

Cross-Shelf Sediment Transport by an Anticyclonic Eddy Off Northern California



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Science, New Series, Vol. 261, No. 5128 (Sep. 17, 1993), 1560-1564.

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"finger" happens to "find" the ion. The existence of these "fingers" was proved in my earlier study of the neat surface (7), and Fig. 3 shows an example of such a "finger" interacting with the ion.

Finally, I have considered (but do not show) the reverse process, namely, the ion starting in the middle of the water phase ($Z \approx -12 \text{ \AA}$) and the polarity of the electric field reversed so that the ion will climb the free energy "hill." The interesting feature here is that the interaction between the water and the ion is still quite appreciable even when the ion reaches the "bulk" of the DCE phase (as judged by the ion's location Z). This clearly shows that the ion carries at least part of the hydration shell. An examination of the animated trajectories shows that the structure of the interface becomes highly disordered, the effective surface region (the region where the density of each liquid is within 10 to 90% of the bulk value) is broadened, and liquid capillaries longer than the one characteristic of the neat surface are observed.

The molecular model described above has provided both a detailed molecular picture of ion transport dynamics and answers to long-standing questions. In particular, direct, molecularly based evidence for the existence of a barrier for the transfer process has been given, and the roles of surface roughness and capillary fluctuations in the ion transfer have been stressed. However, there are several other key issues that this model is capable of addressing. For example, the role of ion pairs in facilitating the transport has been suggested in the literature, and calculations on ion-pair transport similar to the one reported above would be desirable. One important step is to perform comprehensive calculations on several ions with increasing size. This will allow the investigation of the experimentally relevant case of ions whose net free energy of transfer is close to zero. The results of these calculations will be reported elsewhere (9).

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5 March 1993; accepted 26 July 1993

Cross-Shelf Sediment Transport by an Anticyclonic Eddy Off Northern California

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A combination of satellite imagery, shipboard profiles, drifter tracks, and moored current observations reveals that an anticyclonic eddy off the coast of northern California transported plumes of suspended sediments from the continental shelf into the deep ocean. The horizontal scale of the eddy was about 90 kilometers, and the eddy remained over the continental shelf and slope for about 2 months during the summer of 1988. The total mass of sediments transported by the eddy was of order 10^5 metric tons. Mesoscale eddies are recurrent features in this region and occur frequently in eastern boundary currents. These results provide direct evidence that eddies export sediments from continental shelves.

Over continental margins, the rotation of the Earth and the presence of coastal boundaries cause ocean currents to be mainly parallel to isobaths, and, as a result, heat, mass, nutrients, and particles are transported mainly along continental shelves. Cross-shelf flows are much weaker, are intermittent, and consequently are more poorly understood (1). However, property gradients across continental shelves are much larger than gradients parallel to continental shelves, and thus even weak cross-shelf flows can produce large fluxes. Cross-shelf transport processes link the coastal environment and the deep sea and affect the global cycling of carbon and nitrogen (2). The movements of bottom sediments across continental shelves and the export of sediments to the deep ocean influence the fate of primary production and the transport of waste in the coastal ocean, but specific transport mechanisms are difficult to identify (1). We report physical and bio-optical oceanographic observations (3, 4) that show an anticyclonic mesoscale eddy moving from the deep ocean up onto the continental shelf off northern California during the summer of

1988. Layers of resuspended bottom sediments extending as high as 50 m above the sea floor were advected by the eddy across the shelf. Around the periphery of the eddy, sediment plumes extended tens of kilometers beyond the continental shelf break.

The sediment plumes occurred within a coastal upwelling system off northern California between Point Reyes and Point Arena (5). The distribution of sea surface temperature (SST) on 17 July 1988 [Julian day (JD) 199] shows an extensive region of cold water adjacent to the coast that resulted from wind-driven upwelling (Fig. 1A). The velocity field of the anticyclonic eddy in which the sediment plumes were observed is clearly evident as a rotary circulation pattern centered near $38^{\circ}39'N$, $123^{\circ}54'W$ (labeled A in Fig. 1A) (6). The eddy was located inshore of a narrow, meandering current jet that coincided with a filament of cold water and extended about 300 km offshore (7). The anticyclonic rotation of the eddy is also evident in a satellite SST image from 11 July (JD 193), which shows a plume of cold upwelled water wrapping around the southern portion of the eddy in a clockwise sense (Fig. 1B).

