7. Heath, G. R. & Culberson, C. *Bull. geol. Soc. Am.* **81**, 3157-3160 (1970).
8. Broecker, W. S. & Broecker, S. *Soc. Econ. Paleont. Miner., Spec. Publ.* **20**, 44-57 (1974).
9. Berger, W. H., Adelseck, C. G. Jr & Mayer, L. A. *J. geophys. Res.* **81**, 2617-2727 (1976).
10. Heath, G. R. *Bull. geol. Soc. Am.* **80**, 689-694 (1969).
11. Berger, W. H. *Bull. geol. Soc. Am.* **84**, 1941-1954 (1973).
12. Sclater, J. G., Anderson, R. N. & Bell, M. L. *J. geophys. Res.* **76**, 7888-7915 (1971).
13. van Andel, Tj. H. & Bukry, D. *Bull. geol. Soc. Am.* **84**, 2361-2370 (1973).
14. van Andel, Tj. H. & Moore, T. C. Jr *Geology* **2**, 87-92 (1974).
15. van Andel, Tj. H., Heath, G. R. & Moore, T. C. Jr *Mem. geol. Soc. Am.* **143** (1975).
16. Tracey, J. I. *et al. Init. Rep. DSDP* **8** (1971).
17. Yeats, R. S. *et al. Init. Rep. DSDP* **34** (1976).
18. Leinen, M. *et al. Init. Rep. DSDP* **92** (in the press).
19. Rea, D. K. & Leinen, M. *Init. Rep. DSDP* **92** (in the press).
20. Bukry, D. *Init. Rep. DSDP* **34**, 715-735 (1976).
21. van Andel, Tj. H., Thiede, J., Sclater, J. G. & Hay, W. W. *J. Geol.* **85**, 651-698 (1977).
22. Heath, G. R., Moore, T. C. Jr & van Andel, Tj. H. in *The Fate of Fossil Fuel CO_2 in the Oceans* (eds Andersen, N. R. & Malahoff, A.) 627-639 (Plenum, New York, 1977).
23. Hsu, K. J., McKenzie, J. A., Oberhansli, H. & Wright, R. C. *Init. Rep. DSDP* **73**, 771-785 (1984).
24. Savin, S. M. *A. Rev. Earth planet Sci.* **5**, 319-355 (1977).
25. Kennett, J. P. *J. geophys. Res.* **82**, 3843-3860 (1977).
26. Vail, P. R., Mitchum, R. M. Jr & Thompson, S. III *Mem. Am. Ass. petrol. Geol.* **26**, 83-97 (1977).
27. Leinen, M. *Bull. geol. Soc. Am. Part II* **90**, 1310-1376 (1979).
28. Woodruff, F., Savin, S. M. & Douglas, R. G. *Science* **212**, 665-668 (1981).
29. Kennett, J. P. & Srinivasan, M. S. *Neogene Planktonic Foraminifera, A Phylogenetic Atlas* (Hutchinson Ross, Stroudsburg, 1983).
30. Broecker, W. S. & Peng, T.-H. *Tracers in the Sea* (Lamont-Doherty Geological Observatory, Palisades, 1982).

Downslope transport of metalliferous sediments along the East Pacific Rise during the late Miocene

Stephen Knüttel*, David K. Rea† & Sherwood W. Wise Jr*

* Department of Geology, Florida State University, Tallahassee, Florida 32306, USA
† Department of Atmospheric and Oceanic Science, University of Michigan, Ann Arbor, Michigan 48109, USA

The distribution of metalliferous sediments next to active spreading centres has scientific and economic interest[1]. Although metal-rich waters emanating from active hydrothermal vents have been traced in intermediate level water masses far beyond the ridge crest[2], the greatest concentrations of metal oxides in sediments occur near the vents[3]. There, however, it is conceivable that the oxides may be redistributed and possibly further concentrated by redeposition, resulting in misconceptions of the age and relative timing of hydrothermal pulses. Here, we document microfossil evidence of stratigraphical inversion and redeposition of Upper Miocene (Messinian) sediments cored at Deep Sea Drilling Project (DSDP) Site 599 on the East Pacific Rise (EPR). This suggests that where reworking can be confirmed, care should be taken not to correlate directly the occurrences of the metalliferous sediments with apparent coeval pulses of hydrothermal activity or enhanced sea-floor spreading rates.

