A carbon isotope reference scale for the Lower Cambrian succession in Siberia: report of IGCP Project 303

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Abstract — Four sections from the mid-Atdabanian to lowest Toyonian (middle Cambrian) along the Lena River of Siberia were sampled for carbon isotope stratigraphy. These show a mainly heavy but highly oscillatory $\delta^{13}C$ signature for the Atdabanian to mid-Botomian interval, coincident with the major phase of invertebrate innovation. A prolonged interval of negative $\delta^{13}C$ followed until late Toyonian times, coincident with Botomian-Toyonian mass extinctions. Eleven carbon isotope cycles are identified through the lower Cambrian, which should now be tested for their utility in global correlation and relationship to bioevents in the Cambrian explosion.

1. Introduction

Understanding of the major radiation of invertebrate phyla above the Precambrian–Cambrian boundary (e.g. Rozanov et al. 1969; Conway Morris, 1987) has been hampered by problems of global correlation (see, e.g. Rozanov, 1973; Cowie & Brasier, 1989; Knoll & Walter, 1992). This paper documents new data on high resolution carbon isotope stratigraphy from the lower Cambrian of the Siberian Platform, discussed in outline elsewhere (Brasier et al. 1994).

Several studies have explored the potential of carbon isotope stratigraphy in the Cambrian, with emphasis falling upon a positive excursion close to the base of the Tommotian (Tucker, 1986; Magaritz, Holser & Kirschvink, 1986; Aharon, Schidlowski & Singh, 1987; Lambert et al. 1987; Brasier et al. 1990; Latham & Riding, 1990; Derry, Kaufman & Jacobsen, 1992; Knoll & Walter, 1992; Pokrovsky & Missarzhevsky, 1993; Brasier, Khomentovsky & Corfield, 1993) and another close to the base of the Atdabanian (Kirschvink et al. 1991; Brasier, Anderson & Corfield, 1992). One of the aims of IGCP Project 303 on ‘Late Precambrian–Cambrian Event Stratigraphy’ has been to encourage this approach, integrating data on stable isotopes with lithostratigraphy and biostratigraphy. Of prime importance to this work are the classic boundary successions on the Siberian Platform, especially those of the Anabar–Sinyaya facies belt, exposed along the Aldan and Lena rivers (Figs 1, 2) which provide a biostratigraphic scale widely used around the world (Rozanov et al. 1969; Rozanov, 1973; Rozanov & Sokolov, 1984; Nikolaeva et al. 1987). The strata here are well-exposed in river cliffs, where flat-lying carbonate sediments show well-preserved fabrics and a rich diversity of fossils, including index faunas of small shelly fossils, archaeocythans and trilobites.

An opportunity to examine and collect these sections arose during an excursion for the Third International Symposium on the Cambrian System, in July 1990. Here, we describe the isotopic character of these classic lower Cambrian sections and make a preliminary calibration against the fossil record.

2. Material

We sampled the uppermost Precambrian to middle Cambrian sections along the Aldan and Lena rivers of the Siberian Platform (Figs 1, 2). A helicopter, river launch and base camp proved necessary for access to the Aldan River sections. Those on the Lena River were reached via the cruise ship ‘Rossiya’.

Several of these sections, spanning the uppermost Precambrian to lower Atdabanian, have already been analysed for carbon isotopes by Magaritz, Holser & Kirschvink (1986), Magaritz (1989), Magaritz et al. (1991), Kirschvink et al. (1991) and Brasier, Khomentovsky & Corfield (1993). These include the cliff sections at Dvortsy and Ulakhan Sulugur (Aldan River), Isit and Zhurinsky Mys (Lena River). Some 52 samples were collected from these by M.D.B., for comparative analysis with fossiliferous sections along the Uchur River (see Brasier, Khomentovsky & Corfield, 1993). Strontium isotopes are also being studied from these samples by Mr C. Nicholas (Cambridge, UK).

A further four cliff sections along the Lena River, from lower Atdabanian to lowest Amgan, were
Figure 1. Map of Siberia, showing modern rivers, the distribution of major facies belts in the early Cambrian, and the location of key sections referred to in the text. 1, Nemnekey and Mt Konus sections on tributaries of the Uchur River; 2, 3, Dvortsy and Ulukhan Sulugur sections on the Aldan River; 4-9, Lena River sections: 4, Zhurynsky Mys; 5, Achchagy Kyyry Taas; 6, Achchagy Tuoydach; 7, Labaya; 8, Titary; 9, Elanka. Based on Rozanov (1992).