Moored temperature and current time series from the continental slope show that, as the eddy moved onshore, both water temperature and equatorward (along shore) current speed at a depth of 10 m increased (Fig. 2, A and B). This general warming of surface waters by about $3.5^{\circ}C$ occurred despite strongly upwelling-favorable winds, which normally lead to cooling of surface

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waters. On the basis of these temperature and current time series (4) and a sequence of current velocity surveys (7), we believe that the eddy was present over the continental shelf for 2 months beginning on about JD 128. The eddy produced episodes of strong offshore flow near the surface (Fig. 2B, shaded regions), which generally occurred during periods of increased equatorward flow that lasted up to a few weeks. The more consistent offshore flow beginning on about JD 170 may have resulted from poleward movement of the eddy that brought the offshore-flowing (southern) part of the clockwise circulation pattern to the mooring location. Deeper in the water column at 150 m, episodes of equatorward and offshore flow were also observed; these lasted for up to a week (Fig. 2C). Peak offshore current speeds exceeded 0.5 m/s at 10 m and 0.07 m/s at 150 m.

The horizontal scales of the eddy and its anticyclonic rotation are apparent from the looping trajectory of a surface layer drifter (8) that transited through the eddy from 6 to 11 July (JD 188 to 193) (Fig. 1B). We interpret the dimensions of the drifter track

to be a lower bound on the size of the eddy (at least 90 km in along shore extent and 50 km in cross shore extent). The track of the drifter extended well up onto the continental shelf, reaching almost to the 100-m isobath offshore of Point Arena. For 1.5 days beginning on 8 July (JD 190) when the drifter was over the shelf, its average speed was about 0.6 m/s (9), in good agreement with the moored current observations from a depth of 10 m at that time (vertical dashed lines, Fig. 2B). A section of geostrophic velocity (10) on 14 July (JD 196) shows that the velocity field of the eddy was deep, penetrating to at least 400 m in deep water, and that its center was over the continental slope near station 52 (Fig. 3).

At most stations on the continental shelf and slope within the eddy, layers of resuspended sediments were observed near the sea floor (black squares, Fig. 1B). At station 204 (data obtained on JD 195) on the shelf, a deep turbidity layer (11) extended from 150 m down to the bottom at 200 m (Fig. 4A). This finding indicates that sediment particles had been transported upward from the sea floor (12, 13),

although the vertical transport may have occurred at another location and the layer advected to this location by the eddy. A second turbidity layer occurred above 100 m, but it exhibited high levels of chlorophyll fluorescence, which indicates that this layer contained phytoplankton. Phytoplankton are abundant in near-surface waters in this productive upwelling system (14). The sediments near the bottom occurred in a relatively well mixed layer. An abrupt decrease in the vertical density gradient (15) marks the top of this layer and indicates a transition from well-stratified waters at mid-depth to the weakly stratified waters in the bottom layer (Fig. 4B). Similar bottom mixed layers and turbidity layers are common features in shelf waters in this region (16, 17) and result from turbulence and sediment resuspension processes in the bottom boundary layer. Near-bottom current velocities as a result of the eddy alone were probably insufficient to produce the observed turbidity layers. More likely, particles in these layers were initially resuspended by other processes such as oscillatory currents resulting from internal waves or