Hole 599 (19°27.09′ S, 119°52.88′ W; water depth = 3,654 m), located ~600 km west of the present ridge crest, was drilled in a small basin surrounded by a region of low relief with abyssal hills ranging from 200 to 300 m in height (Fig. 1). This site yielded some 41 m of mostly Upper Miocene clay-bearing to clayey calcareous oozes with a basement age of 8.1-8.6 Myr (ref. 5). The lower 31 m of the section is strikingly layered, consisting of alternating light (mostly yellowish brown to dark yellowish brown) and dark (mostly dark reddish brown) coloured layers tens of centimetres thick (Figs 2, 3). The colour variations are the result of changes in the relative amounts of calcium carbonate (70-80% in light coloured sediments, 55-70% in dark coloured sediments[5]) and a noncarbonate fraction which is primarily clays and ferruginous grains. The clays are mixtures of poorly crystalline smectites and amorphous oxides. The ferruginous grains, which range in size from 10 to 100 μm, are a metalliferous hydrothermal component which has been described by Leg 34 scientists as red-brown to yellow-brown, semi-opaque oxides (RSOs)[6].

The strongly layered portion of the section is dated between

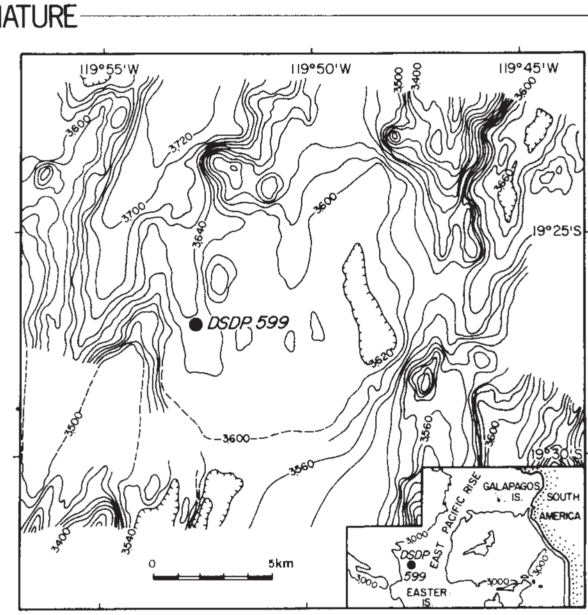

Fig. 1 Bathymetry (from seabeam swath-mapping[4]) and location of Deep Sea Drilling Site 599 on the west flank of the East Pacific Rise. This site, along with the other DSDP Leg 92 sites, was the first on the East Pacific Rise to be drilled using the hydraulic piston corer, which minimizes sediment disturbance during the coring process.

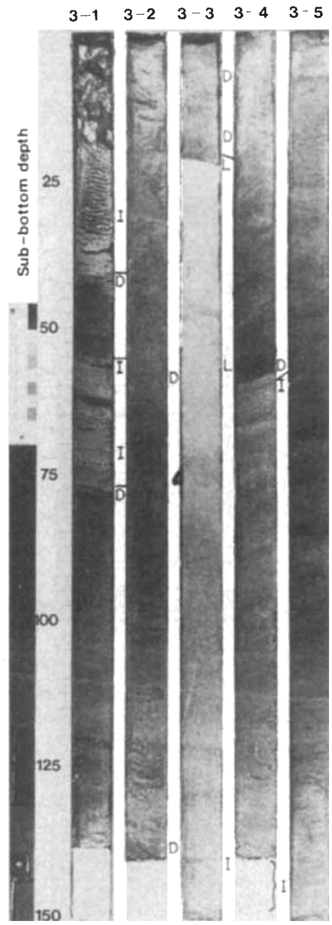

Fig. 2 Sections 1-5 of DSDP Core 599-3 showing alternations of light (L), dark (D), and intermediate (I) coloured lithologies within the Messinian clayey nannofossil ooze sequence (see key in Fig. 3 for detailed colour descriptions). The darker lithologies contain less carbonate and more hydrothermal metalliferous components than do the lighter lithologies. Note the sharp contact (dark over light) at 21 cm in section 599-3-3.

