Precambrian/Cambrian boundary problem: Carbon isotope correlations for Vendian and Tommotian time between Siberia and Morocco

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ABSTRACT

At least three distinctive cycles are preserved in the carbon-isotope patterns for the Vendian/Tommotian interval of the Siberian platform and the Anti-Atlas Mountains of Morocco. In Siberia, an early Tommotian carbon cycle provides the first detailed test of correlations based on archaeocyathid biostratigraphy between classic sequences on the Aldan and Lena rivers, and demonstrates that the Early Cambrian zone boundaries are reasonably good time lines. The carbon signal is preserved in both limestone and dolomite and across regional facies variations. The $\delta^{13}C$ results from the late Vendian section in Morocco display a pattern similar to that found in Siberia, suggesting that carbon isotopes can be used to test stratigraphic correlations on an intercontinental scale.

INTRODUCTION

Of all the biological events in Earth history, the transition from the relatively unfossiliferous Precambrian to the fossil-rich Paleozoic is one of the least well understood. Several major problems plague attempts to unravel the biological events at this boundary, including poor control on intercontinental correlation and poor chronometric calibration of the Cambrian time scale. Carbon-isotope stratigraphy offers a new tool with the potential to solve these correlation problems, because marine carbonates usually preserve an accurate record of $\delta^{13}C$ values of dissolved inorganic carbon, particularly where vital effects and diagenesis are minimal (Anderson and Arthur, 1983). Because the mixing time for the modern oceans is only a few thousand years, carbon isotope stratigraphy has a theoretical resolution comparable to that of magnetostratigraphy. Studies of carbonate rocks have shown that the carbon-isotope system is less subject to exchange during diagenesis and burial metamorphism than the oxygen isotope (Magaritz, 1975, 1983) or paleomagnetic records (Pullaiah et al., 1975). Herein we demonstrate that there are at least three distinctive perturbations in the marine carbon-isotope record of the late Precambrian and Early Cambrian that can be used to resolve correlation problems and should ultimately yield clues about biological and/or tectonic events during this time period.

New $\delta^{13}C$ results are reported here from three stratigraphic sequences of late Vendian and Tommotian age; the results are grouped into two studies. The first tests the utility of local and regional $\delta^{13}C$ correlations between three paleontologically well characterized sections on the Siberian platform, and the second concerns intercontinental correlation and whether the late Vendian carbon-isotope variations established in Siberia are consistent with similar variations in the Anti-Atlas Mountains of Morocco.

GEOLOGIC BACKGROUND AND METHODS

Siberia

On the southeastern half of the Siberian platform, a succession of flat-lying platform carbonates of Late Proterozoic through Cambrian age rests unconformably on Archean basement. Cliffs along the mid-course of the Aldan River expose, in stratigraphic succession, the Late Proterozoic–Early Cambrian Yudomia, Pestrotsvet, and Tumuldur Formations, all of which are tectonically undisturbed and have variable facies. The Yudoma Formation rests on basement, and consists of nearly 200 m of gray, dolomitic, shallow-water carbonates with local levels of stromatolites, cross-bedded oncolites, scarce acritarchs, and rare trace fossils. In most sections the first occurrence of major shelly faunas is found within the top 1 m, at the base of the *Nocho* (*Aldanocyathus*) *sunnaginicus* zone, just below a slight erosional disconformity marking the base of the Pestrotsvet Formation. Overlying the pale dolomites of the Yudoma Formation are ~80 to 85 m of red and white limestone and dolomite of the Lower Cambrian Pestrotsvet Formation. Exposures along the Lena River generally are free of dolomitization except for a few areas outside of our studied sections, whereas along the Aldan River the fraction of dolomite in the Pestrotsvet increases from east to west, reaching a maximum at Dvortsy near the city of Tommot. The rocks are virtually pure carbonate, with negligible amounts of organic or terrigenous matter.

Three sections of the carbonate rocks reported and compared here include two from the Aldan River that span the Vendian/Tommotian boundary (Dvortsy and Ulakhan-Sulugur), and Isit from the Lena River. Ulakhan-Sulugur and Dvortsy are separated by about 60 km, close enough to trace marker beds between them, whereas Isit is isolated from them by about 400 km. Lithostratigraphic sections and facies maps are in Rozanov and Missarzhevsky (1966) and Kirschvink and Rozanov (1984). The Dvortsy section is the original stratotype of the Tommotian Stage (Rozanov and Missarzhevsky, 1966), and Ulakhan-Sulugur was a candidate for the International Stratotype section for the Precambrian/Cambrian boundary (Rozanov, 1984).