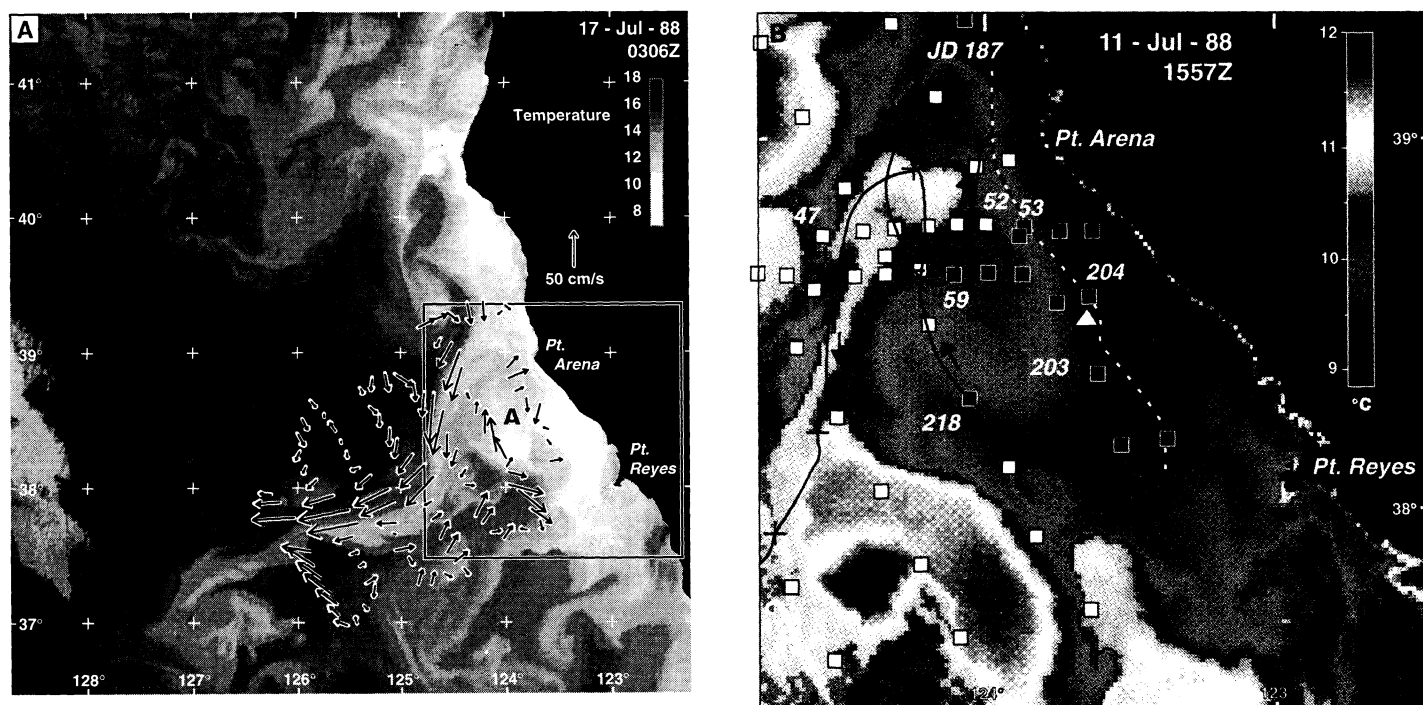


Fig. 1. Satellite SST images of coastal waters off northern California. (A) Image from 0306 UT on 17 July 1988 (JD 199) [adapted from (7)]. Light areas indicate cooler water and dark areas, warmer water. The cold area along the left side of the image between 37° and 39° is due to clouds. Arrows show current direction and magnitude at a depth of 25 m from a shipboard survey (13 to 18 July; JD 195 to 200). The velocity scale is indicated by the upward arrow labeled 50 cm/s. The center of the anticyclonic eddy in which plumes of resuspended bottom sediments were observed is at A. Wind-driven upwelling produced the band of colder water adjacent to the coast. (B) False-color satellite SST image from 11 July 1988 (JD 193) at 1557 UT showing an anticyclonic eddy near Point Arena. The area of the image is shown by the square in (A). A

surface drifter made a single loop around the eddy before it was entrained by a strong current jet and advected away toward the southwest. The drifter track is shown by the solid line and arrows indicate direction. Tick marks on the drifter track are 1 day apart and the drifter location at the beginning of JD 187 (5 July) is shown. The dashed line shows the location of part of the continental shelf break at the 200-m isobath. Numbers identify specific stations mentioned in the text. The triangle near station 204 indicates the mooring position in a water depth of 400 m. Squares mark station positions and black squares show stations where resuspended bottom sediments were observed. Sediments were advected well beyond the continental shelf by the eddy.