Figure 2. Schematic cliff section of Lower Cambrian formations along the Lena River south of Yakutsk, Yakutia, Siberia (right bank except where indicated). Black bars indicate cliff sections sampled to date for isotope stratigraphy (see Fig. 4). Horizontal line represents high water mark of river. ND = Nemakit-Daldynian; TOM = Tommotian; ATD = Atdabanian; BOT = Botomian; TOY = Toyonian.
Lower Cambrian carbon isotope stratigraphy, Siberia

3. Component analysis

Sediments sampled along the Lena River succession and used in constructing these isotopic curves (Figs 4–10) are mostly non-ferroan micritic and microsparitic calcite limestones containing sparse skeletal fossil remains (Rozanov & Sokolov, 1984; Nikolaeva et al. 1987). Such rocks, however, may not be a reliable indicator of the sea water δ18O signal sought for global chronology. Diagenetic overprinting can produce much lighter (or sometimes heavier) δ18O and δ13C, due to exchange with meteoric or burial waters (see, e.g. Irwin, Curtis & Coleman, 1977; Tucker & Wright, 1990). Admixture with skeletal grains show that varying vital effects could also modify the signal

Figure 3. (a, b) Carbon- and oxygen-isotope values of carbonate components from selected horizons in archaeocyathan bioherms on the Lena River (in two plots for clarity). 1, *Dokidocyathus regularis* Zone, *Lapworthella bella* Subzone, By'd'yanaiia; 2, same zone, *L. tortuosa* Subzone, Tiktirikteekh; 3, *D. regularis* Zone, unrecorded locality; 4, *D. lenaicus* Zone, By'd'yanaiia; 5, *Retecoscinus zegebarti* Zone (c. lower *Profallotaspis jakutensis* trilobite Zone), Zhurynsky Mys; 6, 7, *R. zegebarti* Zone (ca. *P. jakutensis* to lower *Pagetiellus anabarus* trilobite Zones), OyMuran. (c) covariance plot of isotopes from whole-rock carbonates reveal little significant covariance between carbon and oxygen isotopes in each section, hence no systematic resetting of during diagenesis. (d) regression analysis of oxygen isotopes against Mg%, and Mn, Fe and Sr ppm (from a sample subset). Based on Brasier et al. (1994).
Table 1. Trace elements and isotopes from Titary

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<th>Fe/Sr</th>
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(see, e.g. Grant, 1992). These unwanted effects can be traced by multiple isotopic analyses on matrix and components from a single sample (see, e.g. Brasier, Anderson & Corfield, 1992; Brasier, Khomentovsky & Corfield, 1993).

Slabs of heterogeneous carbonate from archaeocyath bioherms were first studied using stained acetate peels. Five main components were distinguished: micritic-microsparitic carbonates, microbial carbonates, fibrous calcite fringe cements and blocky calcite cements (Fig. 3 a, b). Micritic carbonates are fine-grained sediments (typically reddish brown in colour) that provide the matrix of the bioherms and the bulk of the carbonates studied. Bimineral carbonate is a minor component, except in archaeocyath bioherms; only the thicker parts of archaeocyathans and ‘coralmorphs’ were studied. The former are sponge-like organisms with a finely microgranular skeleton, suggestive of a primary calcitic origin (Kruse & Debrenne, 1989). *Cysticyathus* and *Kasakhthia* are ‘coralmorphs’ with a calcite skeleton of microdigitate granules, of possible cnidarian origin (Debrenne, Lafuste & Zhuralev, 1990).

Microbial carbonates are typically pink, grey or white in colour, and represent carbonate laid down within or between the calcitic thalli of calcimicrobes *Renalis* and *Epiphyton*. The biothermal fabrics contain conspicuous primary cavities (within archaeocythans, or within the matrix).

Two generations of calcite cement can usually be distinguished: an earlier fibrous calcite fringe cement, whose fibrous fabric indicates an original high Mg calcite or aragonite origin; and a later blocky calcite cement, whose more equant crystals suggest a low Mg calcite origin, likely to have formed during burial diagenesis (see, e.g. Tucker & Wright, 1990).

