustained by low or infrequent episodes of enhanced secondary productivity.

One explanation for the fact that elevated stocks of biomass were not found in the CCR during the March 1993 transect is that biomass may "grow in" only when cyclones are "spun up" into surface waters. That is, if "new" nitrate is but episodically injected into the photic zone of cyclones, there may be lag times of days or weeks between what we hypothesize should be pulses of new production and secondary production. Alternatively, as these cyclones spin up, nitrate levels may be slowly domed and then decrease as the ring spins down and loses its cold-core surface expression.

Because Gulf of Mexico cyclones contain water of the same temperature-salinity properties as the rest of the Gulf of Mexico, only when they are well "spun up" will they have colder surface as well as colder interior temperatures. In fact, the cyclone of the present study was one of the few that has been visible in SST as well as in altimeter imagery; it may have spun up to have locally cool surface temperatures in response to cyclonically favorable wind curl from the passage of a strong atmospheric cold front. This strong "norther" passed through Texas and out across the Gulf of Mexico 36 hours before the cruise; the cloud banks that stretch NE to SW along the trailing edge of this norther can be seen in Figure 1. Rapid (hours-to-days scale) and intense cyclogenesis has been reported to occur after cold front passage in the northern Gulf of Mexico, especially when the cold fronts stall over deep water off the edge of the continental margin (Lewis and Hsu, 1992).

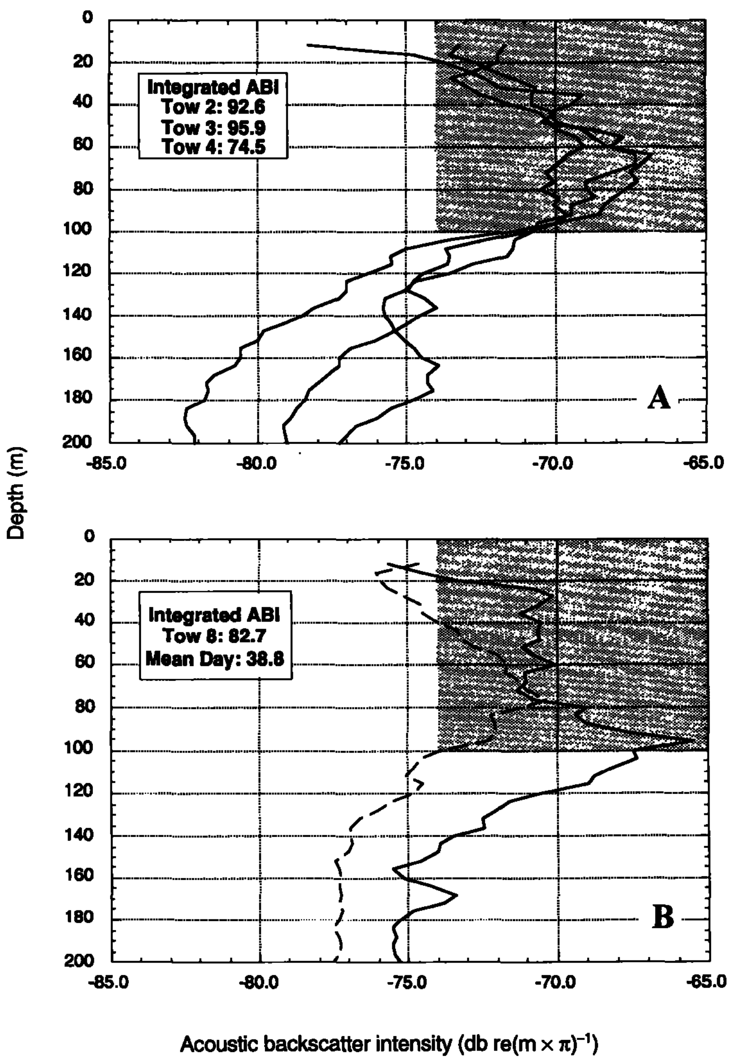

Figure 3

Acoustic backscatter intensity versus depth for time-averaged ADCP (acoustic Doppler current profiler) records (mean of three ensembles of 5-min duration each) that were concurrent with times of plankton net tows: (**A**) three nighttime tows in the cold-core ring (CCR); (**B**) night tow southeast of CCR (solid line) and mean of four day tows outside CCR (dashed line). The region 10–100 m where acoustic backscatter intensity (ABI) >–74 db is shaded; the inset at top left summarizes this integrated ABI > –74 db (IABI).

[2] Roffer, M. 1994. Ocean Fishing Forecasting Service, Miami, FL. Personal commun.

[3] Davis, R. W., and G. A. Fargion (eds.). 1996. Distribution and abundance of cetaceans in the north-central and western Gulf of Mexico. Outer Continental Shelf Study (OCS) Study MMS 96-0027. U.S. Dep. Interior, Minerals Manage. Serv., Gulf of Mexico OCS Region, New Orleans, LA, 357 p.

Clearly, we need additional information on how and when the biological productivity of Gulf of Mexico cyclones may "spin up." As a corollary, however, we need to remember that Gulf of Mexico cyclones are analogous but not homologous to Gulf Stream cold-core rings. As a consequence of their cyclonic nature, Gulf of Mexico cyclones are regions of elevated near-surface nutrients but unlike Gulf Stream cold-core rings, they are not regions of biological expatriation. Studies of the fauna within Gulf Stream cold-core rings have documented that because these rings are "oases" of temperate slope water that are transported into an oligotrophic subtropical central gyre, some of their resident fauna succumb to thermal stress as the cold-core of temperate origin dissipates by mixing with the surrounding subtropical water (Wiebe et al., 1976; Boyd et al., 1978). In contrast, populations of plankton and nekton in Gulf of Mexico cyclones should be sustained (rather than stressed) by mixing with surrounding subtropical water and so persist as local aggregations of enhanced food supply for apex predators that feed on krill-size food.

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