surface waves (18). We hypothesize that, once the sediment layers were resuspended, the eddy provided a quasi-steady current that transported particles off the shelf (19). At some locations such as station 203 (data obtained on JD 195), turbidity layers were observed at depths below 300 m within the eddy, an indication that sediment resuspension and transport processes were not only confined to the shelf but also occurred on the continental slope.

The eddy carried sediments well beyond the continental shelf into the deep ocean. At station 218 (data obtained on JD 196), about 45 km from the shelf break, a turbidity layer 60 m thick was centered at 225 m (Fig. 4C). The top of this layer coincided with an inversion in temperature where the water was 0.1°C warmer and saltier by 0.03 practical salinity unit (psu) than water immediately above. Because of the increased salinity, the density is greater and the interface is stable. The differences in properties between the sediment layer and ambient waters at this station indicate that the layer intruded into the surrounding water column and was derived from a different water mass. Comparison of properties within this sediment layer and the bottom

layer of station 204 (Fig. 4A) reveals that the temperature, salinity, and density of these two layers were virtually identical and supports the hypothesis that this sediment layer originated on the shelf. Low vertical density gradients within the layer at station 218 (Fig. 4D), particularly in the upper 25 m, are consistent with strong mixing from contact with the bottom. The layer advected from the shelf to station 218 in about 9 days (20). Several other sediment layers were observed within the eddy at stations offshore of the shelf break (Fig. 1B).

These observations indicate that plumes of sediments originating on the shelf and slope were advected into deep offshore waters by the eddy. Turbidity layers were observed seaward of the continental shelf in all four hydrographic surveys conducted during June and July 1988. This suggests that sediment transport was frequent while the eddy was in the vicinity of the shelf and slope. Mesoscale eddies often occur in the vicinity of Point Arena (21), so eddy transport of sediments off the continental shelf may be a frequent occurrence here. The observed turbidity level of about 0.45 m^{-1} in the 50-m-thick layer at station 218 corresponds roughly to a suspended mass concentration of 0.2

mg/liter. Over the shelf at station 204, concentrations in the bottom layer were 0.3 to 0.5 mg/liter (22). The decrease in turbidity within the plumes around the eddy may result from mixing and dilution of the sediments with clearer ambient waters and suggests that the eddy produced a net cross-shelf transport of sediments. Sediment layers were not observed at the few stations off Point Arena where the eddy flow was directed back toward shore.

The exact mechanism by which the plumes were entrained into the eddy from the continental shelf and slope is not clear, but the cross-shelf transport could occur in a number of ways, including (i) during the episodes of deep offshore flow while the

Fig. 2. Moored time series of (A) temperature at a depth of 10 m, (B) current velocity at a depth of 10 m, and (C) current velocity at a depth of 150 m from JD 120 to JD 200, 1988. Mooring was in water 400 m deep at the position indicated by the triangle in Fig. 1B. Along shore current speed is positive toward 317° true (poleward), and cross shore current speed is positive toward 47° true (onshore). All data have been smoothed with a 1.5-day running mean. Vertical dashed lines between JD 190 and JD 192 show when the surface layer drifter was over the continental shelf. Warming of surface water beginning on JD 128 indicates the warm core of the eddy moving shoreward and coincides with increasing equatorward flow at 10 m. The eddy produced strong, persistent offshore flow at 10 m (shaded regions) between JD 170 and JD 196. Episodes of offshore flow lasting several days occurred at 150 m (shaded regions) and may have been partly responsible for the transport of sediment plumes off the continental shelf.

