Deep-Sea Carbonates: Dissolution and Mass Wasting on Ontong-Java Plateau

Abstract. *Seismic reflection profiles and the structure of sediments in box cores from Ontong-Java Plateau indicate large-scale land sliding and sediment flow processes, respectively. The topographic morphology of sliding and slumping is depth-dependent, suggesting control by dissolution processes.*

The distribution and composition of deep-sea carbonates is largely controlled by dissolution processes (*1*), a circumstance which has given rise to the concepts of compensation depth and lysocline (*2*). Fluctuations in these dissolution levels and the associated depth gradients of dissolution reflect changes in the depositional environment of deep-sea carbonates through geologic time. In addition to dissolution, processes of redeposition and erosion exert considerable influence on the sedimentation of deep-sea carbonates (*3, 4*).

Here we present evidence that abyssal dissolution also controls the physical properties of deep-sea carbonates, specifically their strength and therefore their style of deformation during redeposition by subaqueous slumping and flow. We show that such gravitational transport ("mass wasting") is important on Ontong-Java Plateau, a relatively undisturbed area of deep-sea carbonate deposition, and we suggest that similar processes may be widespread with significant implications for carbonate stratigraphy and carbonate chemistry of the deep ocean.

The Ontong-Java Plateau, also referred to as the Solomon Rise and the Kapingamarangi Rise, is a broad, elevated area in the western equatorial Pacific, north and east of the Solomon Islands (Fig. 1). In its central position the plateau rises above a depth of 2 km and carries well over 1 km of highly stratified calcareous sediments (*5*). The origin of the plateau is unknown. Deep-sea drilling (*6*) revealed basalt below a sequence consisting of Lower Cretaceous to Upper Eocene siliceous limestones and Upper Eocene to Quaternary nannofossil-foram chalk and ooze. The chalk and ooze contain calcareous fossils in an excellent state of preservation, indicating that the upper plateau has stood above the lysocline for the last 30 million years (*6*).

We surveyed the equatorial part of the plateau, using two 40-cubic-inch air guns (Fig. 1) (*7*). Twenty large-volume box cores were taken (*8*); sediment shear strengths were measured with a motorized vane shear device; and $CaCO_3$ contents were determined in samples from the top, middle, and bottom of the cores, which were approximately 40 cm deep. Sedimentary structures in the cores were studied and photographed. Sound velocities in the sediment were determined from wide-angle reflection data obtained with expendable sonobuoys (*9*).

Although our seismic reflection profiles show the ideal "layer cake" stratigraphy over much of the upper plateau, there are striking exceptions (Fig. 1, A to C). The profile in Fig. 1A shows the top 50 m of sediment missing along a transect about 200 km long. A large, relatively thin sheet of sediment apparently has been removed from a shallow region close to where the slope steepens in a northeasterly direction. The event or series of events leading to the development of this hiatus appears to be geologically recent. An increase in tectonic activity or an increase of bottom water erosion during the last few million years might be en-