These various components were drilled using a fine dental drill to yield powders analysed for their stable isotopic composition (Fig. 3 a, b). Note that micrite-microspar values plot well away from the blocky calcites of later diagenetic origin, whose values are negatively displaced, suggesting formation during later burial diagenesis (see, e.g. Irwin, Curtis & Coleman, 1977). Micrite-microspar carbonates plot close to well-preserved microgranular calcite skeletons of archaeocythans and coralmorphs, and also to calcimicrobial carbonate.

Fibrous fringe cements are thought to have formed by active pumping of sea water through biothermal cavities, and may therefore have precipitated in isotopic equilibrium with sea water (Gonzalez & Lohmann, 1985). Micritic carbonates tend to show only slight negative displacement (<1 ‰ δ18O, <0.5 ‰ δ13C) from these values. We take this to infer that the micrite-microspar values generally record δ13C values close to those of Cambrian seawater.

4. Further diagenetic and metamorphic studies

Oxygen isotopes indicate some diagenetic modification of micrites, with values ranging mainly between −4.03 and −9.28 ‰ δ18O PDB. Elsewhere, we have shown that covariance between oxygen and carbon values in the Yudoma dolomites at Dvortsy and Ulakhan Sulugur, implies diagenetic overprinting that can be back-tracked using a set of assumptions (Brasier, Khomentovsky & Corfield, 1993). At levels above the Yudoma dolomites, however, no clear covariance is seen with δ13C values (Fig. 3c), excepting in parts of the Titary section (e.g. Fig. 9) and most δ18O values are close to the best so far obtained from Cambrian carbonates (−5 to −6 ‰, Hudson & Anderson, 1989).

Negative resetting of carbon isotopes at certain horizons in the Titary section is also implied from variability studies on a selected sample (B-1-101) from member II, bed 5. Here, covariance was found between carbon and oxygen in a traverse of seven spots across the sample (e.g. −6.821 to −5.272 ‰ δ18O against −0.719 to 0.176 ‰ δ13C).

As a further test of diagenesis, we analysed the covariance of δ18O and ppm of Sr, Fe, Mn, and Mg (Fig. 3d) at 30 points through the succession, using atomic absorption, and 87Sr/86Sr values obtained from a Finnigan 262 thermal ionization mass spectrometer at Nancy. Mn/Sr and Fe/Sr proved to be correlated in limestones (less so in dolomites), and covery with 87Sr/86Sr values but not with δ18O or δ13C values. Reasonable confidence can be placed in samples that are not dolomitized, and that have Mn/Sr values of <0.5 and Fe/Sr values of <0.3. In this respect, four test samples from Titary appeared to be relatively little altered (Table 1). We infer that, with minor exceptions, the micrite-microspar δ13C values of these sections have not been largely reset by meteoric or burial diagenesis. In Newfoundland, it was found that post-Cambrian plutonic intrusions...
have adversely affected the stable isotopic signal in the Precambrian–Cambrian boundary GSSP (Brasier, Anderson & Corfield, 1992). This brought about $\delta^{18}O$ depletion of up to $-22.00\%$. No such plutons occur in the present study area, nor are such major $\delta^{18}O$ depletions recorded. The carbonates are cut, however,
by a number of basaltic dykes, whose effect on stable isotopes was tested in the same layer of bed 1 at Achchagy Tuoydach. This dyke was from 4.6 to 4.9 m wide and limestones were sampled at five intervals from the dyke margin (Table 2).

These results should be compared with the values of —5.300% δ18O and +2.82% δ13C obtained from a similar level in bed 1, 1 km northeast of the dyke (Fig. 7). From this it appears the intrusion may have resulted in carbon isotopic depletion of about —0.2‰ within 5 m of the dyke, with little alteration beyond this zone. All samples used in this study were distant from such minor intrusions, usually by 1 km or more.

Finally, we note that stable isotopic data obtained in the Oxford laboratory (Brasier, Khomentovsky & Corfield, 1993) yielded similar results to those obtained from comparable materials studied by the Weizmann Institute, Rehovot, Israel (Magaritz, 1989; Kirschvink et al. 1991). We therefore combine these data together in Figure 4.

From these studies, we note that the range of variation that can reasonably be attributed to alteration and diagenesis is rather small compared with the observed total range variation in carbon isotopes. This implies that the major shifts are in fact real and do not merely reflect secondary processes. If these shifts reflect seawater δ13C through Tommotian to Toyonian times, then the isotopic record of the Siberian Platform has excellent potential for global correlation.

