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Equatorial Pacific Seismic Reflectors as Indicators of Global Oceanographic Events

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The origin of a series of regionally correlatable seismic horizons in the Neogene sediments of the central equatorial Pacific is examined through seismic modeling and the detailed analyses of stratigraphic and physical property relationships in Deep Sea Drilling Project cores. These regionally traceable reflectors are synchronous; the younger reflectors are the direct result of carbonate dissolution events, the older ones of stratigraphically selective diagenetic processes. The changes in ocean chemistry associated with these events appear to be linked to global reorganizations of surface- and bottom-water circulation patterns, the most dramatic of which are associated with reorganizations of North Atlantic bottom waters. These deepwater seismic horizons appear to correlate with the major events on the "relative sea-level" curve of Vail *et al.* for the Neogene.

A FUNDAMENTAL GOAL OF SEISMIC exploration is the complete extraction of geologic information from the seismic record. Recent improvements in seismic sources and advances in data acquisition, processing, and analytical techniques have brought us much closer to this goal, especially in the continental margin areas that have been the subject of detailed petroleum industry exploration. Of particular significance has been the pioneering work of Vail *et al.* (*1*) in developing an approach toward seismic interpretation that permits identification of the depositional environment through "seismic facies analysis" and the establishment of stratigraphic position based on the analysis of relative onlap and offlap curves and their correlation with globally derived sea-level curves. Although the approach of Vail *et al.* has proven invaluable to industrial and academic researchers, several aspects remain controversial, including the validity of the correlation with global sea-level fluctuations (*2, 3*) and the applicability of this technique to deep-sea studies (*4*). These two issues are not necessarily separate. If the seismic events that Vail *et al.* have correlated in marginal sedimentary basins around the world are indeed representative of global events, then there should also be some indication of these events in the deep sea. In this report we examine the origin of a series of regionally correlatable seismic horizons in the Neogene pelagic sediments of the central equatorial Pacific, a region of key importance to paleoceanographic studies and one far removed from the dynamic processes of the continental margins responsible for the Neogene seismic events correlated by Vail *et al.*

The fertile waters of the central equatorial Pacific have produced a thick section of biogenic sediment that is an extremely sensitive indicator of the interplay among tectonism, circulation, productivity, and diagenesis. Deep-sea drilling in the region has produced an intriguing record of paleoceanographic change for the past 40 million years (*5*), but detailed studies have been frustrated by incomplete coring and core disturbance. These difficulties were overcome during Deep Sea Drilling Project (DSDP) Leg 85, which used the hydraulic piston corer in the upper, unconsolidated part of the section and rotary coring in the deeper parts, thereby collecting nearly complete and relatively undisturbed sedimentary records of the past 40 million years. These cores provide a wealth of data for detailed studies of biostratigraphy, isotopes, carbonates, and physical properties in the central equatorial Pacific (*6*). In preparation for Leg 85 drilling, seismic surveys at each drill site and in the general region used the relatively new, high-resolution, watergun seismic source (*7*). The collection of detailed physical property and stratigraphic data, in conjunction with high-quality, digital high-resolution seismic profiles, presents an opportunity to use quantitative modeling techniques (synthetic seismograms) to understand the origin of seismic reflectors in the region and to examine the potential of equatorial Pacific seismic stratigraphy as a paleoceanographic tool.

If we use DSDP core data to examine the geologic origin of seismic horizons, we must know where in the cores to look for a particular reflector. An initial difficulty is that the core information (for example, physical properties or biostratigraphy) is measured as a function of depth below the sea floor (a spatial-domain record) but the seismic profile is recorded as a function of travel time (a time-domain record). Fundamental to the correlation of seismic data with drill hole results is the accurate conversion from travel time to depth (or vice versa). This requirement demands an exact knowledge of the in situ velocity versus depth function—information that is rarely available.

In the absence of well-log data, the detailed velocity structure for the Leg 85 sites was obtained from closely spaced (1 m) shipboard measurements of sonic velocity on core samples corrected to in situ values [a correction that has a mean value of 7.1% and that can be as great as 18% in the 500-m-thick section (*8*)] in order to produce an in situ velocity profile. By combining corrected velocity values and corrected saturated bulk density values (also from shipboard measurements), we generated an in situ acoustic impedance profile that, in conjunction with a measured watergun outgoing pulse, becomes the basis for constructing synthetic seismograms. The details of measurement techniques, in situ corrections, the seismic

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system, and synthetic seismogram generation have been presented elsewhere (*8*). The synthetic seismograms test the validity of our travel time to depth conversion and provide insight into the interactions between the outgoing pulse and the geologic structure.