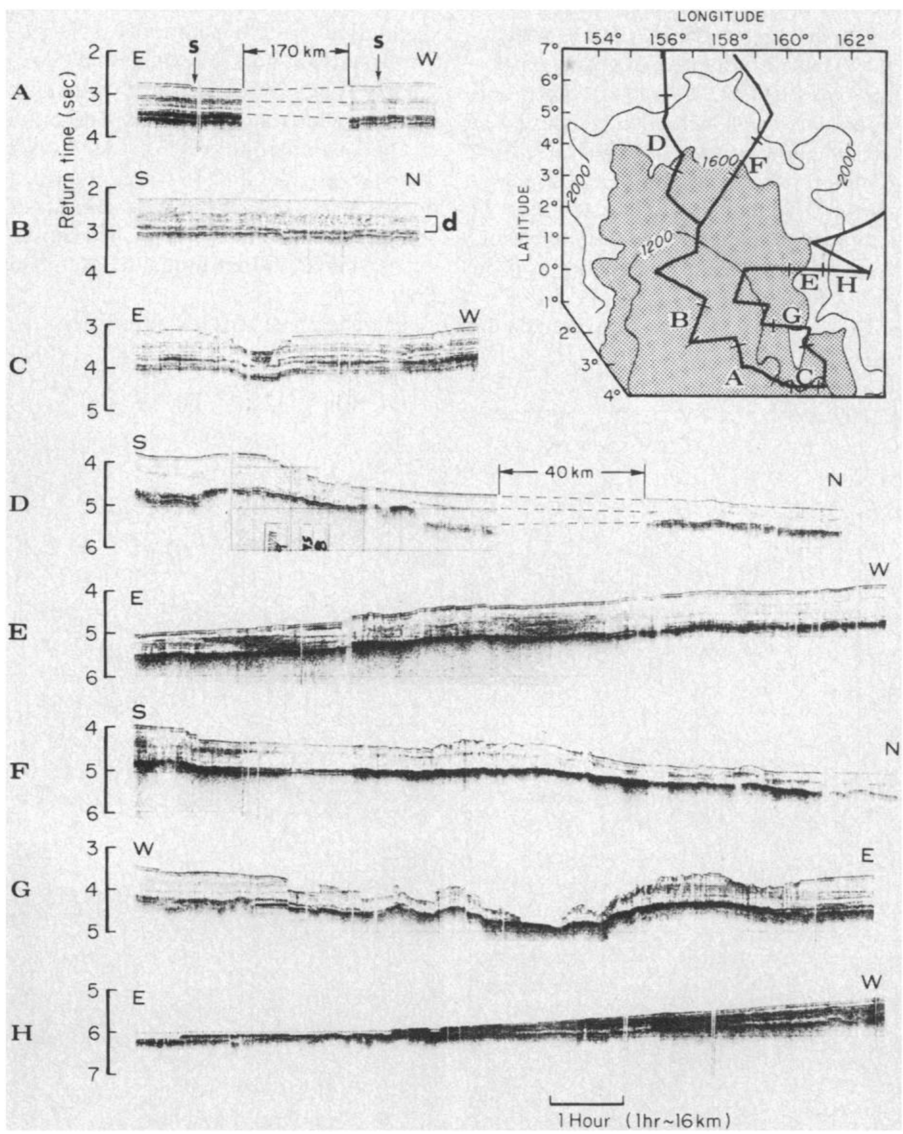

Fig. 1. Acoustic profiles from Ontong-Java Plateau, showing differences in the style of deformation of strata, as a function of depth. Suggested interpretations are as follows. (A and B) Shallow plateau. Note sheet erosion (A) between steps (*s–s*) and internal disturbance in midsection, marked *d* (Neptunian dikes?). (C) Cross section through a sediment slide originating from graben tectonics. Note steep bounding cliffs. (D) Rotational slumps apparently generated by withdrawal of support at the lysocline. (E and F) Smoothing of record by mass flow and pileup (?). (G) Sediment slides on chert basement, due to steep slopes and downhill withdrawal of support by dissolution. Note steepness of remnant stacks, showing high stability of sediment. (H) Smoothing of topography by ooze flow.

visaged. Increased erosion downslope would remove support, causing upslope sediments to slump.

The profile in Fig. 1B, at the shallowest part of the upper plateau, shows deformation resembling large and closely spaced tension cracks in the lower half of the sediment stack. This deformation apparently is not shared by the upper half of the stack. The profile in Fig. 1C again demonstrates the loss of uppermost sediment, apparently by sliding into the valley to the north. The location of the slide is associated with a slight basement depression. The borders of the slide are steplike, the steps being formed of individual slump blocks. Sides are steep, indicating firm, cohesive sediment.

On the upper flanks of the plateau, there is much evidence for sliding of sediment masses (Fig. 1, D to F). Steep outcrop faces occur here also, primarily on the shallower parts. At increasing depths, both smoothing of the topography and hummocky accumulations of sediment are common. At the same time, there is a considerable thinning of sediments downslope.

Comparison of a section across the aforementioned valley with a profile on the lower flank (Fig. 1, G and H) emphasizes the great differences in the physical character of sediments as a function of depth. Sliding and slumping of carbonate into the valley imparts a rugged topography to the area of mass waste (Fig. 1G). Sediments are stiff and support steep cliffs, even in the upper part of the stack, where cementation is still far from complete (*10*). In contrast, sublysoclinal sediments are seen to smooth the underlying rougher topography and give the impression of flowage (Fig. 1H). Such flowage also could form the observed acoustically transparent sediments, because of homogenization of the material.

The depth distribution of sediment thicknesses yields additional evidence for dissolution-controlled mass flow processes (Fig. 2A). Sediment thickness changes with water depth, as a function of chemical dissolution. For each 200-m increase in depth of water between depths of 2.5 and 4.5 km the thickness of sediment decreases by 100 m. This gradient is similar to that found on Manihiki Plateau (*4*).

