Carbon-isotope events across the Precambrian/Cambrian boundary on the Siberian Platform

Mordeckai Magaritz*, William T. Holser† & Joseph L. Kirschvink‡

* Isotopes Department, Weizmann Institute, Rehovot 76100, Israel
† Department of Geology, University of Oregon, Eugene, Oregon 97403, USA
‡ Division of Geological and Planetary Sciences, The California Institute of Technology, Pasadena, California 91125, USA

Variations of marine isotopes with time have been observed through the Phanerozoic[1,2], in association with some period boundaries: Pleistocene/Holocene[3], Cretaceous/Tertiary[4], Permo-Triassic[5,6] and Frasnian/Fammenian[7]. Most of these changes are associated with extinction events, reflecting changes in life on Earth. One of the major biological changes in Earth's history occurred near the end of Proterozoic time, with widespread increase of biomineralization and the appearance of shelly fauna[8-10]. We present here an initial survey of carbon isotope ratios in a section on the Siberian Platform that spans the Proterozoic/Palaeozoic boundary. After a high of $\delta^{13}\mathrm{C} = +3.4‰$, 15 m below the boundary, $\delta^{13}\mathrm{C}$ drops sharply in two cycles across the boundary, to $\delta^{13}\mathrm{C} = -2‰$ near the end of the Tommotian Stage. These variations suggest an initial bloom of biomass in late Vendian time corresponding to the dramatic diversification that must have preceeded the widespread appearance of new taxa in the Cambrian fossil record.

The section studied comprises 250 m of carbonate rocks that include the Yudoma Formation of late Vendian age and the Pestrotsvet Formation of Tommotian age along the Aldan River (Dvortsy section, 57.47° N, 129.30° E, 650 km south of Yakutsk) on the Siberian Platform in Yakutia[11-13]. The Vendian/Tommotian boundary, close to the top of the Yudoma Formation, is a candidate for designation as a stratotype of the Precambrian/Cambrian boundary[14]. Arguments have been advanced against this selection[15-17], but our concern here is with the fossil record rather than the formalities of stratigraphy. Consequently in the following discussions we will informally refer to the Vendian/Tommotian boundary as the Precambrian/Cambrian (P€/€) boundary. The Dvortsy sequence is transgressive over a shelf of the Archaean Aldan Shield, and this is part of a worldwide transgression that continues through Tommotian time[18]. The rocks range from very fine (<10 μm) pelletal dolomite to medium-coarse (100–150 μm) xenomorphic dolomites. Part of the topmost Vendian sequence is dolomite replacing earlier oolitic sediments. As one approaches the suggested P€/€ boundary from below, de-dolomitization and staining with iron oxide indicate an unconformity, suggested by Khomentovsky *et al.*[11]. Our Cambrian samples were also dominantly dolomite, although this section is often described as limestone[11].

Our samples were obtained as part of IGCP Project 29, and were collected in a similar fashion to a previous set of Tommotian samples from along the Lena River, studied for magnetostratigraphy by Kirschvink and Rozanov[19]. Palaeomagnetic studies of the new samples are in progress by Kirschvink.

$\mathrm{CO_2}$ for mass spectrometry was generated by the method of Magaritz and Kafri[20]. $\mathrm{CO_2}$ generated by calcite in the de-dolomite was removed, and then the remaining dolomite reacted to provide the measured sample. Although the section has suffered dolomitization, probably in an early diagenetic stage, we know from much younger dolostones that the dolomite preserves the original $\delta^{13}\mathrm{C}$ values[21,22].