Synthetic seismograms were generated for each of the three Leg 85 drill sites (573, 574, and 575) that form a 600-km-long, north-south line along 133° from the equator to 6°N (*6*). Watergun seismic profiles were collected at each of the sites and in the general area of the central equatorial Pacific (*7*). Eight regionally traceable reflectors were identified and correlated from site to site (*9*); most of these reflectors can be tied through a 400,000-km^2 region, and several are recognizable on lower resolution airgun records over an area of 1.6 million square kilometers. Figure 1 displays the field record and synthetic seismogram at site 574, located in the middle of the north-south line of sites (4°N). The field record here is typical of those at the other sites, as is the degree of correlation between the synthetic and the field records.

The degree of correlation found between the synthetic seismograms and the field record implies that the travel time–depth conversions are reasonable and permits the precise (±5 m) determination of the depth of the reflectors at each site. Given these depths, an age, based on the biostratigraphic studies of Leg 85 cores (*10*), can be determined for each reflector at each site. Within the limit of our biostratigraphic resolution (conservatively estimated at ±0.5 million years), a given reflector occurs within the same zone at each site for each of the four microfossil groups evaluated (Table 1). Their positions within these zones indicate that the reflectors represent synchronous events. A preliminary investigation of watergun profiles at other DSDP sites in the region (sites 71, 72, 73, and 77) also supports the synchroneity of the reflectors, although spot coring and different biostratigraphic bases make detailed correlations difficult.

Any claim for synchroneity must be tempered by a discussion of the limits of temporal resolution associated with the intercore correlations. In terms of the seismic reflectors discussed here, several factors define the limits to which correlations can be made. One factor is the ability to define where, in depth, a particular reflector is found. The precision of the depth determination depends on the degree of fit between the position of a reflector identified on the field record and the same reflector identified on the synthetic seismogram. For the three Leg 85 drill sites, the maximum misfit between a field record reflector and the equivalent synthetically derived reflector is 0.006 second or approximately 10 m (most are much better), and thus our depth resolution is taken to be ±5 m. For an average Leg 85 sedimentation rate of 20 m per 10^6 years (*10*), this converts to a temporal resolution of ±250,000 years.

More critical than the depth resolution is the error associated with core-to-core correlations. Pisias *et al.* (*11*) examined the stratigraphic resolution associated with intersite correlations for the Leg 85 sites. Based on first and last occurrence datums, they determined the stratigraphic resolution between sites to be 125,000 to 380,000 years. To correlate the reflectors, biostratigraphic zones [as defined in (*10*)] were used; the resolution of these correlations is taken as the time period defined by the overlap of the four major microfossil group zones at the depth of the reflector. The widest time interval associated with any of the Leg 85 reflectors is approximately 1 million years (it is much narrower for most), and thus our temporal resolution is conservatively estimated at ±500,000 years. In the absence of a detailed magnetostratigraphy (the Leg 85 sediments showed extremely low natural remanent magnetization intensities), the limit of our stratigraphic resolution is determined by the biostratigraphic zonations. Within this limit, the regionally correlatable seismic horizons are synchronous.

An examination of the interrelation among the physical properties at the Leg 85 sites provides insight into the origin of the seismic reflectors. As expected, each of the major, regionally traceable seismic horizons is associated with a large acoustic impedance contrast; numerous other impedance contrasts produce reflectors, but most of these are not regionally correlatable. Evaluation of the relative contribution of velocity and density to changes in impedance reveals that, for all but the deepest two regionally traceable reflectors (eM-Y and eM-O), the changes in impedance are due almost entirely to changes in saturated bulk density and not sonic velocity (Fig. 2). The density contrasts are directly related to shifts in the percentage of calcium carbonate, that is, the shifts from high to low carbonate [see (*12*) for details of this phenomenon]. The two