5. Carbon isotope stratigraphy

5.a. Achchagy Kyry Taas (AKT)

This important section (Fig. 5) spans much of the Atdabanian Stage, beginning a little higher than the top of the Isit section sampled by Kirschvink et al. (1991). It contains the stratotype sections for the Judomia Zone (trilobites), and the Carinacyathus pinus, Nochorocycathus kokoulini and Fansycathus lermontovae Zones (archaeocythans). Carinacyathus pinus is a senior synonym of Porocyathus pinus (Debrenne, Rozanov & Zhuralev, 1990). The lithology comprises a variety of red and pink argillaceous micrites and paler grey micrites, with occasional fossils. Marker beds 'Bachyk', 'Chopchun' or 'x-y', 'Sakkyryr' or 'a-b' can traced along the outcrop for tens of kilometres (Khomentovsky & Repina, 1965; Rozanov & Missarzhevsky, 1966).

The Bachyk marker bed contains archaeocythans that mark the base of the C. pinus Zone. This marker lies within the lower part of the Pagetiellus anabarus trilobite Zone. Marker bed x-y contains this index fossil plus the trilobite Nevadella groenlandica. Unpublished palaeontological data obtained by V. Astashkin during joint field work 500 m upstream of the Achchagy Tuoydach section (by A. Yu. R., A. Yu. Z. and V. Astashkin in 1987) confirms that an archaeocyathan assemblage of Carinacyathus pinus/Pagetiellus anabarus Zone age occurs 7.7 m below the a-b marker bed. A little higher, the marker bed a-b is taken to mark the base of the Judomia Zone across the region, although the index here appears at the bottom of the overlying bed 9. Archaeocythans occur in bioherms at the base of bed 18 and mark the base of the Fansycathus lermontovae Zone at the top of the Atdabanian Stage. The sampled section stopped in the upper part of bed 20, some 10–12 m below member III and the base of the Botomian Stage (Astashkin et al. 1990).

The carbon isotope profile (Fig. 5) shows a relatively steady signal in the lower part of the section, with a distinct positive excursion in the upper part of the Pagetiellus anabarus/Carinacyathus pinus Zones. The top part of this cycle is calibrated by the a-b marker bed, and the Judomia/N. kokoulini Zones. The rest of the Judomia Zone shows minor oscillations, tending to negative values in the upper part.

These results from Achchagy Kyyry Taas (AKT) throw some light on the problems of stratigraphic correlation using archaeocythans and magnetostratigraphy. Kirschvink & Rozanov (1984, Fig. 11) correlated the lower part of AKT with the lower part of Bed 8 at Zhurinsky Mys on the basis of similar palaeomagnetic reversals, and their presumed position within the Carinacyathus pinus Zone (Fig. 6). The higher part of Bed 8 at Zhurinsky Mys has even been ascribed to the Nochorocycathus kokoulini Zone (Astashkin et al. 1990). At that time a major disparity between archaeocythans and trilobite zones was suspected in different sections, but it remained unclear as to whether either group was diachronous (see, e.g. Rozanov & Sokolov, 1984, p. 22, figs 1 and 2).

If the archaeocyathan zones were correctly drawn, then the carbon isotope stratigraphy of these two sections should match. But the Zhurinsky Mys section shows a zero to negative δ13C trend at its top, while AKT shows a zero to positive δ13C trend over the interval in question (Fig. 6; Kirschvink et al. 1991). Nor does the lower part of Bed 8 at Zhurinsky Mys contain any of the index species of the Carinacyathus pinus Zone. We infer that Bed 8 at Zhurinsky Mys belongs either to the Retecoscinus zegebarti or Carinacyathus pinus Zones and lies stratigraphically below the Bachyk marker bed at the base of the AKT section. The magnetostratigraphic correlation of Kirschvink & Rozanov (1984) is therefore questioned.

5.b. Achchagy Tuoydach (AT)

This section (Fig. 7) overlaps with the preceding one, allowing a test of biostratigraphic, lithostratigraphic and chemostratigraphic markers (see Fig. 6). The lower part of the section spans the Pestrotsvet Formation, with its red, pink and grey, largely micritic
Figure 5. Carbon- and oxygen-isotope stratigraphy of the Atdabanian at Achchagy Kyyry Taas (AKT), Lena River. Numbers 1–8 to the right of the carbon curve characterize isotopic features seen at the same level at Achchagy Tuoydach (cf. Figs 6, 7). Stratigraphic log based on Astashkin et al. (1990). See Figure 10 for lithological key.