Data from the Isit locality are new; the $\delta^{13}C$ results for the Aldan River sections have been reported elsewhere (Magaritz et al., 1986; Magaritz, 1989).

Morocco

The Precambrian to Early Cambrian section in Morocco was described by Latham and Riding (1990): it consists of a nearly 3-km-thick sequence of platform carbonates and siliciclastic sedimentary rocks on basement of Pan-African age. On the basis of new fossil discoveries and earlier carbon isotopic work (Tucker, 1986), Latham and Riding (1990) suggested that the Vendian/Tommotian boundary should be located near the top of the Adoudon Formation (formerly called the Calcaire Inférieur), whereas the Tommotian/Atdabanian boundary would be in the upper quarter of the Lie de Vin Formation. This is consistent with recent comparisons of the earliest Moroccan assemblages of archaeocyathids and trilobites, which show they are of middle or late Atdabanian age (Bengston et al., 1990).

We report here additional $\delta^{13}C$ results from the Adoudon and basal Lie de Vin Formations at the classic sequence near the village of Tiout (Tucker, 1986), as well as an offset section 5 km to the east at Oued Sdas that includes the entire Adoudon Formation (~1100 m), including the basal member (formerly called the Séri de Base).

Methods

Samples from Siberia were collected for magnetostratigraphic work (Kirschvink and Rozanov, 1984), and we took hand samples from the Moroccan sections. Care was taken in all cases to avoid coarsely recrystalline dolomites, veins, or cavity-filling calcite. The calcite/dolomite ratio was determined first using a Rigaku X-ray diffractometer. For the dolomitic samples (dolomite >50%), CO_2 for mass spectrometric analyses was generated by the method described in Magaritz and Kafri (1981). CO_2 generated from the calcite fractions was removed and then the remaining dolomite reacted to provide the measured samples.

RESULTS

Figure 1 shows results from the $\delta^{13}C$ comparison between the Vendian/Tommotian boundary intervals at Isit, Dvortsy, and Ulakhan-Sulugur. All of the early Tommotian curves have a similar pattern of $\delta^{13}C$ variation (designated here as Siberian carbon cycle II), which starts with $\delta^{13}C$ values between $-1‰$ and $-2‰$ in the *sunnaginicus* zone, reaching peak values of about $+1.4‰$ in the *D. regularis* zone, and returning to slightly negative values. As defined on the Siberian platform, the Precambrian/Cambrian boundary occurs slightly lower in the sequence, approximately where there is a sharp drop in $\delta^{13}C$ values in the interval around the base of the Pestrotsvet Formation and the top of the Yudoma Formation (Magaritz et al., 1986). Note that this carbon signature is preserved in both dolomite and limestone at Ulakhan-Sulugur and Isit, and in dolomite at Dvortsy. Carbon isotopes are consistent with an isochronous nature of the *N. sunnaginicus–D. regularis* zone boundary across the 400 km distance and different carbonate facies zones on the Siberian platform.

A slight difference between these sections exists around the top of the Yudoma Formation on the Aldan sections. At Dvortsy, the drop in $\delta^{13}C$ ratios from values of around $+2.5‰$ to the isotopic minimum spans an interval of about 10 m, whereas at Ulakhan-Sulugur this same shift happens over about 3 m of section. Two local disconformities have been noted at the Ulakhan-Sulugur locality, although the significance and extent of the missing section have been the subject of an intense debate within the Precambrian/Cambrian Working Group (Cowie, 1985; Rozanov, 1984; Moczydlowska and Vidal, 1988). The relatively abrupt nature of the isotopic shift