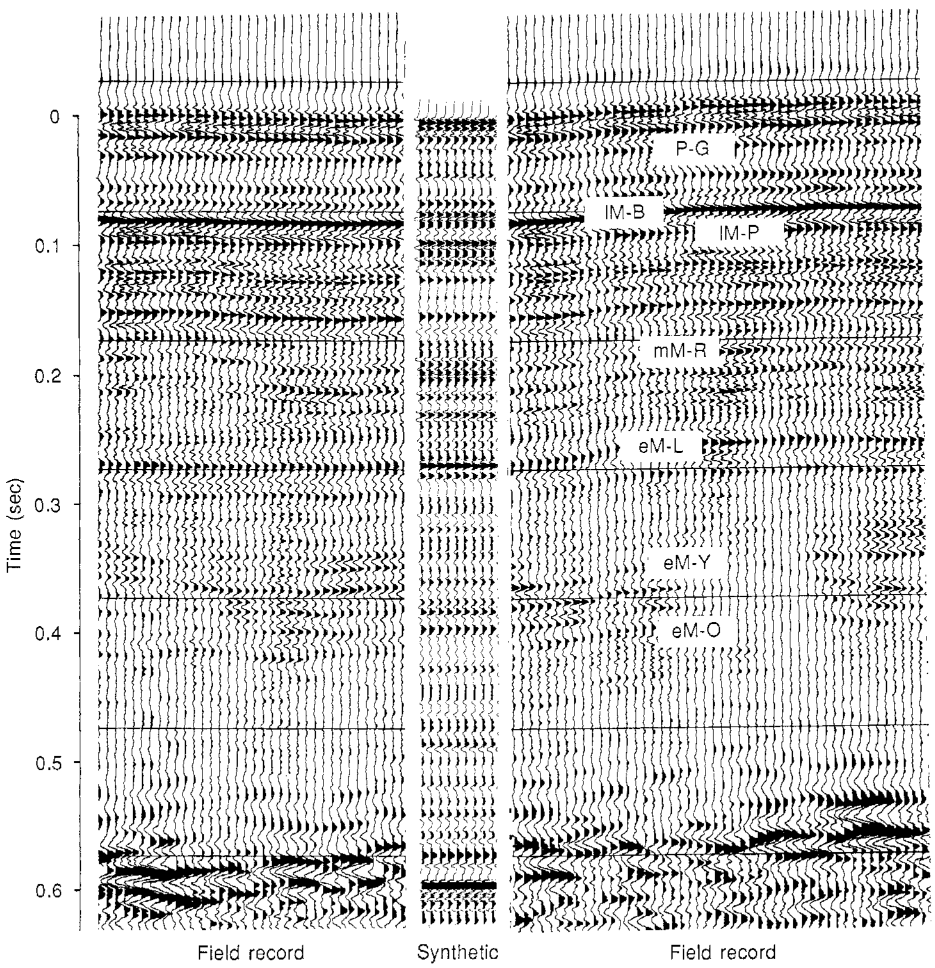

Fig. 1. Correlation of field seismic data (80-cubic-inch watergun) with synthetic seismogram at DSDP site 574. This degree of correlation is also typical of sites 573 and 575.

