Patchy deposits of Cenozoic pelagic sediments in the central Pacific

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ABSTRACT

Export of pelagic carbonate tests from surface waters and their deposition at the seafloor plays a significant role in the CO_2 cycle and ability of the oceans to absorb atmospheric CO_2. Sediment ^{230}Th and ^{3}He measurements have been interpreted as evidence that significant lateral advection of pelagic material occurs in the water column, leading to marked spatial variations in deposition rates and, in particular, to significant focusing of deposits on the Pacific equator. We report spatially continuous stratigraphy from two 1000 km seismic lines that show evidence of depositional anomalies near the equator. Accumulation rates were apparently enhanced locally by a factor of two, similar to the proposed modern sediment-focusing factors, but the anomalies are surprisingly patchy over the 20 m.y. period analyzed—they are not confined to an equatorial region, and they are not necessarily found on adjacent seismic profiles. These intermediate-scale anomalies are >~100 km across and represent areas of seafloor that received more deposits for one period, less in following periods, and vice versa. Variogram analysis was used to determine how the spatial scales of deposition changed over the Neogene. The period when the spatial scale of depositional variability was largest correlates with hiatuses in drill cores, a correlation that we interpret as caused by enhanced and spatially heterogeneous carbonate dissolution at that time. The study suggests that seismic stratigraphy has the potential to reveal spatial patterns related to unsteady bottom-water flow and chemistry.

Keywords: pelagic carbonate seismic stratigraphy, sediment focusing, pelagic carbonate dissolution, Pacific Ocean circulation, variogram analysis.

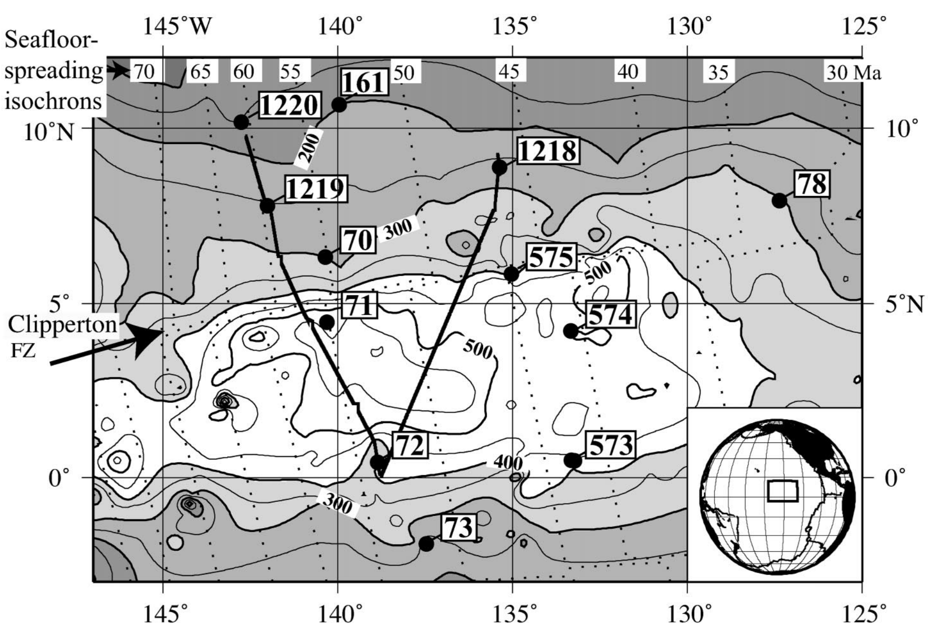

Figure 1. Map of central Pacific sediment bulge. Contours (in meters) show seismically derived sediment thickness modified from data released by National Geophysical Data Center of National Oceanic and Atmospheric Administration (Mitchell, 1998). Boxed numbers associated with solid circles are Deep Sea Drilling Project and Ocean Drilling Program drill sites. Dotted lines with numbers at top are basement seafloor-spreading isochrons. R/V *Ewing* seismic data discussed in this paper were collected along two bold lines. FZ—fracture zone.

INTRODUCTION

The accumulation of sedimentary material in the oceans is rarely pelagic in the ideal sense of perfectly draping the underlying topography. Drilling recovers a record of deposition that is severely undersampled spatially. Fortunately, large-scale changes in bottom-water chemistry have left density anomalies in equatorial Pacific sediments that create distinctive reflectors in seismic reflection images, allowing derivation of a spatially continuous stratigraphy (Mayer et al., 1986). Such reflectors have been correlated over vast distances, from 134°W (Mayer et al., 1986) across to 110°W (where they also reflect productivity events) (Bloomer et al., 1995), a distance of >2000 km. In 1997, a seismic survey of the R/V *Ewing* collected reflection data from the equator to >1000 km north along two lines shown in Figure 1. Here we use stratigraphy interpreted from these data (Knappenberger, 2000) to address the variability of pelagic sediment deposition in the central Pacific.