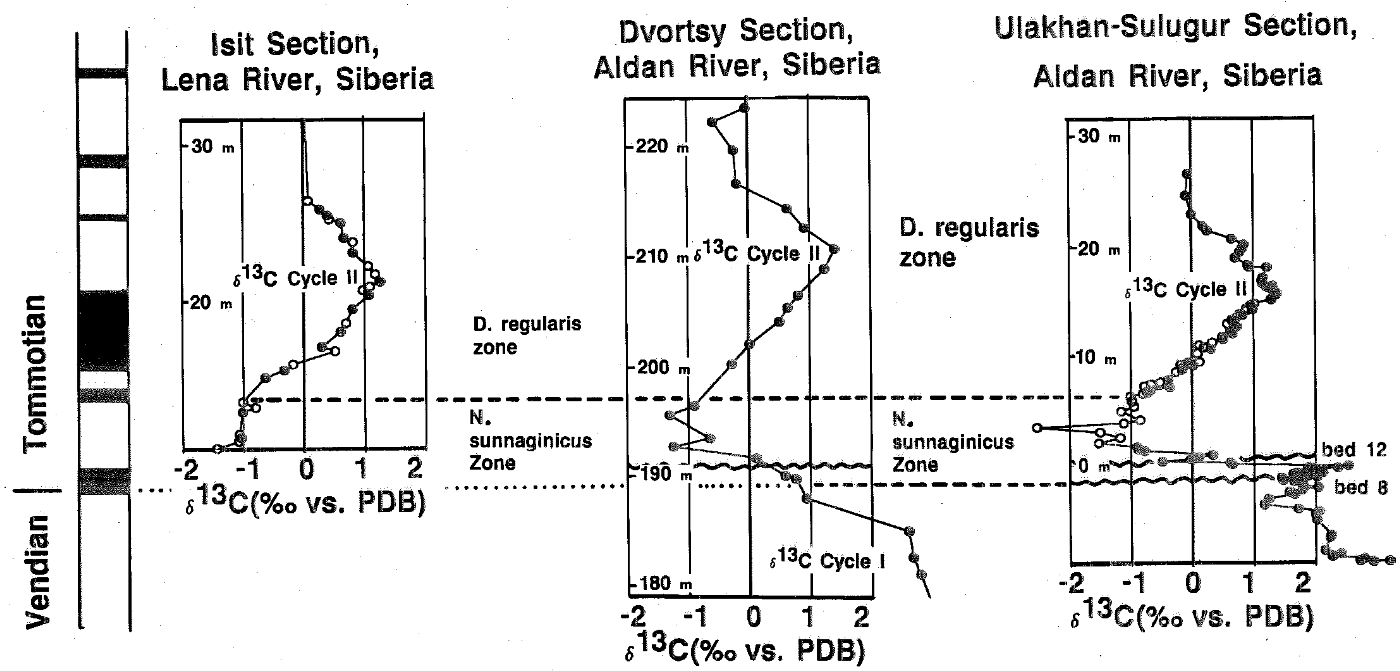

Figure 1. Carbon-isotope comparisons between three Precambrian/Cambrian boundary sections in Siberia. Dvortsy is type section for Tommotian Stage, and Ulakhan-Sulugur is candidate for International Stratotype Section for Precambrian/Cambrian boundary. Dashed lines show approximate limits for basal zone of Tommotian stage, *N. sunnaginicus*; wavy lines indicate location of known sedimentary disconformities that may indicate removal of some sequence. Data from Isit are new; those from Aldan River are compiled from Magaritz et al. (1986) and Magaritz (1989). Locality information is from Kirschvink and Rozanov (1984). Solid symbols show results from isotopic analyses of dolomite fraction; open symbols are for whole-rock analyses (PDB = Peedee belemnite). Magnetic reversal pattern (normal = black, reversed = white) has been compiled from Tommotian pattern of Kirschvink and Rozanov (1984), using polarity reinterpretation of Kirschvink (1991). Vendian/Tommotian boundary lies within short normal-polarity magnetozone recognized at both Dvortsy (in four samples) and at Ulakhan-Sulugur (in ten samples).

at Ulakhan-Sulugur suggests that there is indeed a small stratigraphic break within this interval. However, beds 8 and 12 at Ulakhan-Sulugur have distinctly different $\delta^{13}C$ values: bed 8 is heavier than 12; therefore, bed 8 could not have been derived directly from bed 12 during karst formation. Furthermore, diagenetic alterations generally yield lighter $\delta^{13}C$ values, and the heavier bed 8 values argue against significant diagenetic effects on the carbon isotopes. Abrupt shifts in $\delta^{13}C$ at chronostratigraphic boundaries have been documented elsewhere as the result of a depositional hiatus (Magaritz et al., 1988; Baud et al., 1989), and the apparent continuity of this isotopic shift at Dvortsy suggests that this section may be more continuous.