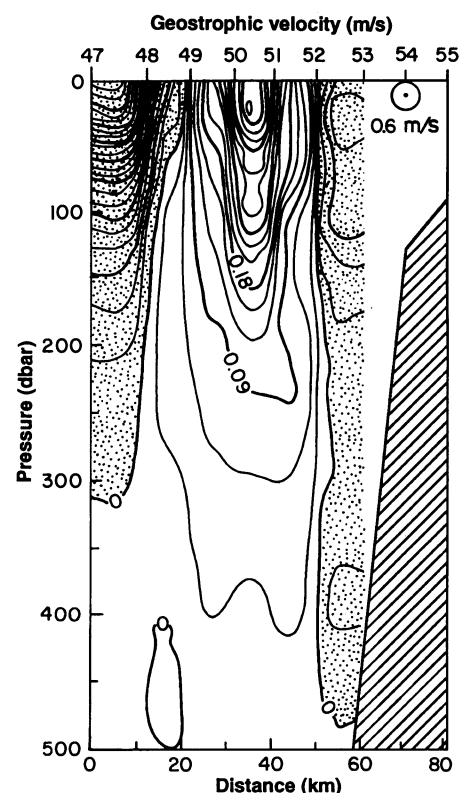
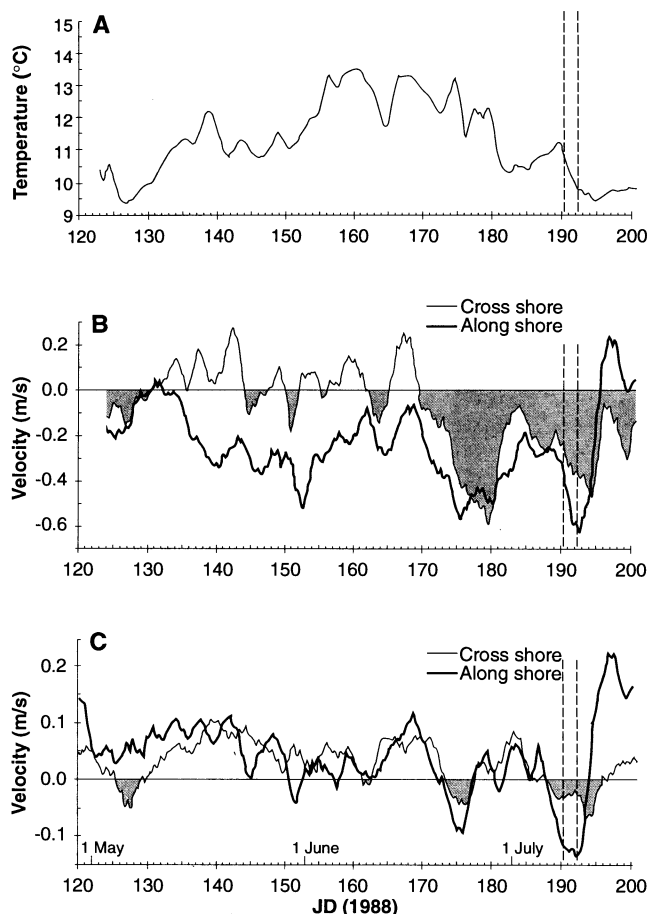


Fig. 3. Vertical section of geostrophic velocity (500-dbar reference level) across an anticyclonic eddy for stations 47 to 53 (Fig. 1B) obtained on 14 July 1988 (JD 196). Southward flow is indicated with stippling; the continental shelf and slope are shown with cross-hatching. Strong northward flow between stations 49 and 52 and southward flow between stations 52 and 53 resulted from the anticyclonic eddy. Southward flow between stations 47 and 49 was part of the flow field of a strong current jet lying offshore of the eddy (Fig. 1A). A southward current speed of 0.6 m/s at a depth of 15 m near station 54 was estimated from the path of a surface layer drifter (Fig. 1B) that crossed over the continental shelf 2 days before this velocity section was obtained. The velocity field of the eddy extended to a depth of at least 400 m and transported plumes of sediments from the continental shelf and slope to the deep ocean.

eddy was over the shelf and slope, such as those observed at the mooring location at a depth of 150 m (Fig. 2C) and (ii) during the more persistent episodes when the near-bottom flow over the outer shelf and slope is poleward and the Ekman transport in the bottom boundary layer is offshore. In this latter case, the sediment layers may be moved toward the shelf break until they are entrained in the eddy and swept into the deep ocean. More observations are required to clarify the interaction between eddies in this region and the deeper flow fields of the shelf and slope.