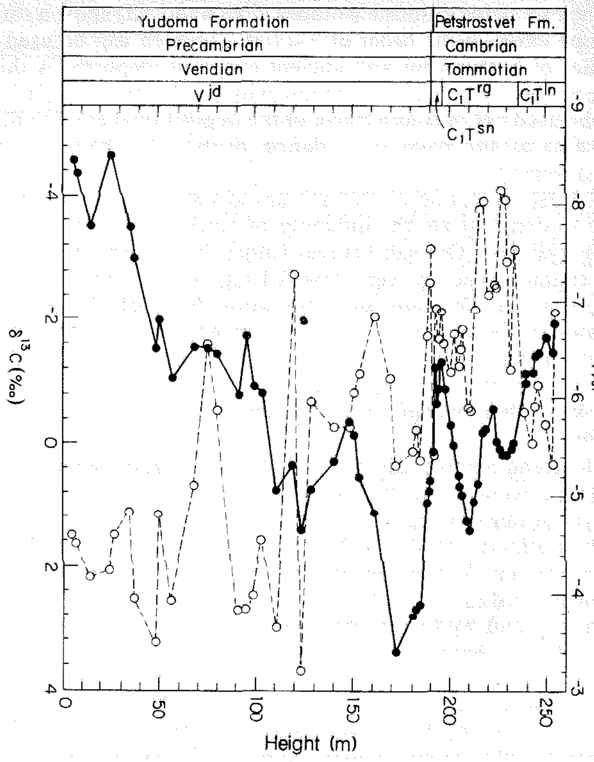

Fig. 1 Profiles of $\delta^{13}\mathrm{C}$ (●, solid line) and $\delta^{18}\mathrm{O}$ (○, dashed line) at the Dvortsy section, Aldan River, Yakutia. The metre scale corresponds to the standard scale scribed on the outcrop, which starts at an arbitrary zero about 10 m above the unconformity on the Archaean; the isotope profile begins at +10 m on that scale, or about 20 m above the unconformity. Stratigraphical zone symbols[11]: $\mathrm{V^{jd}}$, Vendian Yudoma Formation; $\mathrm{C_1T^{sn}}$, Cambrian Tommotian Pestrotsvet Formation, *A. sunnaginicus* zone; $\mathrm{C_1T^{rg}}$, *D. regularis* zone; $\mathrm{C_1T^{ln}}$, *D. lenaicus* zone.

From the base of the Dvortsy section $\delta^{13}\mathrm{C}$ becomes gradually more positive, from $\delta^{13}\mathrm{C} = -4$ to $+3.4‰$ (Fig. 1). The most positive samples are found at about 170 m, 15 m below the P€/€ boundary. From this point, a decline of $\delta^{13}\mathrm{C}$ to a minimum of $\delta^{13}\mathrm{C} = -1.3‰$ crosses the P€/€ boundary, as well as the rest of the Yudoma Formation and the *Aldanocyathus sunnaginicus* zone (Fig. 1: $\mathrm{C_1T^{sn}}$, of lower Tommotian age) of the Petrotsvet Formation. From this point, $\delta^{13}\mathrm{C}$ rises sharply by 2‰ within a 15-m section of the *Dokidocyathus regularis* zone (Fig. 1: $\mathrm{C_1T^{rg}}$, of middle Tommotian age), and then decreases by 3.3‰ to the end of the analysed section about 10 m below the Tommotian/Atdabanian boundary.

The rise of 7.5‰ in $\delta^{13}\mathrm{C}$ (Fig. 1) within the Vendian, is at an average rate of change of 0.04‰ $\mathrm{m^{-1}}$. The second rise, in the *D. regularis* zone ($\mathrm{C_1T^{rg}}$) is of the order of 0.2‰ $\mathrm{m^{-1}}$, about five times as fast as in the late Vendian, on the admittedly tenuous assumption of a uniform sedimentation rate. The drop of $\delta^{13}\mathrm{C}$ across the P€/€ boundary is at a faster rate, of 0.5‰ $\mathrm{m^{-1}}$. Part of this section may be missing at the unconformity, which may mean that the drop is at a similar rate to the previous Vendian increase. Because each of these changes continues over a thick sequence, it is likely that none of them is caused by an instantaneous mechanism. The carbon isotope variations reflect corresponding variations of $\delta^{13}\mathrm{C}$ in $\mathrm{HCO_3}$ in shelf waters, which presumably equals that of the surface ocean water mass. Several models have been proposed to explain variations of $\delta^{13}\mathrm{C}$ in surface ocean waters. For this case, we can ignore those models dependent on the mass of land flora. The remaining models are: (1) changes in biological productivity in the surface ocean[23]; (2) changes in vertical circulation rate for the whole ocean[24]; (3) changes in the fractional preservation of organic carbon on the sea floor, caused by expansion and contraction of the oxygen-minimum zone[25].

Although we have only a single profile, previous experience with profiles of $\delta^{13}C$ at other boundaries suggests that at least the general trends of variation represent worldwide oceanic events, rather than simply basinal changes.

The number and size of phosphorite deposits near the PꞒ/Ꞓ boundary is unequalled at any other time in the geological record[12,26,27]. Phosphorite deposition suggests increased biological productivity, which (model (1)) should increase $\delta^{13}C$ in these surface waters. Cook and Shergold[26] connect this burst of phosphorite deposition with the explosive faunal diversification in early Cambrian times, including taxa with phosphatic skeletons. Their time control for the phosphate event(s) is necessarily imprecise, and carbon isotope profiles may eventually refine this course of events. In accordance with the above model, the two periods of increased $\delta^{13}C$ correspond to increases in biological activity. The first rise of $\delta^{13}C$ occurs in the Vendian system, which has little skeletal fauna and may correspond to a time of diversification, the descendants of which appeared at once in the early Cambrian. This general development was probably interrupted by a decline of productivity, revealed by the reversal across the PꞒ/Ꞓ boundary, which recovered only in the *D. regularis* zone (middle Tommotian). A second decline continued to the top of our record of $\delta^{13}C$ (Fig. 1).