Figure 2 shows a $\delta^{13}C$ comparison between the Vendian Yudoma Formation at Dvortsy on the Aldan River in Siberia, and new results from the Adoudon Formation (Calcaire Inférieur) from the Anti-Atlas Mountains of Morocco. The two Moroccan sections are essentially one; beds can be traced laterally between them, demonstrating the overlap in the upper part of the Adoudon Formation, as shown. The $\delta^{13}C$ values in rocks from the Oued Sdas section show a gradual increase from the base of the section to values above +6‰ at the 890 m level. The extension of the section at Tiout shows the upper interval decreasing from 4.2‰ to −2‰ in $\delta^{13}C$, a drop of more than 6‰. It shows clearly that ^{13}C-depleted carbonate is present in the upper 100 m of the Adoudon at Tiout, in contrast to the report of Tucker (1986), who found a similar change occurring at the top of the Adoudon Formation in the same section. It is suggested that the excursion reported here is the same as that found initially by Tucker (1986), but that the stratigraphic metre levels disagree because of the degree of exposure of the transition into the overlying Lie de Vin Formation. (The transition is well defined in the Oued Sdas section, where it is found in a single large cliff. The Tucker section comes from a relatively poorly exposed hillside.) The $\delta^{13}C$ values for the basal Lie de Vin are rather negative, similar to those reported by Tucker (1986).

The pattern of the carbon-isotope curve in Morocco compares favorably with that from Dvortsy on the Siberian platform (Fig. 2). A similarity is apparent between the curves, particularly in the pattern of increase and decrease in ^{13}C content. In both regions the section starts with a transgressive phase over older Precambrian rocks, with $\delta^{13}C$ values of −4‰. The $\delta^{13}C$ values at the maxima in Morocco are in all cases more positive than the data from Siberia, suggesting perhaps that the two localities were not close to each other during late Vendian time. The paleogeographic model of Kirschvink (1991) is consistent with an equatorial separation of several thousand kilometres.

DISCUSSION AND CONCLUSIONS

Three cycles of carbon-isotope oscillation are present in the sections studied. Cycle I (Fig. 2) begins in the uppermost Vendian Yudoma Formation in Siberia (and in the Moroccan Adoudon Formation) with a large shift in $\delta^{13}C$ values from −4‰ to +3‰, and drops back down to values near −2‰ near the base of the Tommotian. This cycle contains both the largest