Limestones. These are succeeded by mainly greenish-grey limestones of the Perekhod Formation, grey to black argillaceous limestones and shales of the Sinyaya Formation, and paler brown limestones of the lower Kutorgina Formation. This part of the succession therefore appears to record an increase in water depth, to a maximum in the Sinyaya Formation, followed by shallowing in the Kutorgina Formation.

The base of the Judomia Zone is traditionally taken at the base of the marker bed a–b or ‘Chopchun’, though the first occurrence here lies 4.1 m above the marker. The base of the overlying Botomian Stage is not defined here, but some 10 km upstream at Ulkahan Kyyry Taas. There, incoming trilobites of the Bergeroniellus micmaccaformis–Erbiella Zone, and archaeocythans of the Botomocyathus zelenoví–Porocyathus

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Lower Cambrian carbon isotope stratigraphy, Siberia

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Achchagy Kyyry Taas

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<td>T. M. Brasier and Others</td>
<td>?</td>
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Achchagy Tuoydakh

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<td>Nochoricyathus krauseni</td>
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Geomorphic polarity interpretation

- B_1 Suggested base of Nochoricyathus kokoulini Zone according to Astashkin et al. (1990).
- B_2 Datum according to interpretation herein.

Figure 6. For legend see facing page.
**squamosus Zone**, occur at the base of member III of the Perekhod Formation. Unfortunately, this boundary is not clearly recognized in the AT section, but is officially placed within 8 m of non-exposure below bed 5 (Astashkin et al. 1990). The strata in bed 5 are certainly of early Botomian age, since they contain the first *Neocobboldia paradentata* (Repina, 1981).

Carbon isotopes in the lower part of the section show remarkable similarity with those from coeval strata at AKT. Note, for example, the points of similarity numbered from 1 to 8 on the two profiles (Fig. 6; see also Figs 5 and 7). Note also that samples from the alleged interval of non-exposure below bed 5 compare isotopically with the uppermost Atdabanian of the previous section. The base of the Botomian is therefore drawn, tentatively, at the base of bed 5.

Although the abrupt positive shift in δ¹³C at the base of bed 5 (Fig. 7) may partly reflect poor sample spacing, or even a hiatus, an important isotopic excursion clearly begins here, leading to a distinctly positive δ¹³C interval in the *B. miciaciniformis* Zone. Further sampling is needed from the zonal type section at Ulakhan Kyry Taas to characterize this event.

Carbon isotopes in the overlying Sinyaya Formation show a gradual increase in δ¹³C values from c. 1 to 2‰o, continuing into the basal Kutorgina Formation, followed by a more rapid decline to 0.5‰o at the top of the sampled section.

5.c. Labaya

This section spans the upper Botomian to lowermost Toyonian Stages (Fig. 8) and has horizons with abundant trilobites. It contains the stratotype of the *Bergeroniaspis ornata* Zone, of uppermost Botomian age. Sampling began in the lower part of the Kutorgina Formation, in the underlying *Bergeroniellus asiaticus* Zone, at a level thought to lie perhaps 5 m higher than the top of the AT section.

Rocks of the Kutorgina Formation consist predominantly of light brown fine-grained, thin- to medium-bedded limestones, while the Keteme Formation marks a change to cream-coloured and more massive limestones and dolomites, with cavernous weathering and lacking fossils. This change suggests a shallowing upwards from open marine to restricted shelf environments. Only the very basal part of the Keteme Formation was sampled here.

The carbon isotope profile (Fig. 8) contrasts markedly with underlying sections in showing a relatively steady, negative δ¹³C signature, with minor fluctuations near the lower and upper part of the Kutorgina Formation. This is taken to be a continuation of the trend towards lighter isotopic values seen at the top of the AT section (Fig. 7).

5.d. Titary

The Titary (or Tit-Ary) section spans uppermost Botomian to mid-Toyonian (Fig. 9). Since there was no access to these rocks during field work in 1990, spot samples have been provided from measured sections. Unfortunately, this means that coverage is more sporadic than in the underlying units.

Here, the Keteme Formation consists largely of grey, fine-grained limestones in the lower part, supposedly becoming more mixed with dolomite in the upper part. Trilobites are rather scarce, but give evidence for the zones shown in Figure 9. The carbon isotope profile begins with negative values like those found in the underlying Kutorgina Formation, and tends towards neutral values with minor oscillations (Fig. 9). Oxygen isotopes (Fig. 3c) show less stability, however, which may indicate localized resetting of δ¹⁸O, perhaps through meteoric diagenesis.