To obtain an estimate of the mass flux of sediments across the shelf due to the eddy, we assume that the layer at station 218 is part of a continuous plume extending around the eddy from the shelf break, about 80 km. Taking the layer width to be 10 km (23) and the thickness to be 50 m and using the advection time scale of 9 days, we estimate that the cross-shelf sediment mass flux was of order 10^6 kg/day. Assuming that this eddy remained in the vicinity of the shelf and slope for about 2 months, we

estimate that the total mass of sediments transported to the deep ocean may be 10^5 metric tons. This amounts to about 4% of the total mass of sediments, 2×10^6 to 3×10^6 metric tons, discharged onto the shelf annually from the Russian River (19). Although this is a small fraction of the total input, it probably represents a large fraction of the annual flux of sediments reaching the region of the shelf around Point Arena.

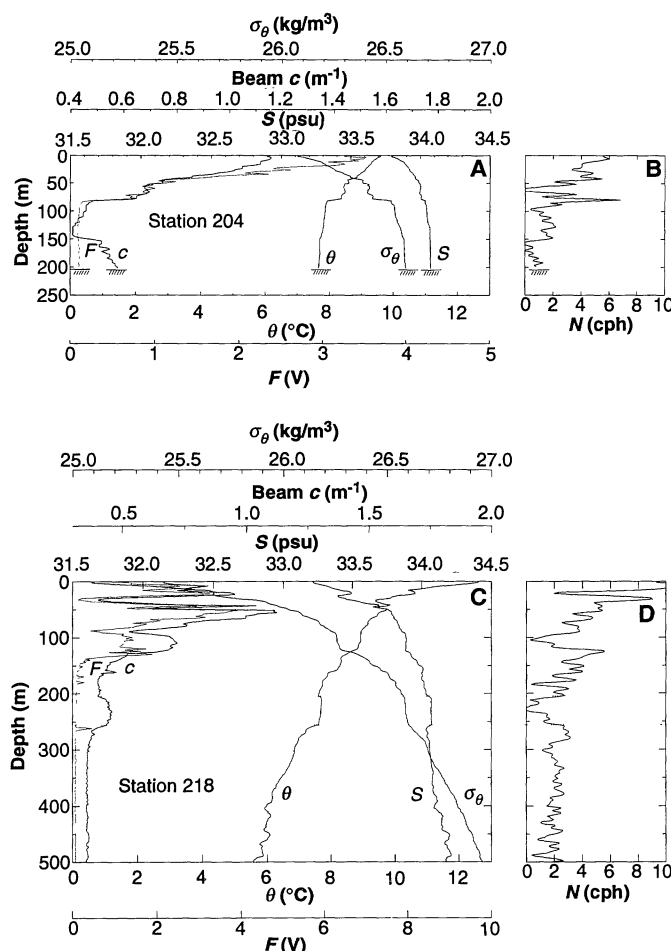
A flux of this order is likely to be a dominant factor in the cross-shelf transport of sediments during summer when other transport processes are generally weak; most sediment flux on this shelf occurs during winter storms (13). The sediments on this shelf contain organic carbon (24). Thus the suspended particles within the turbidity layers are also likely to contain carbon, and a significant cross-shelf carbon flux to the deep ocean may result from eddy transport of sediments here. Mesoscale eddies are common features of the California Current system and other eastern boundary currents, and these observations suggest that these eddies may play an important role in

the transport of shelf sediments to the deep ocean.