SPATIAL HETEROGENEITY DERIVED FROM SEISMIC REFLECTION DATA

Characteristic reflectors defined by Mayer et al. (1986) were identified and mapped out from the two lines in Figure 1. Reflector two-way traveltimes were converted to the sediment dry mass per unit seafloor area (herein called ''interval mass'') for each stratigraphic interval by using physical property data from Deep Sea Drilling Project (DSDP) Leg 85 (Mitchell et al., 2003). The results in Figure 2 reveal that deposition was remarkably inhomogeneous; areas alternately received an anomalous excess or deficit of sediment with length scales of >100 km. Temporal changes in depositional style (draping vs. basin filling) have been observed before (Laguros and Shipley, 1989), but not changes at this scale. Furthermore, these data do not show much evidence for simple depth-dependent dissolution (Mitchell et al., 2003); rather they suggest a broad lysocline in this area without simple linearly increasing dissolution with depth.

PATTERN OF MODERN AND 0–11 Ma DEPOSITS

Comparison with modern deposition at 135°W and with deposits on shallower sea-

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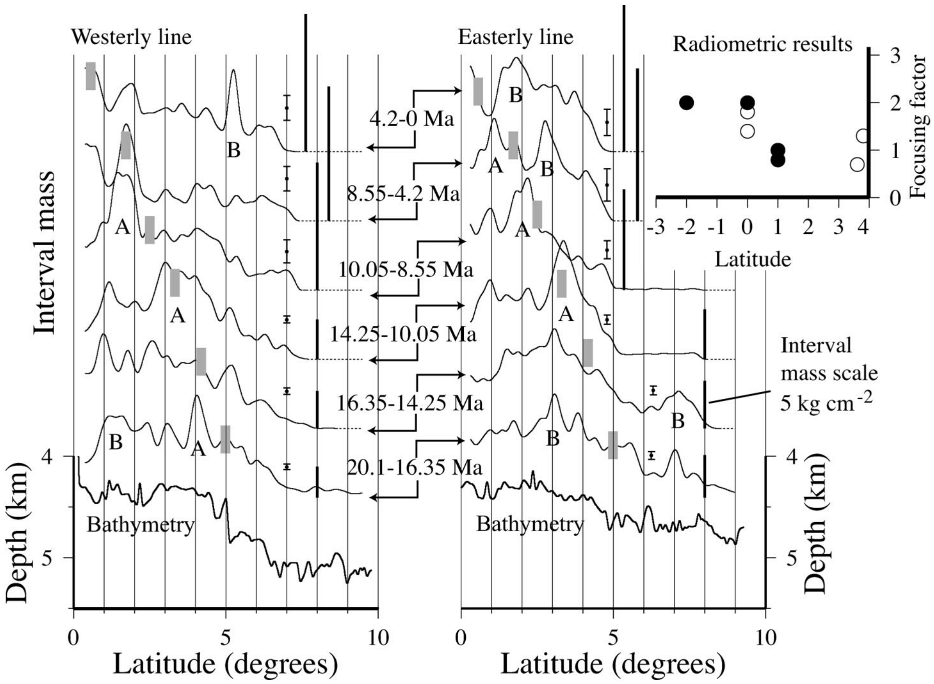

Figure 2. Bathymetry and interval mass (dry bulk mass of sediment per unit seafloor area) for various periods derived from interpreted seismic intervals for two R/V *Ewing* lines in Figure 1. Seismic two-way traveltime has been converted to interval mass by using physical property data from Deep Sea Drilling Project Leg 85 sites (Mitchell et al., 2003). Interval mass data for each interval are plotted with varied scales (vertical solid scale bars each represent 5 kg cm^{-2}) so that shapes of successive intervals can be compared. Dotted sections represent areas where sediment interval was too small to be resolved seismically. Data have been smoothed with cosine-tapered filter (Wessel and Smith, 1991) of full width 66 km, which effectively removes variations smaller than 33 km. Calculation of representative 2σ uncertainty bars is described in caption to Figure DR2 (see footnote 1 in text). Age intervals follow reflector ages of Mayer et al. (1986) updated to newer time scales (Mitchell, 1998). Wide vertical gray bars indicate average paleoequator latitude for each interval derived from paleomagnetic apparent polar wander path for Pacific plate (Sager and Pringle, 1988). Anomalies that may be explained by enhanced equatorial productivities are marked A; others that may not are marked B. Inset at top right illustrates sharpness of equatorial anomaly in interval mass to be expected if it were purely caused by mechanical focusing of particles, as interpreted from sediment radiometric data (solid circles from Marcantonio et al., 2001; open circles from Higgins et al., 1999).