5.e. Elanka

This section (Fig. 10) spans the uppermost part of the Siberian lower Cambrian (Toyonian Stage) and basal part of the middle Cambrian (Amgan Stage). The Titary Formation, which was not sampled here because of time limitations, comprises creamy yellow dolostones with cavernous weathering. The Elanka Formation is a more heterogeneous unit, consisting of glauconitic dolostones, conglomeratic dolostones and limestones, and calcarenites with abundant fossils. The start of the middle Cambrian lies within this formation at the base of bed 18, with the appearance of trilobites from the *Schistocephalus antiquus* Zone.

Carbon isotopes for the Elanka section (Fig. 10) show a relatively steady, positive δ¹³C signature, varying from 0.51 to 1.24‰o. There is no evidence for a major isotopic shift across the lower-middle Cambrian boundary.

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Figure 6. Comparative carbon-isotope stratigraphy between upper Zhurinsky Mys (ZM) and lower Achchagy Kyry Taas (AKT) at the point of a previously supposed palaeomagnetic marker (asterisked; see text). A revised, isotopic correlation between these sections is shown here, as are numbered points of correlation between the AKT and Achchagy Tuoydach (AT). Carbon isotopes for ZM, and geomagnetic polarity for ZM and AKT (pars) are from the data of Kirschvink & Rozanov (1984), reinterpreted by Kirschvink et al. (1991). Stratigraphic logs for ZM are based on Kirschvink et al. (1991), and for AKT and AT on Astashkin et al. (1990).
Figure 7. Carbon- and oxygen-isotope stratigraphy of the Atdabanian-Botomian at Achchagy Tuoydach (AT), Lena River. Numbers 1–8 to the right of the carbon curve characterize isotopic features seen at the same level at Achchagy Kyyry Taas (cf. Figs 5, 6). Stratigraphic log based on Astashkin et al. (1990). See Figure 10 for lithological key. Asterisks denote parts of section logged in this study but shown as not exposed in Astashkin et al. (1990).
Figure 8. Carbon- and oxygen isotope stratigraphy of the Botomian-Toyonian at Labaya, Lena River. Stratigraphic log based on Astashkin et al. (1990). The position of the Botomian-Toyonian boundary is placed as discussed in the text. See Figure 10 for lithological key.
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Figure 9. Carbon- and oxygen-isotope stratigraphy of the Botomian–Toyonian at Titary, Lena River. Stratigraphic log partly based on Rozanov & Sokolov (1984). See Figure 10 for lithological key.
6. Discussion

A summary of present data on the carbon isotope curve through the lower Cambrian of the Siberian Platform is shown in Figure 3. Relatively negative values prevail below the Nemakit-Daldynian, and from mid-Botomian to mid-Toyonian, while a distinctive positive interval with sharp oscillations lies between.

Taking the most negative values to mark turning points (Kirschvink et al. 1991, Magaritz et al. 1991), we extend their terminology to a further six carbon cycles. Cycle Z is named for an excursion in the Anabarites trisulcatus Zone (Brasier, Khomentovsky & Corfield, 1993). Cycles V to X are named for oscillations from mid-Atababanian to lower Amgan.

Several processes could lead to positive and negative excursions in $\delta^{13}C$ such as these: an increase/decrease in the fraction of inorganic carbon buried as organic matter; or a rise/fall in productivity among primary producers. The former tends to be associated with changes in sedimentation rate (see, e.g. Derry, Kaufman & Jacobsen, 1992) or anoxic black shales, while the latter may also be associated with phosphatic and siliceous sediments (Brasier, 1992). Distinguishing between these is difficult since it really requires a
global understanding of $\delta^{13}C_{\text{carb}}$, $\delta^{13}C_{\text{org}}$ and $\delta^{34}S$, including data from different levels in the water column. There is evidence, however, from phosphorites and other data, for the concept of nutrient enrichment and productivity changes over this interval (Cook & Shergold, 1984; Donnelly et al. 1990; Brasier, 1990a, b, 1992).