There are marked deviations from the depth gradient of sediment thickness described. Above the lysocline, slumping provides for points far to the left of the "normal." Also, on the uppermost plateau, thicknesses appear to decrease. Several possible causes can be envisaged, including winnowing and diagenesis. These will not be elaborated on here. Another deviation from the overall depth gradient of sediment thickness is the failure of the profiles to continue thinning as the carbonate compensation depth is approached. The effect is greater than that expected from the fact that much of the soluble part of the sediment has been removed. Also, at 4500 m, our cores still show nearly 70 percent carbonate. We suggest that piling up of flowing sediment helps produce this phenomenon. This interpretation is supported by structures of sediment raised in box cores (Fig. 2, B to D).

In the shallow parts of the plateau, the highly bioturbated ooze is characterized by a coarse grid pattern, featuring horizontal and vertical burrows (Fig. 2B). Burrows distinctly cutting across this grid are rare. The sediment is stiff and supports a vertical face 40 cm high for at least 10 hours without appreciable deformation, although it does settle downward during this time by about 10 percent. Shear strength measurements in box cores obtained from depths shallower than 2500 m yield a mean value of 136 g cm^{-2}, and a standard deviation of 50 g cm^{-2}, based on 18 measurements.

In the vicinity of the lysocline, the grid pattern is absent (Fig. 2C). Two cores were taken which showed tilt of near-vertical burrows. There is some indication of structural elements trending at right angles to the near-vertical tilted features. The dark zone near the bottom of the core, tentatively interpreted as a redox-controlled Fe-Mn precipitation level, is horizontal, indicating that the corer did not penetrate obliquely. Vertical burrows are not seen above this level. The sediment is still rather stiff, but less so than ooze in shallow cores. Shear strength in cores obtained from lysoclinal depths (3300 to 3800 m) was measured at 71 ± 14 g cm^{-2} (15 measurements).

Cores from the lower flank of the plateau recovered soft sediment showing much evidence for deformation (Fig. 2D). No grid pattern (as in shallow cores) is seen, neither is a strain pattern apparent. Vertical burrows are absent, except in a zone of light-colored, frazzled lumps of ooze, which suggest a broken-up layer in the bottom part of the core. Inclined, smeared-out burrows also are seen in this material. The sediment does not