floor close to the East Pacific Rise at 110°W allows us to assess the extent to which these anomalies were caused by spatially varied biological productivity; in the modern ocean, upwelling at the equator leads to sharp gradients in water temperature, chlorophyll, and productivity (Honjo et al., 1995; Pena et al., 1990). The carbonate flux to the seabed measured by using moored sediment traps (Fig. 3, plus symbols) is enhanced over a broad region extending to at least 5° either side of the equator; a secondary maximum at 5°N marks oceanic divergence associated with the North Equatorial Countercurrent (Dymond and Collier, 1988). Dissolution at 135°W occurs at ~1 mg cm^{-2} yr^{-1} (Dymond and Lyle, 1994) and sharpens this primary input pattern (Lyle, 2003), as shown in Figure 3 (solid circles) by the deposition rates over a 12 k.y. interval that are derived from sediment cores. The core data also show enhanced deposition around the equator and a secondary maximum at 4°N.

Over longer geologic time scales, however, the progressive northward movement of the Pacific plate acts as a convolution (smoothing) filter on the pattern of deposition (Mitchell, 1998). This movement, combined with instabilities in the oceanographic system, is likely to smear out localized anomalies and leave a smoother pattern of primary input for the time scales represented by the *Ewing* seismic intervals. The drilling results at 110°W provide our nearest record of the long-term pattern of primary input as this area lies on shallower seafloor and carbonates are less dissolved. Figure 3 (open circles) shows the pattern of mean accumulation rate of bulk sediment computed in periods of 1 m.y. from the Ocean Drilling Program (ODP) Leg 138 chronology (Shackleton et al., 1995) and physical properties. The mass-accumulation rates (MAR) were normalized to the maximum value of each period. Also plotted in Figure 3 is the distribution of sediment mass derived from a water-gun seismic reflection line along 110°W (Mayer et al., 1992), representing the cumulative deposition over 11 m.y. Besides the 2°N anomaly, which is an artifact of a basement feature crossed by the seismic line, both data types show that deposition was smooth with a scale of a few degrees either side of the equator and with little sign of the secondary depositional maximum.

To relate these anomalies to equatorial productivity and focusing, we computed the progression of the paleoequator by using a paleomagnetic apparent polar wander path for the Pacific plate (Sager and Pringle, 1988). The average equator location for each period is shown by the wide, vertical gray bars in Figure 2 and has an uncertainty scaling to 1°–2° at 20 Ma. An uncertainty of ~1° for 11–0 Ma is also constrained by the variability in the center of enhanced deposition derived from the ODP Leg 138 MAR data (Mitchell, 1998). Whereas some anomalies in Figure 2 (marked A) may be explained by enhanced equatorial productivity, many others (B) are not, and the general appearance of each interval is patchy and quite different from the smooth pattern at 110°W.

CORRELATION WITH DRILLING HIATUSES

In explaining these anomalies, we connect observations of spatial variability in the modern ocean with evidence from hiatuses in DSDP cores. World Ocean Circulation Experiment observations have revealed significant topography in the carbonate saturation horizon for the Pacific, in particular three-dimensional complexity as the horizon shallows from the Antarctic Bottom Water in the south to the more corrosive Pacific Deep Water in the north (Feely et al., 2002, 2004). Although the relationship between saturation horizon and carbonate dissolution rates is not straightforward (Feely et al., 2004), there are comparable spatial anomalies in the carbonate content of modern surface sediments in this area (Archer and Maier-Reimer, 1994), suggesting that the pattern of dissolution rates has not been a straightforward function of latitude and depth as described earlier (Berger, 1978; van Andel et al., 1975). We hypothesize that spatially varied chemical properties and flow rates of Pacific bottom waters have changed throughout the Cenozoic, leaving a complex spatial and temporal pattern of deposition (observed in Fig. 2) superimposed on the equatorial sediment bulge.