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9. Time series of current speed were formed from successive observations of drifter position. Drifter latitude and longitude were interpolated to regular intervals of 0.125 day, and speed was obtained from moving centered differences over 0.25 day. Final velocity estimates were smoothed with a 21-hour moving average.
10. Geostrophic velocity was computed with respect to a reference level of 500 dbar along the line of stations 47 through 53 (Fig. 1B). Data were obtained from the R.V. *Thomas Washington* on 14 July (JD 196). At each station in all shipboard surveys, vertical profiles of temperature, conductivity, pressure, beam transmission, and chlorophyll fluorescence were measured to a depth of 500 m or to the bottom in shallower waters. At station 53 where the water depth was 450 m, we estimated dynamic height by first extrapolating the specific volume anomaly to 500 dbar and then integrating upward.
11. The beam attenuation coefficient or beam c is a quantitative indicator of water turbidity and is computed from the transmissometer signal by
$$c = -\ell^{-1} \ln \left(\frac{T}{100} \right)$$
where T is the percent transmission over the path length $\ell = 0.25$ m. The transmissometers used in all surveys are manufactured by SeaTech, Inc., Corvallis, OR, and operate at a wavelength of 660 nm.
12. Surface sediments on the middle and outer shelf

Fig. 4. Vertical profiles at station 204 over the continental shelf (obtained on JD 195) of: (A) turbidity (c), potential temperature (θ), salinity (S), potential density anomaly (σ_θ), chlorophyll fluorescence (F), and (B) buoyancy frequency (N), a measure of the vertical density gradient [in cycles per hour (cph)]. The bottom is shown by cross-hatching. A layer of resuspended sediments corresponding to high c and low F occurred between 150 m and the bottom. Within this bottom turbidity layer, profiles of θ , S , and σ_θ were relatively well mixed and vertical density gradients (N) were reduced as a result of bottom turbulence processes. High levels of c and F above 100 m indicate phytoplankton. (C) As in (A) but for station 218 (data obtained on JD 196) located 45 km seaward of the continental shelf break and along the track of the surface drifter (Fig. 1B). (D) As in (B) but for station 218. A 60-m-thick turbidity layer (bracketed by the dotted lines) occurred below 200 m and resulted from the advection of sediments from the continental shelf into the deep ocean. Low values of N and relatively well mixed θ , S , and σ_θ profiles within the layer are consistent with previous mixing at the sea floor.



between Point Reyes and Point Arena are composed mainly of fine silt derived from the Russian River outflow and have mean grain sizes in the range 30 to 125 μm .

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15. The vertical density gradient is expressed as the buoyancy frequency N and is a measure of the static stability of the water column. It is defined by

$$N = \left(-\frac{g\partial\rho}{\rho\partial z} \right)^{1/2}$$

where g is the acceleration of gravity, ρ is seawater density, and z is the vertical coordinate, positive upward. Vertical density gradients are estimated from moving centered differences of ρ and z over vertical scales of about 4 m followed by smoothing with a running mean over a 12-m vertical scale.

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20. The length L scale over which the layer advected is estimated from the distance along the drifter track from the point at which it crossed the continental shelf break to station 218 where the sediment layer was observed, about 80 km. An advective speed U of 0.1 m/s is estimated by as-

suming that the speed within the layer is similar to the geostrophic current speed in the velocity section of Fig. 3 at the layer depth. The advection time scale L/U is about 9 days.

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22. Suspended sediment concentration is derived from transmissometer and bottle sample data for the Russian River shelf reported in figures 3 and 5 and table 2 of (17). An approximately linear relation is found between the beam attenuation coefficient c in reciprocal meters and suspended sediment mass concentration C in milligrams per liter of the form $c = 0.475C + 0.37$ (SE 0.14 m^{-1}).
23. The scale for the width of the region containing resuspended sediments is estimated from the maximum distance the drifter moves inshore of the continental shelf break (200-m isobath) and is about 10 km. Turbidity layers of this scale have been observed on this shelf (17).
24. The carbon content of sediments is indicated by their combustible fraction, which is also an indicator of phytoplankton abundance. Suspended sediment samples obtained over the Russian River shelf have combustible fractions in the range of 8 to 53% (17). In the CTZ experiment a few bottom turbidity layers exhibited weak but measurable levels of fluorescence, which suggests that they contained phytoplankton that had previously settled to the sea floor.
25. The CTZ Experiment was funded by the Coastal Sciences Program of the Office of Naval Research. The Northern California Coastal Circulation Study was funded by the Minerals Management Service (U.S. Department of the Interior) and was conducted in collaboration with EG&G Washington Analytical Services Center, Inc. D. Lawson of the University of California, Santa Barbara, produced the final satellite images.