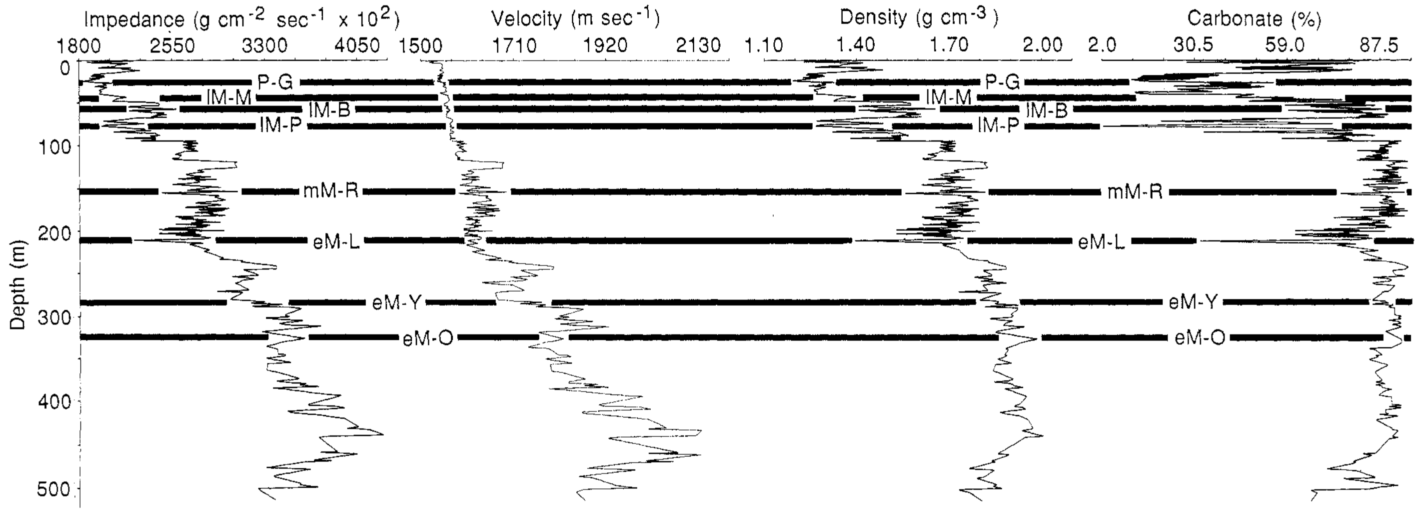

Fig. 2. Summary of downhole physical properties measured on cores from DSDP site 574. Similar analyses were done at sites 573 and 575. Noncarbonate component of cores is almost entirely biogenic silica.

oldest regionally traceable reflectors are associated with only minor density and carbonate changes, but they do show significant velocity contrasts. Core descriptions at these levels reveal the highest occurrence of chalk at eM-Y and numerous thin indurated layers associated with eM-O. These two reflectors thus appear to be related to diagenetic change. Numerous other velocity changes, chalk layers, and associated reflectors occur in this part of the section, but these reflectors do not seem to be regionally traceable. To explain this phenomenon we call upon the concept of diagenetic potential introduced by Schlanger and Douglas (*13*) and speculate that the original depositional conditions that predisposed the sediment at eM-Y and eM-O to indurate were regional in extent whereas the conditions responsible for the other velocity contrasts were local.

Since the major, regionally traceable reflectors represent time surfaces associated with basinwide carbonate dissolution or diagenetic events, we can look at the paleoceanographic significance of these events. We begin by identifying (from Leg 85 results and previous studies) significant changes in oceanographic conditions that correlate with the ages established for the seismic events. These are general correlations; the detailed biostratigraphic analyses necessary to establish precise relations are beyond the scope of this study.

A summary of the oceanographic events associated with each of the regionally traceable reflectors is presented in Table 2. The two oldest reflectors (eM-Y and eM-O) are grouped together because of the limited seismic and biostratigraphic resolution at these depths in the section. Each of the reflectors is associated with climatic and oceanographic events (some related to tectonic events). These events reorganized surface and bottom waters and produced equatorial Pacific-wide carbonate events during the deposition of the younger sediments and predisposed the older sediments for diagenetic change. The carbonate or diagenetic events create the acoustic impedance contrasts that are directly responsible for the reflectors. The most extreme carbonate events appear to be associated with changes in North Atlantic Deep Water (NADW) circulation (P-G, lM-P, and eM-L). This relation is consistent with the concept of basin-basin fractionation (*14*), whereby expansions or reorganizations of NADW inhibit the upwelling of silica-rich Antarctic Bottom Water (AABW) in the Atlantic and intensify AABW delivery to the Pacific, fractionating silica and carbonate between the two oceans. Intensified, highly corrosive AABW in the Pacific results in increased carbonate dissolution and regionally traceable seismic events. Also temporally associated with each reflector is the occurrence of a globally recognized hiatus (*15*). This is not surprising in light of the carbonate dissolution events that give rise to the reflectors; in many less productive environments where sediment accumulates more slowly than in the equatorial Pacific, these dissolution events would certainly lead to the formation of a hiatus.

A further correlation is the association [within the limits of our resolution and that of the data of Vail *et al.* (*1*)] of each of the regionally traceable Neogene deep-sea reflectors (with the exception of eM-Y) with a sea-level event on the relative sea-level (coastal onlap) curve of Vail *et al.* (*1*). This association does little to support or refute the validity of the assumption of global sea-level change as the mechanism responsible for continental margin unconformities. However, it provides evidence (from a region far removed from the dynamic processes responsible for these Neogene unconformities) of global reorganizations of deep-sea circulation patterns coincident with the formation of unconformities on continental margins. Also apparent are the temporal

Table 1. Biostratigraphic zones for regional equatorial Pacific reflectors. Biostratigraphy is based on (*10*). See (*9*) for reflector abbreviations.