We calculated the spatial scale of the anomalies in Figure 2 by fitting a fourth-order polynomial to the unfiltered interval mass, subtracting the polynomials from the data and then calculating variograms (Davis, 2002) from the residuals (Data Repository Figs. DR1

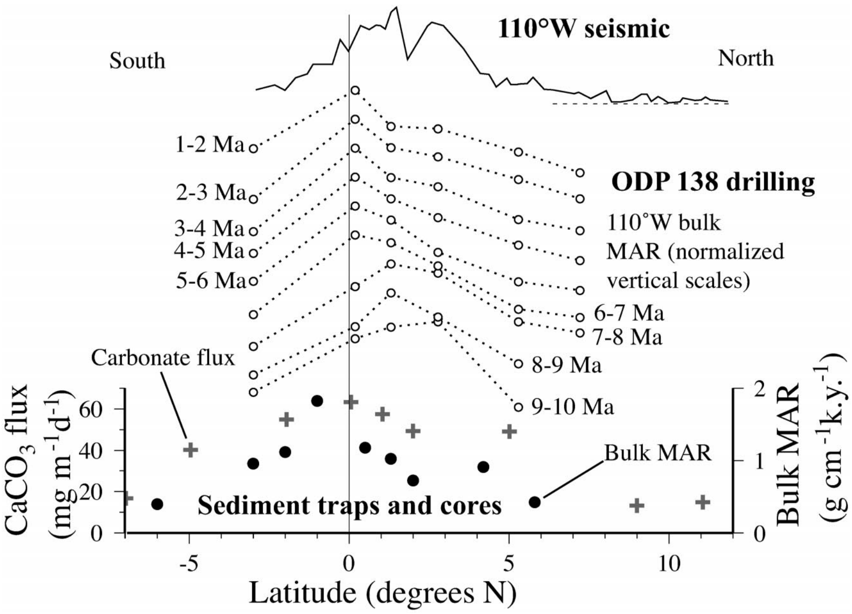

Figure 3. Distribution of sediment mass and other depositional data. Plus symbols—north-south transects at 135°W of carbonate flux measured in deep sediment traps (Dymond and Lyle, 1994; Honjo et al., 1995). Solid circles—mean mass-accumulation rates (MAR) of bulk sediment over 12 k.y. from cores (Murray et al., 1993). Open circles connected by dotted lines—mean MARs of bulk sediment over 1 m.y. derived from orbitally tuned stratigraphy of Ocean Drilling Program (ODP) Leg 138 sites at 110°W (Shackleton et al., 1995) combined with physical property data. At top is sediment thickness at 110°W derived from seismic reflection profile (Mayer et al., 1992) and decompacted by using ODP Leg 138 physical property data (Mitchell, 1998). All these 110°W data have been normalized to peak values and offset to reveal spatial patterns; hence no vertical scale is given.

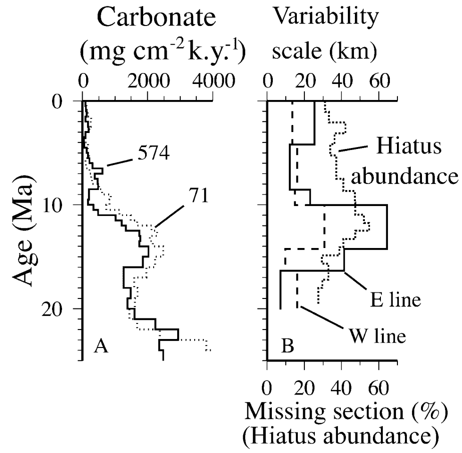

Figure 4. Carbonate mass-accumulation rates and variability length scales. A: Carbonate-accumulation rates from Deep Sea Drilling Project (DSDP) Sites 71 and 574 (dotted and continuous lines, respectively) from revised chronology (Lyle, 2003). Sites 71 and 574 are at 4419 and 4561 m, respectively. B: Scale of spatial variability for two seismic lines computed as described in text. Note that this scale does not obviously correspond to effect of abyssal-hill geometry as east line cuts seafloor-spreading fabrics more obliquely than west line (dotted lines in Fig. 1) but shows larger scale. Also shown (dotted line, with scale below) is abundance of hiatuses in DSDP sediment cores (Moore et al., 1978; van Andel et al., 1975) with updated time scale.

and DR2[1]). The spatial scale of the variability was then derived by fitting an exponential model to the variograms. The *e*-folding lengths of this model are shown by the continuous and dashed lines in Figure 4B (variability scale). These reveal a tendency toward anomalies on a larger spatial scale in the period 20–10 Ma, which can also be observed in Figure 2. Anomalies tend to be more localized after 10 Ma.