7 April 1993; accepted 12 July 1993

new gravity anomaly map (5) of northern Yucatán (Figs. 1 and 2).

The gravity data set comprises 3134 offshore measurements and 3675 land stations (Fig. 2A) between 19.5°N to 22.5°N and 88°W to 90.5°W (6). After removing obviously spurious points, we gridded the data by a bivariate interpolation scheme designed for irregularly distributed points (7). Gravity anomalies in the mapped region range from -16.4 mgal (10^{-5} m s^{-2}) to $+53.6$ mgal.

The Chicxulub basin is a broad, nearly circular region in which gravity values are 20 to 30 mgal lower than regional values. A distinct 15- to 20-mgal high occupies the geometric center that we place at 21.3°N and 89.6°W (Figs. 1 and 2). Analysis of radial profiles compiled for each 10° increment of azimuth clearly reveals multiple rings expressed as local maxima in the gravity anomaly data. Besides the central gravity high, we recognize three major rings and evidence of a fragmentary fourth ring (Figs. 1, 2, and 3). Basins with three or more concentric rings are the largest impact landforms observed on planetary surfaces. Analyses of multiring impact basins on all the silicate planets of the inner solar system have shown that the radial positions of these topographic rings follow a "square root of 2" spacing rule (8). The concentric gravity highs within the Chicxulub basin (Figs. 1 and 2) also follow this spacing rule (Table 1), indicating that they correspond to topographic rings of this now-buried impact basin.

The central gravity high most likely reflects the mass concentration associated with the dense impact melt sheet and the uplift of silicate basement rocks in the middle of the structure. The concentric gravity trough separating the central dome from the inner ring (Fig. 1, ring 1) could mark the position where the dense melt rock sequence is thin enough for the low-density breccias filling the crater to dominate the gravity expression. The diameter of the inner ring is 105 ± 10 km. Ring 1 probably corresponds to the topographic central-peak ring associated with the structural uplift of large complex impact craters (9).

Gravity values increase substantially and abruptly between ~ 70 and ~ 100 km from the basin center. Near the inside edge of

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Chicxulub Multiring Impact Basin: Size and Other Characteristics Derived from Gravity Analysis

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The buried Chicxulub impact structure in Mexico, which is linked to the Cretaceous-Tertiary (K-T) boundary layer, may be significantly larger than previously suspected. Reprocessed gravity data over Northern Yucatán reveal three major rings and parts of a fourth ring, spaced similarly to those observed at multiring impact basins on other planets. The outer ring, probably corresponding to the basin's topographic rim, is almost 300 kilometers in diameter, indicating that Chicxulub may be one of the largest impact structures produced in the inner solar system since the period of early bombardment ended nearly 4 billion years ago.

The Chicxulub structure is widely considered to be an impact crater related to the ~ 65 -Ma (million years ago) K-T boundary layer (1-3). Because this feature is buried under 300 to 1100 m of Tertiary carbonate rocks in the Northern Yucatán Platform, geophysical exploration is essential to understand its morphology and structure. Indeed, concentric patterns in gravity and magnetic field data over this feature led to its discovery (1). Hildebrand *et al.* (2) later

recognized two concentric rings in gridded gravity data then available and interpreted their 180-km-diameter outer ring as the rim crest of Chicxulub. They could not resolve concentric structure in the northern one-third of the feature, however, and proposed that an east-northeast trending fault had removed the crater's signature in this region (2, 4). To better understand the nature of the Chicxulub impact structure and its regional setting, we compiled and analyzed a