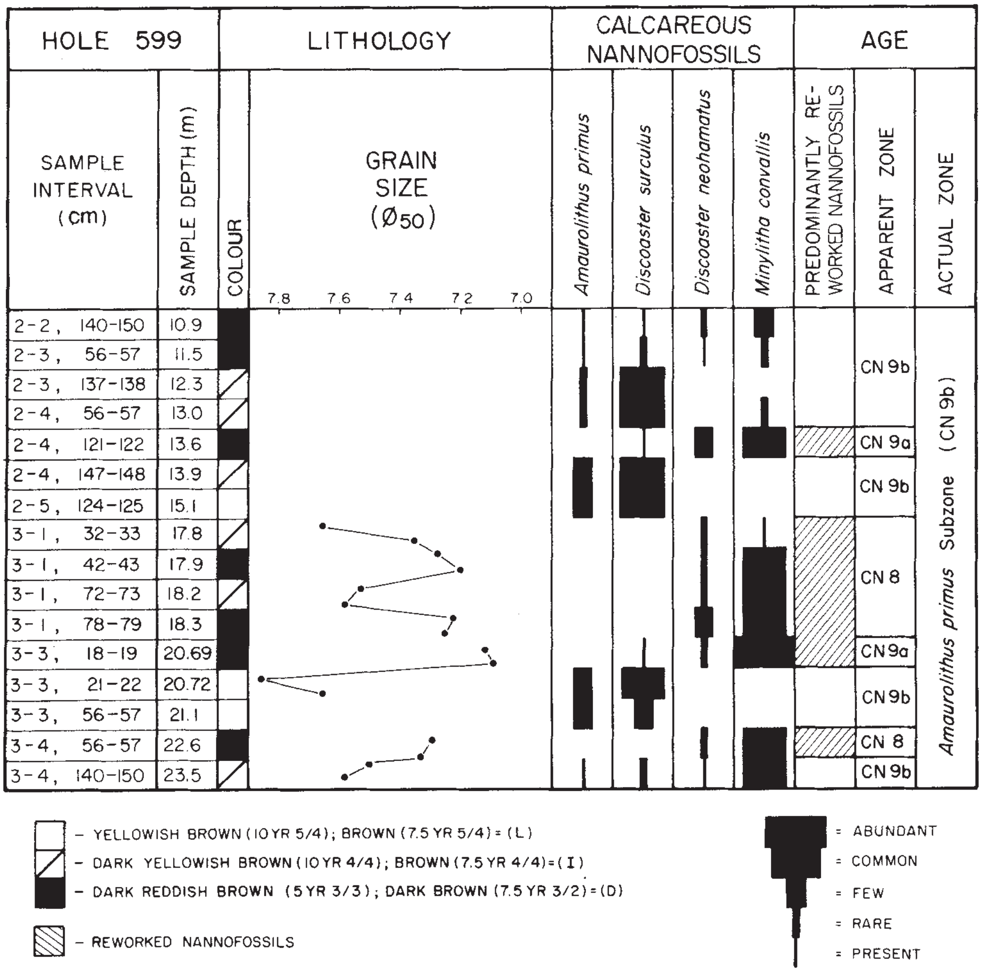

Fig. 3 Correlation of colour, grain size and calcareous nannofossil assemblages in a portion of the Messinian section at Site 599. The darker and coarser grained, redeposited metalliferous sediments contain reworked microfossil assemblages which indicate apparent ages up to 2.5-Myr older than the actual age of the sequence.