The changes of $\delta^{13}C$ in Fig. 1 probably represent a final episode of a long record of generally high $\delta^{13}C$ in late Proterozoic time, as displayed in thick sections in Svalbard and Greenland (A. H. Knoll, personal communication). In that view, the low $\delta^{13}C$ with which our shorter section begins would have been only a temporary drop to a low value.

On a section that is still shorter than ours, $\delta^{13}C$ across a zone designated as the PꞒ/Ꞓ boundary at two localities in China shows a sharp negative excursion within 20 cm of the boundary, associated with a possible iridium anomaly[28,29]. However, the levels at which the PꞒ/Ꞓ boundary has been placed in China and Siberia are probably not stratigraphically correlative. In any case, our sampling would probably have missed so sharp an excursion as found in China.

The $\delta^{18}O$ values in Fig. 1 have a negative trend, from a mean of −4‰ in the first 150 m of our Vendian section, to about $\delta^{18}O = -7‰$ in the rest of our Vendian and Cambrian section. No major change occurred at the P C/ C boundary. The correlation of $\delta^{18}O$ with $\delta^{13}C$ is −0.36, whereas a positive correlation would have been expected if both $\delta^{13}C$ and $\delta^{18}O$ had been distorted by freshwater diagenesis. As with other dolomites, one cannot be sure that they preserve an original record of $\delta^{18}O$. Further analyses, especially of phosphate $\delta^{18}O$ (ref. 29), may help to explain the variations in $\delta^{18}O$.

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Note added in proof: The recent paper by Tucker[31] gives a carbon isotope profile across the PꞒ/Ꞓ boundary in the Anti-Atlas of Morocco. In that section the boundary is undefined within a 200-m section, which in turn forms part of a 300-m interval for which Tucker has no $\delta^{13}C$ data. But Tucker's $\delta^{13}C$ values rise from −3‰ below this interval to +2.5‰ above this interval, which probably corresponds to the late Vendian rise in Fig. 1 above. A more complete profile of $\delta^{13}C$ in the Moroccan section may give a precise correlation with the Siberian section.

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Radiolarian and silicoflagellate response to oceanographic changes associated with the 1983 El Niño

Nicklas G. Pisias, David W. Murray & Adrienne K. Roelofs

College of Oceanography, Oregon State University, Corvallis,
Oregon 97333, USA

Strong seasonal signals in fluxes and composition of siliceous microfossils have been recorded in sediment traps from two sites in the equatorial Pacific, deployed from December 1982 to March 1984. During the early part of the sampling period, the 1982–83 El Niño event had a profound effect on the radiolaria and silicoflagellates within these two areas. During the El Niño, the radiolarian trap assemblages at Site C (1° N, 139° W) most resembled faunal assemblages in western equatorial Pacific sediments, whereas the trap assemblages resembled equatorial divergence sediments in the latter half of the period. At Site S (11° N, 140° W), the radiolaria and silicoflagellate species can be correlated with organic carbon fluxes. In general, silicoflagellate shell fluxes are correlated to total opal fluxes where radiolarian fluxes do not exhibit this relationship. Approximately 20–25% of the total count of radiolaria in traps are not present in underlying sediments with a significant loss of the weakly silicified forms. However, the comparison of trap sample assemblages with underlying sediments reported here shows that dissolution does not alter relative abundances of the fossil species used in palaeoclimatic reconstructions. A significant difference is observed between the silicoflagellate trap assemblage and the underlying sediment assemblage.

The samples used in this study were collected with the Oregon State University single-cone traps equipped with five-cup sample changers[1]. The sampling period was 7 days for the first cup and ~100 days for each of the other four cups. At Site C the traps were deployed at 1,095, 1,895 and 3,495 m, at Site S, 700, 1,600 and 3,400 m. Microfossil assemblages were examined to determine the changes in the fluxes and species abundance associated with the marked changes in organic carbon fluxes measured in the sediment traps. In addition, we wanted to determine if the known distributions of radiolaria and silicoflagellates in surface sediments of the equatorial Pacific could be used to infer the