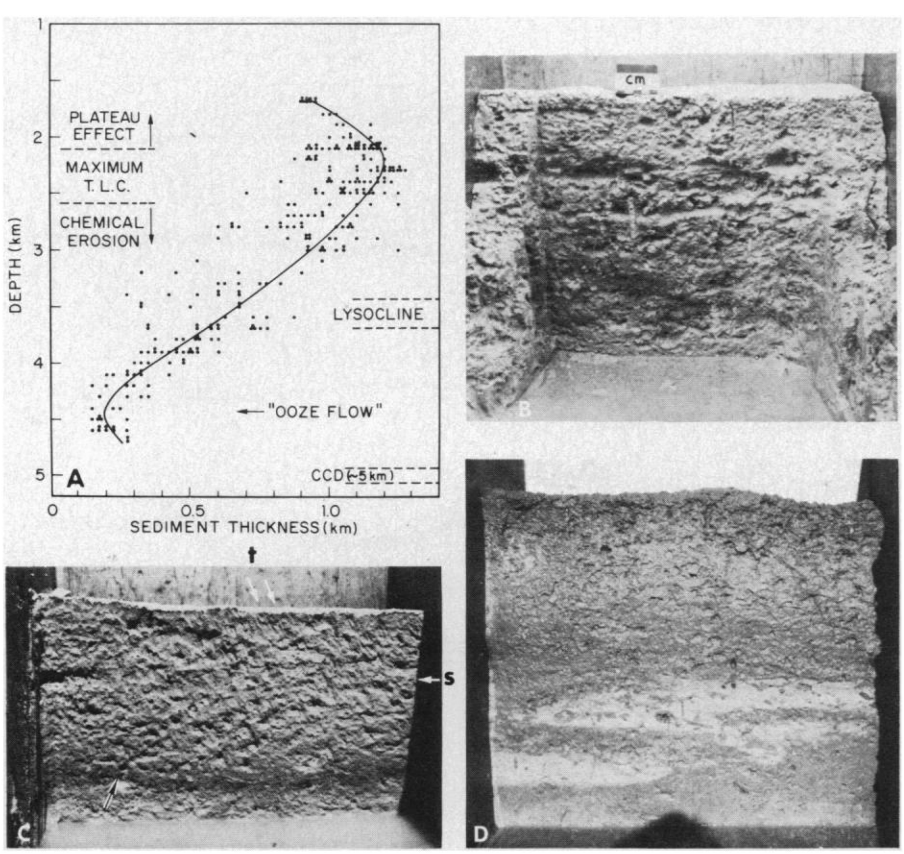

Fig. 2. Depth control of sediment properties. (A) Thickness of sediment plotted against depth [see (*9*)]. Abbreviations: TLC, transparent layer of carbonate; CCD, carbonate compensation depth. (B) Box core 83, 2373 m, 83 percent $CaCO_3$. Note grid pattern. (C) Box core 135, 3509 m, 82 percent $CaCO_3$ (upper 5 cm removed). Note strain pattern. Arrows marked *t* show where tilt is most obvious; arrows marked *s* show position of strain feature normal to tilt. (D) Box core 139, 4118 m, 74 percent $CaCO_3$. Note flowage, absence of vertical burrows.

maintain a vertical face for very long and tends to flow out of the box within a few hours. Shear strengths average 53 ± 12 g cm^{-2} (12 measurements).

We interpret the structural features of the box cores as indicating undisturbed sediment in the shallow parts, creeplike deformation in the lysocline zone, and appreciable flow on the lower flanks of the plateau. This flow is thought to be general, but may be relatively fast in shallow, wide, flat-bottomed channels. We cored in one such channel at a depth of 4410 m and found sandy ooze and unexpectedly well-preserved foraminifera. The fines had been removed, perhaps during repeated washing of the sediment while it flowed over irregularities in the "stream bed."

The shear strengths of sediments accumulating above the lysocline on the Ontong-Java Plateau are greater than most other reported values for near-surface marine sediments (*11*). This is possibly due to incipient cementation by mobilized (metastable?) carbonate, although we have no direct evidence for this process at the present time. Lysoclinal and sublysoclinal sediments in the vicinity of the plateau exhibit shear strengths that are more typical of most marine sediments. Application of infinite-slope stability analysis (*12*) to the topography and strength of the plateau sediments indicates that the sediments should be stable and not subject to slumping. Therefore, the large-scale mass movement of these pelagic carbonates cannot be readily explained, and may result from complex interactions involving dissolution, thixotropic properties of the sediments, and liquefaction triggered by earthquakes in the nearby Solomon Trench.

In summary, we observed mass movement of deep-sea carbonates on two scales: (i) large-scale slumping and sliding and (ii) flow (or creep) of near-surface sediment. We propose that both phenomena owe much to dissolution processes, the first showing a depth dependence of topographic morphology, the second showing a depth dependence of preserved burrow patterns and of shear strength.

If our interpretations are correct, there are critical implications for the stratigraphy of deep-sea carbonates and for carbonate geochemistry. Concerning the explanation of missing sections in Deep-Sea Drilling Project cores (*13*), the removal of large sheets of ooze as a consequence of earthquakes or dissolution of downslope support, or both, has to be considered as a mechanism producing hiatuses, in addition to the direct influence of bottom currents on erosion of carbonates from the sea floor.

Our results raise questions that need to be resolved in two major areas: (i) To what extent is such mass wasting episodic over large areas of the sea floor, in response to bottom water action, and to what extent is it regional, resulting from tectonic events? and (ii) What are the conditions (slope, type of ooze, and depth range) under which carbonate transfer by mass movement occurs, and what are the applicable rates of such transfer to abyssal depths?