5.0 and 8.6 Myr (ref. 7) using the calcareous nannofossil zonation of Okada and Bukry[8] as calibrated against time by Haq[9]. The bulk of that section (12.3-30.7 m), however, falls within the *Amaurolithus primus* Subzone (CN9b) of the *Discoaster quinqueramus* Zone which, according to Haq[9], spans the Messinian Stage (6.7-5.4 Myr). That age determination is not immediately apparent, however, because this part of the section contains anomalous stratigraphical inversions of coccolith assemblages with older assemblages (represented in Fig. 3 by zones of lower numbers or letters) interbedded with the younger sediments of Subzone CN9b. The older assemblage of the 'apparent' Zone CN8 ('apparent age' = 9.2-8.1 Myr) is characterized by many *Minylitha convallis* and few *Discoaster neohamatus*, whereas the younger assemblage of Subzone CN9b is characterized by many *Discoaster surculus* and few *Amaurolithus primus*. The older assemblages are considered to be reworked and/or redeposited. There is little detectable mixing between these assemblages.

Detailed studies were carried out on Core 599-3 where the colour banding is pronounced (Fig. 2). As indicated in Fig. 3, there is a strong correlation between the occurrence of the older coccolith assemblages and the dark or intermediate-coloured metalliferous sediments[7]. There is also a strong correspondence between colour and grain size of the sediment, with the darker sediment containing coarser material[10] (Fig. 3). These correlations are particularly evident at the sharp contact in Section 599-3-3 at 21 cm. We conclude that this contact marks the base of a turbidite which transported or concentrated sediments with an anomolously high content of metalliferous components into the basin. As indicated for other parts of the section depicted in Fig. 3, this process of redeposition could well account for much of the hydrothermal material deposited in this portion of the section recovered at Site 599.

The juxtaposed coccolith assemblages correlated above with textural characteristics of the sediments, which include examples of graded bedding, provide strong evidence for downslope processes active on the EPR during the late Miocene. The timing of these mass movements correlates closely with the Messinian sea-level drop and intensified current activity which have been widely recorded in many ocean basins[11-13]. Displaced shallow-water fossils of a similar origin are also recorded in many other tropical and sub-tropical Pacific DSDP sites[14-16], therefore the triggering mechanism for the turbidites at Site 599 may be related to erosion by intensified currents. An alternate explanation is tectonic instability associated with possible increased seismic activity along the EPR. This, in turn, might be coupled with accelerations in volcanic discharge and seafloor spreading rates which are thought to have peaked in the Pacific at ~5 Myr (ref. 17). These speculations are further elaborated in more extended discussions to be described elsewhere[7,10]. By either mechanism, however, the concentration and distribution of the metalliferous sediments seem to be appreciably affected by processes of redeposition at this locality. Redistribution of these sediments was probably enhanced by their relatively low specific gravity and by the topographic relief at this site (Fig. 1). Should a similar configuration of strongly banded sediments with sharp basal contacts beneath the dark coloured layers be encountered elsewhere, redeposition might reasonably be suspected. If reworking and/or redeposition is suggested by palaeontological evidence, care should be taken not to correlate directly the increased concentration of metalliferous sediments with episodes of heightened hydrothermal activity or enhanced seafloor spreading rates.

We thank Philip Froelich and Jörn Thiede for their reviews of the manuscript and the NSF for financial support. All samples related to this project were made available through the Deep Sea Drilling Project.

Received 19 February; accepted 26 June 1985.