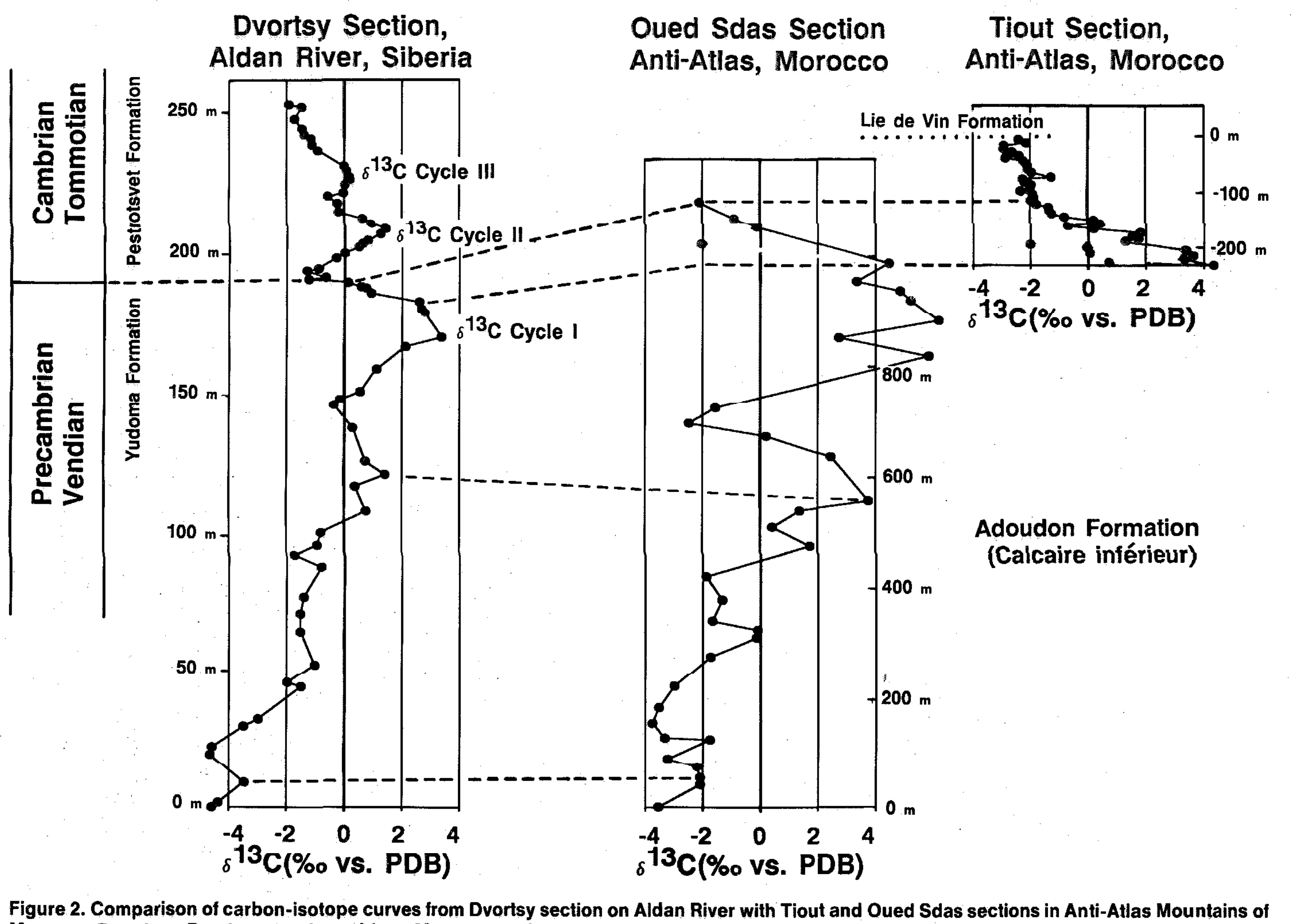

Figure 2. Comparison of carbon-isotope curves from Dvortsy section on Aldan River with Tiout and Oued Sdas sections in Anti-Atlas Mountains of Morocco. Data from Dvortsy are adapted from Magaritz et al. (1986); those from Morocco are from this study. Symbols as in Figure 2.

changes in $\delta^{13}C$ values and the most ^{13}C-enriched rocks found in the studied interval. Cycles II and III are confined to the early Tommotian. Note that these isotopic data are difficult to generate by diagenesis, because most cycles are defined by large numbers of samples with gradual changes between them, and they have identical patterns in parallel sections.

Two $\delta^{13}C$ cycles were also found in the Tiout section in Morocco. Although Tucker (1986) suggested, on the basis of stromatolite dating and the appearance of trilobites, that the Precambrian/Cambrian boundary is associated with the upper cycle, recent work suggests that it may correlate instead with the lower $\delta^{13}C$ cycle. Onset of the second carbon cycle in Morocco and the first appearance of trilobites correlate best with the younger Tommotian/Atdabanian boundary in Siberia (Kirschvink et al., 1991). The absence of cycles II and III in Morocco may be due to large sampling intervals; it is difficult to find suitable subtidal beds in the mostly nonmarine lower part of the Lie de Vin Formation (Latham, 1990).

The cause of these carbon-isotope oscillations remains a puzzle. They could be the result of an increase in deposition of organic matter in the ocean basin or a change in the biological productivity of the ocean surface. Indirect evidence can be found for both models. Large deposits of phosphorites, commonly associated with deposition of organic-rich sediments from anoxic bottom waters, are found in various Early Cambrian localities around the world (Cook and Shergold, 1984). Thus, $\delta^{13}C$ cycles could reflect periods of deposition and erosion of these organic-rich sedimentary rocks. There is evidence for tectonic activity, including continental breakup and suturing events, that could provide the mechanisms for perturbing these sedimentary carbon reservoirs (e.g., Bond et al., 1984; Kirschvink, 1991). Pronounced ^{13}C-depletion events associated with many extinction-related boundaries, including the Cretaceous/Tertiary (Hsü et al., 1982), the Permian/Triassic (Magaritz et al., 1988), the Frasnian/Famennian (Playford et al., 1984), the Devonian/Carboniferous (Xu et al., 1986), and the Ordovician/Silurian (Orth et al., 1986), argue for a productivity-related mechanism.

It is intriguing to note that three of the major positive swings in $\delta^{13}C$ values in Siberia follow the first appearance of new body plans. The Nemakit-Daldyn fauna is associated with the base of the Yudoma Formation (base of carbon cycle I); carbon cycle II is near the base of the Tommotian stage with the first molluscan and other small shelly-fossil mineralized faunas; and carbon cycle IV begins near the first mineralized trilobites and other arthropods (Kirschvink et al., 1991). Perhaps the next event, onset of mineralized echinoderm faunas in the upper Atdabanian, will prove to have produced another shift in the carbon isotopes.

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