The abundance of hiatuses, which were defined as missing biostratigraphic zones in northeast Pacific DSDP cores (Moore et al., 1978; van Andel et al., 1975), is shown by the dotted line in Figure 4B as the proportion of missing section. Hiatuses defined in this way are a rough measure of nondeposition or erosion caused chemically and/or mechanically, leading to loss of microfossils (Berger, 1978; Keller and Barron, 1983; Moore et al., 1978; van Andel et al., 1975). Neogene hiatuses correspond to periods of high $\delta^{18}O$ values in foraminiferal carbonate and to lowstands interpreted from continental-margin stratigraphy, suggesting times of global cooling with intensified bottom-water formation and corrosiveness (Keller and Barron, 1983). The peak abundance immediately prior to 10 Ma (middle to late Miocene boundary) occurred when hiatuses were particularly widespread. This was a period when accumulation rates were high (Fig. 4A) and when our recorded anomalies in deposition had the largest spatial scales (Fig. 4B). The period's termination at 10 Ma coincides with an abrupt shoaling of the carbonate compensation depth in the eastern Pacific (Lyle et al., 1995). Furthermore, a decrease in $\delta^{13}C$ values in benthic foraminifera relative to deep-dwelling pelagic foraminifera occurred over the middle to late Miocene transition (Theyer et al., 1989). The combined information suggests that bottom waters became corrosive here partly because of high inputs of organic carbon as well as through stronger bottom-water circulation and undersaturation. After 10 Ma, erosion by dissolution would have continued as the plate subsided further below the carbonate compensation depth, producing the localized anomalies frequently observed in seismic data (e.g., Johnson, 1972; Mayer, 1981).

[1]GSA Data Repository item 2005007, Figures DR1 and DR2, profiles of unfiltered sediment interval mass and associated variograms, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

RADIOMETRIC DATA AND SEDIMENT FOCUSING

Higgins et al. (1999) found western Pacific ^{230}Th accumulation rates at 160°E to be 1.4–1.8 times higher on the equator than expected from production by ^{234}U decay in the immediately overlying water column, but the rates were closer to normal at 3.6–3.8°N. One explanation put forward was that lateral advection of particles occurs in the water column, leading to commensurably enhanced deposition rates. Accumulation rates of extraterrestrial ^{3}He in cores at 140°W have been interpreted as showing a factor of two focusing of deposits on the equator compared with more nearly normal deposition at 1°N (Marcantonio et al., 2001). As the carbonate compensation depth is depressed (van Andel et al., 1975) and primary carbonate flux is enhanced (Fig. 3) broadly over a region of a few degrees centered on the equator, a focusing factor X should result in equatorial carbonate deposition rates locally enhanced by at least the factor X compared with the adjacent seafloor (inset, Fig. 2).

For the anomalies marked A in Figure 2, which were collected close to 140°W, a deposition-enhancement factor was derived from the ratio of the peak value to the adjacent background of each anomaly. This factor had a mean value of 2.1 and ranged from 1.7 to 3.2. The equatorial peak does not occur consistently on adjacent seismic lines for all periods shown in Figure 2, however, and some peaks marked A could be misidentified given the equator-location uncertainty. Further testing of the equatorial focusing hypothesis would benefit from radiometric measurements from transects of cores to resolve the spatial scale of focusing and correlation with the pattern of enhanced Quaternary deposition rates, which can be derived from characteristic ash reflectors in sediment-profiler records (Lyle et al., 2004).

The subject of paleoceanography is concerned with correlating geochemical and biological events observed at drill sites across and between oceans, as such correlations can reveal regional and global changes in circulation or chemistry (e.g., Hybers and Wunsch, 2004). To illustrate, DSDP Sites 71 and 574 are in similar water depths and at a common latitude (Fig. 1); hence they had a similar primary input of pelagic material. Their carbonate MARs are remarkably coherent (Fig. 4). What has been less studied is the degree to which such synchronous down-core variations have differing magnitudes, but such differences could contain important information on bottom waters. The degree of incoherence in global correlations (Hybers and Wunsch, 2004), for example, is a potentially important signature of bottom-water properties and flow if mapped out and studied with geographical context. Combining records having high temporal resolution from cores with spatially continuous stratigraphy from seismic data, as shown here, could lead to valuable insights into the structure of ocean bottom-water circulation.

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