1. Kennett, J. P. *Marine Geology*, 492-503 (Prentice-Hall, Englewood Cliffs, 1982).
2. Klinkhammer, G. & Hudson, A. *Earth planet. Sci. Lett.* (in the press).
3. Boström, K. *Nature* **227**, 1041 (1970).
4. Lonsdale, P. *Init. Rep. DSDP* Leg **92**, (in the press).
5. Leinen, M. *et al. Init. Rep. DSDP* Leg **92** (in the press).
6. Quilty, P. G. *et al. Init. Rep. DSDP* Leg **34**, 779-794 (1976).
7. Knüttel, S. *Init. Rep. DSDP* Leg **92** (in the press).
8. Okada, H. & Bukry, D. *Mar. Micropaleontol.* **5**, 321-325 (1980).
9. Haq, B. L. in *Benchmark Papers in Geology* (ed. Haq, B. L.) 358-378 (Hutchinson Ross, Stroudsburg, 1984).
10. Rea, D. K. & Janecek, T. R. *Init. Rep. DSDP* Leg **92** (in the press).
11. Adams, C. G., Benson, R. H., Kidd, R. B., Ryan, W. B. F. & Wright, R. C. *Nature* **269**, 383-386 (1977).
12. Ciesielski, P. F. & Wise, S. W. *Mar. Geol.* **25**, 175-207 (1977).
13. Keller, G. & Barron. J. A. *Bull. geol. Soc. Am.* **94**, 590-613 (1983).
14. Cook, H. E., Jenkyns, H. C. & Kelts, K. R. *Init. Rep. DSDP* Leg **33**, 837-847 (1976).
15. Rea, D. K. & Thiede, J. *Init Rep. DSDP* Leg **61**, 549-555 (1981).
16. Thiede, J., Boersma, A., Schmidt, R. R. & Vincent, E. *Init. Rep. DSDP* Leg **62**, 495-512 (1981).
17. Rea, D. K. & Scheidegger, K. F. *J. Volcan. Geotherm. Res.* **5**, 135-148 (1979).

'Strangelove ocean' before the Cambrian explosion

Kenneth J. Hsu*, Hedi Oberhänsli*, J. Y. Gao*, Sun Shu†, Chen Haihong† & Urs Krähenbühl‡

* Geological Institute, Swiss Federal Institute of Technology, Zurich, 8006, Switzerland
† Geological Institute, Academia Sinica, Beijing, China
‡ Institute of Inorganic Chemistry, University of Bern, Bern, 3001, Switzerland

The Palaeozoic and Mesozoic eras were terminated by faunal changes involving mass extinction of the old and explosive evolution of the new fauna, but the fossil record shows only a Cambrian Explosion at the end of the Precambrian. Stanley speculated that the explosion was only possible after the ubiquitous algae community had been largely eliminated[1]; ecological niches were thus liberated for explosive evolution. If the Cambrian Explosion were preceded by a mass mortality (or by a mass extinction), such an event should leave a record in the form of geochemical anomalies. We have undertaken a search for geochemical anomalies at the Precambrian/Cambrian contact. We report here the discovery of a sharp negative carbon-isotope shift in the carbonate of a clay immediately above a marker in the Precambrian/Cambrian boundary, the China C marker, and interpret this signal as evidence of sudden decrease in fertility before the Cambrian explosion of invertebrate evolution. The discovery suggests that the Precambrian/Cambrian boundary might be defined by an event-marker at a palaeontologically correlative horizon.

Investigations of the Cretaceous/Tertiary boundary reveal that the boundary event left a signature in an iridium anomaly and a carbon isotope anomaly[2,3]. The dual Ir-$\delta^{13}C$ anomalies were also found recently in a Permian/Triassic boundary clay[4]. The exact placement of Precambrian/Cambrian boundary has not yet been established. Chinese scientists have suggested three datum levels as candidates: China A marks the first appearance of inarticulate brachiopods and China B defines the base of the *Paragloborilu Siphongonuchites* Zone, characterized by a more diversified shelly fauna. The third, or the China C marker, is slightly above the China B (Fig. 1), and defined by a remarkable lithological change from a phosphate-rich rock to a black shale. This horizon marks the base of a formation containing the first trilobites[5], and has been correlated for thousands of kilometres across South China.