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References and Notes

1. J. Murray and A. F. Renard, *Deep-Sea Deposits Based on the Specimens Collected During the Voyage of H.M.S. "Challenger" in the Years 1872–1876, Report Voyage "Challenger"* (Longmans, London, 1891; Johnson Reprint, New York, 1965).
2. M. N. Bramlette, in *Oceanography*, M. Sears, Ed. (AAAS, Washington, D.C., 1961), p. 345; W. H. Berger, *Mar. Geol.* **8**, 111 (1970).
3. Tj. H. van Andel and P. D. Komar, *Geol. Soc. Am. Bull.* **80**, 1163 (1969); D. A. Johnson and T. C. Johnson, *Deep-Sea Res.* **17**, 157 (19 D. A. Johnson, *Geol. Soc. Am. Bull.* **83**, 3121 (1972); G. de V. Klein, *Initial Rep. Deep Sea Drill. Proj.* **30**, 423 (1975).
4. E. L. Winterer, P. F. Lonsdale, J. L. Matthews, B. R. Rosendahl, *Deep-Sea Res.* **21**, 793 (1974).
5. L. W. Kroenke, R. M. Moberly, E. L. Winterer, G. R. Heath, *Initial Rep. Deep Sea Drill. Proj.* **7**, 1161 (1971); L. W. Kroenke, *Hawaii Inst. Geophys. Tech. Rep. HIG-72-5* (1972).
6. J. E. Andrews *et al.*, *Initial Rep. Deep Sea Drill. Proj.* **30**, 753 (1975).
7. Scripps Institution of Oceanography, Eurydice Expedition, Leg 9, R.V. *Washington*, Guam (3 April 1975) to Majuro (5 May 1975).
8. The apparatus was described by R. R. Hessler and P. A. Jumars [*Deep-Sea Res.* **21**, 185 (1974)]. We also took gravity and piston cores; these will be reported on elsewhere.
9. See X. LePichon, J. Ewing, R. E. Houtz, *J. Geophys. Res.* **73**, 2597 (1968). Our empirical equation relating sound velocity to two-way travel time is $V_t = 1.54 + 1.6t - 0.2t^3$, where V_t is the velocity corresponding to the depth in the sediment for which the two-way travel time is t. This equation yields a slightly lower velocity gradient than that presented by G. L. Maynard, "Seismic wide angle reflection and refraction investigation of the sediments of the Ontong Java Plateau" [thesis, University of Hawaii (1973)].
10. S. O. Schlanger and R. G. Douglas, *Spec. Publ. Int. Assoc. Sedimentol.* **1**, 117 (1974).
11. G. H. Keller, *in Proceedings of a Conference on Civil Engineering in the Oceans* (American Society of Civil Engineers, New York, 1968), p. 391; D. G. Anderson, *Nav. Civ. Eng. Lab. Tech. Note N-1177* (1971).
12. See D. G. Moore, *J. Sediment. Petrol.* **31**, 343 (1961).
13. T. C. Moore, Tj. H. van Andel, C. Sancetta, N. Pisias, in *Marine Plankton and Sediments*, W. R. Riedel and T. Saito, Eds. (Micropaleontology Press, American Museum of Natural History, New York, in press).
14. Supported by the Office of Naval Research, contract USN-N-00014-69-A-0200-6049. T.C.J. was supported at Scripps Institution of Oceanography by a postdoctoral fellowship from the National Science Foundation, Oceanography Section, grant DES 75-04335, during most of the period of this research. We thank our colleagues at the Hawaiian Institute of Geophysics, especially J. E. Andrews, G. H. Sutton, and G. P. Woollard, for providing access to unpublished data. G. de Vries Klein made helpful suggestions for improvement of the manuscript.

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Fossil Peccary from the Pliocene of South Africa

Abstract. ?Pecarichoerus africanus, *new species, from Langebaanweg, Cape Province, is the first fossil peccary to be described from Africa and represents the youngest record of the peccary family in the Old World.*

The superfamily Suoidea is comprised of two families, the peccaries (Tayassuidae) and the true pigs (Suidae). Peccaries are now confined to the New World (*1*), where they are also not uncommon as fossils, while the pigs are, and apparently always have been, an Old World group. In 1927 peccaries of Tertiary age were identified in Europe (*2*), which broke down the traditional view that they had always been restricted to the Americas. A few years later a fossil peccary was also recorded from Asia (*3*). Several Oligocene and Miocene peccaries are now known in Europe (*4*), but there is still only one Asian species, which is Miocene in age. Although true pigs feature in both the living and extinct faunas of Africa, the fossil peccary described here is the first to be identified on this continent. It also represents the most recent record of its family in the Old World.

The new peccary is from the Pliocene Varswater Formation exposed in an open-cast phosphate mine, E Quarry, at Langebaanweg, 105 km north-northwest of Cape Town (*5*, *6*). Although this formation has not been dated in absolute terms, comparisons between its fauna and radiometrically dated ones in East Africa suggest an age of between 4 million and 5 million years. Even the latest of the Eurasian peccaries predates the Langebaanweg species by several million years. The Varswater Formation has yielded the largest and most diverse assemblage of Pliocene fossils known anywhere in Africa (*7*), and included among the mammals are several in addition to the peccary which belong to groups otherwise known only, or mainly, from Eur-