Reflector	Planktonic foram	Coccoliths	Radiolaria	Diatoms
P-G	N19	CN12	*Spongaster pentas*	*Nitzschia jouseae*
lM-M	N18	CN9	*Stichocorys peregrina*	*Thalassiosira convexa*
lM-B	N17	CN8	*Didymocyrtis penultima*	*Nitzschia miocenica, Nitzschia porteri*
lM-P	N16?	CN7	*Diartus petterssoni*	*Actinocyclus moronensis*
mM-R	N10/N11	CN4/CN5	*Dorcadospyris alata*	*Coscinodiscus lewisianus*
eM-L		CN3	*Calocycletta costata*	*Denticulopsis nicobarica*
eM-Y	N5	CN2/CN1	*Stichocorys delmontenis*	*Rossiella paleacea*
eM-O	N4	CN1	*Lychnocanoma elongata, Cyrtocapsella tetrapera*	*Rossiella paleacea, Rocella gelida*

links between tectonic and climatic events that may be directly responsible for unconformity formation or may be the cause, or effect, of sea-level fluctuations. Because the detailed stratigraphic data on which the curve of Vail *et al.* (*1*) is based are not yet published, the precise determination of the stratigraphic position of the equatorial Pacific reflectors on the curve of Vail *et al.* (*1*) is not possible. According to the biostratigraphic zonations and curve of Vail *et al.* (*1*), the Neogene deep-sea events recorded by the Pacific reflectors occur at times of high stands of sea level preceding sea-level falls. This timing would be consistent with the mechanism proposed (*16*) to explain Pleistocene equatorial dissolution cycles, in which the flooded shelves during high stands of sea level become a sink for carbonate, depleting the deep sea of carbonate and resulting in particularly corrosive bottom waters.

Equatorial deep-sea sedimentary sections contain a multivariate record of climatic and oceanographic changes. Carefully selected deep-sea drilling sites, connected through a web of high-resolution seismic reflection profiles, can yield a detailed paleoceanographic picture of those times that are consistently missing from the continental margin record and may provide the key to unraveling the mechanisms responsible for globally synchronous events.

Table 2. Summary of correlative events associated with central equatorial Pacific-wide seismic reflectors. See (*9*) for reflector abbreviations.

Reflector	Age (Ma) (*17*)	Associated hiatus (*18*)	Correlative paleoceanographic events	References
P-G	3.0–3.5	NH8	General climatic degradation Northern hemisphere glaciation Reorganization of NADW and North Atlantic seismic event Closing of Isthmus of Panama Vail event	(*1, 19, 20*)
lM-M	5.2–6.2	NH7	General cooling Final isolation of Mediterranean, formation of evaporites Increased South Atlantic glaciation Vail event	(*1, 21–23*)
lM-B	6.4–7.2	NH6	General climatic degradation Shoaling of the calcite compensation depth Increased provincialism in all microfossil assemblages Vail event	(*1, 21, 22, 24*)
lM-P	9.1–10.1	NH4	Major cooling Increase in provincialism in all species Change in style of carbonate deposition in Pacific from high values with low-amplitude fluctuations to large-amplitude oscillations Increase in silica deposition in Pacific Major reorganization of western North Atlantic bottom-water circulation and North Atlantic seismic event Vail event	(*1, 22–24*)
mM-R	13.6–14.2	NH3	High-latitude cooling Faunal changes Ice buildup in Antarctica Intensification of AABW Vail event	(*1, 23, 25, 26*)
eM-L	16.3–17.2	NH1b	Cessation of Miocene warming Closing of Tethys Norwegian Sea overflow into North Atlantic Intensified Pacific upwelling Monterey carbon excursion Vail event	(*1, 26, 27–29*)
eM-Y eM-O	20.6–22.8	NH1a PH	Opening of Drake Passage Establishment of circum-Antarctic current and steep north-south thermal gradients Faunal changes Vail event	(*1, 29–31*)

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