Following the discovery in 1982 of an iridium anomaly in a black shale above the China C marker (C. C. Woo, personal communication) one of us (K.J.H.) took samples across the iridium-rich horizon. Six samples from a 12-m section were obtained at the Type Locality for the Precambrian Sinian Group in the Yangtze Gorge section, ~20 km west of Ichang, Hupeh Province, China. Analysis confirmed the presence of higher

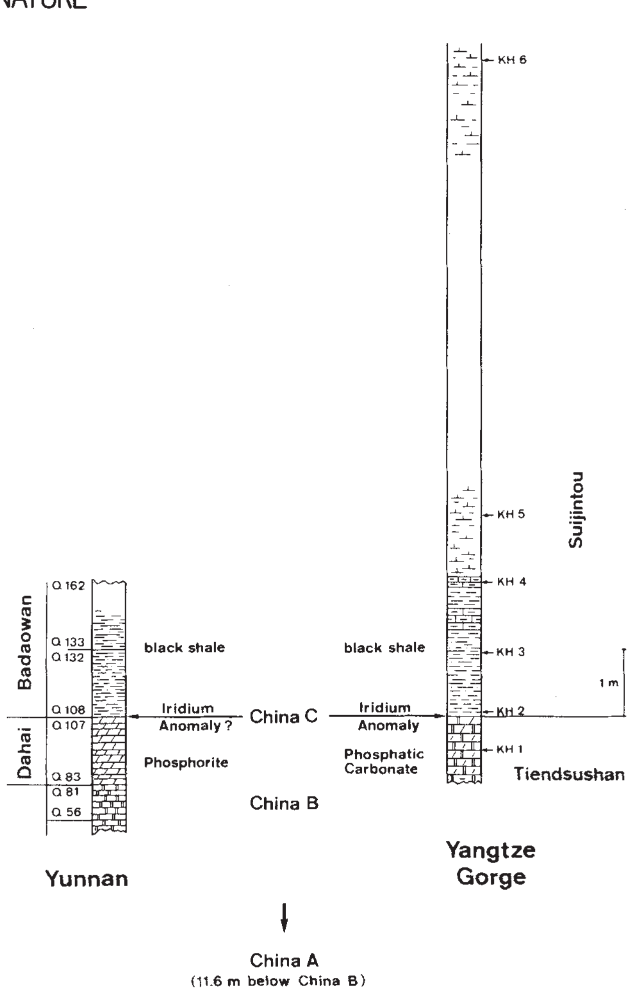

Fig. 1 Stratigraphical columns across a proposed Precambrian/Cambrian contact (China C marker) at two localities in south-west China. Iridium anomaly has been identified in the boundary clay at the Yangtze Gorge locality. The Q and KH numbers are sampling numbers. The Q samples have been obtained at 2-cm intervals apart. KH samples were taken for a reconnaissance study. Not shown are the densely spaced samples from the Yangtze locality. China B marks the base of Dahai.

iridium and osmium contents in a black clay immediately above the China C marker. Also found was a carbon-isotope anomaly at the iridium-enriched horizon (Fig. 2).

The discovery prompted us to resample across the China C marker in 1984 to produce a more systematic investigation. Fifty-three samples were taken from the Yangtze Gorge locality near the marker at intervals spaced 2-cm apart. Some 100 samples were taken from the Kunyang Mine with 2-cm sampling intervals, not only across China C, but also across China A and China B markers. The close sampling was done to define precisely the carbonate-isotope anomaly, and to determine whether the anomaly is a signal or a random variation. The stratigraphy of both localities has been described in detail elsewhere[5,6]. Note that the first trilobite specimens were collected in a calcareous shale within 1 m above the China C marker at the Yangtze locality, but at a horizon some 10 m higher at Kunyang.

The isotope analyses were carried out at ETH Zurich. The phosphatic rocks contain 90% carbonate and the black shale contain between 8 and 26% carbonate, which is mainly dolomite. A thin seam of black shale immediately above the China C marker can, however, be considered a boundary clay layer; the sample at the Kunyang Mine contains 0-4% carbonate, and the one at the Yangtze Gorge locality is practically carbonate-free, thus yielding no isotope results.

The $\delta^{13}C$ values of the dolomite at the two localities are shown by Fig. 3. The background values are slightly more negative at