7. C-isotopes and innovation bioevents

Below, we calibrate this new carbon isotope curve against major innovation bioevents, diversity changes and extinction events (Fig. 4, A to P), for the most part, based on occurrences in Siberia. These occurrences will therefore need to be tested against the isotopic scale in other regions. Archaeocyathan data (Fig. 4, at right), however, is based on the global syntheses of Zhuravlev (1986), Debrenne, Rozanov & Zhuravlev (1990) and Debrenne (1991). Magaritz et al. (1991) have already speculated on correlations between three major positive $\delta^{13}C$ swings in the early Cambrian and the first appearance of new body plans. Here, we emphasize biorstratigraphic calibration of the carbon isotope curve.

The earliest small shelly fossil assemblages in this region of the southeast Siberian Platform contain anabaritids and protoconodonts of the Anabarites trisulcatus Zone, found at level A in the Uchur region of east Siberia (Brasier, Khomentovsky & Corfield, 1993) and more questionably at about level A (Fig. 4) in the Priababar region of north Siberia (Pokrovsky & Missarzhevsky, 1993; correlation questioned by A. Yu. R.). An assemblage containing Anabarites trisulcatus, Jakutoichrea? sp. and Cloudina sp. has recently been found at about level A or just below, in the Kyra-Ytyga section, middle Yudoma River, but there are as yet no isotopic data to confirm this (Federov & Zhuravlev, 1993). This early biota is joined at about level B and B' in the Uchur region by carbon isotopes and the contemporaneous rise in the diversity of phosphatic skeletons, are indicative of aged, oxygen-depleted, nutrient- and $^{12}C$-enriched waters over the shelf during this massive transgression (Brasier, 1992). It is not impossible, of course, that some of these innovations evolved earlier, during the rising part of cycle I. The earliest Chinese ?brachiopods and ?tommotids of 'China Zone II', are argued by some to be of this age (e.g. Popov, 1992; Brasier et al. 1990), but correlation of these Chinese assemblages is still controversial.

Certain innovations appeared through cycle II in the Tommotian Stage: bivalves (Fordilla), true hyoliths (hyolithomorphs), brachiopods of the class Calcita and the earliest coralomorphs (Rozanov & Zhuravlev, 1992). The next main phase of radiation took place during the early Atadanian, most notably in the form of mineralized arthropods (polymeroid trilobites, miomeroid trilobites, phyllocarid and bradoriid crustaceans), true articulate brachiopods, cirrincychaths and hydroconozoa from levels F to H. Major innovations also took place in archaeocyathan architecture at this time (e.g. Rozanov, 1973; Rozanov & Debrenne, 1974; Debrenne, Rozanov & Zhuravlev, 1990; Debrenne, 1991). These events clearly coincide with the positive $\delta^{13}C$ excursion of cycle IV, in this region.

Few innovations seem to be connected with the major excursion of cycle V in Siberia. But echinoderm plates first appear in the F. lermontovae Zone (Rozanov, 1992) coincident with cycle VI, as Magaritz et al. (1991) anticipated. This cycle is also associated with the first appearance of biomineralized onychophorans (Microdictyon) and palaeoscolecid worms (Hadimopanella) at level L. Archaeocyatha reached peak diversity between levels M and N (Rozanov, 1973; Rozanov & Debrenne, 1974; Debrenne, Rozanov & Zhuravlev, 1990; Debrenne, 1991), during the positive $\delta^{13}C$ excursion of cycle VII.

It is, of course, not possible to prove a causal connection between these biological innovation events and positive or negative carbon isotope excursions. It is even difficult to identify which of the first occurrences of a fossil group may be the earliest (see, e.g. Brasier, 1989). Even so, the predominantly heavy isotopic character of pre-Toyonian carbonates deserves emphasis, since it contradicts the common assumption of a significant swing to negative and neutral $\delta^{13}C$ values above the Precambrian–Cambrian boundary (Veizer, Holser & Wilgus, 1980; Strauss et al. 1992). Such a change appears to have come later, in the late Botomian.

8. Carbon isotopes and the B-T crisis

Most intriguing among our findings is the apparently prolonged negative interval near the top of the lower Cambrian (upper cycle VIII to lower cycle X). It is consistent with preliminary data from the Bonnia–Olenellus Zone of North America (Grant, 1992;
Brasier, 1993). Its interpretation may contribute to understanding of the great Botomian–Toyonian mass extinction event, when trilobites (Olenellidae, Redlichiidae and other families), archaeocythans, and numerous small shelly fossil groups appear to have suffered extinction (Boucot, 1990; Sepkoski, 1992).

In Siberia, the first indications of crisis are seen in trilobites, which experienced a rapid turnover in shallow-shelf forms (including the invasion of protozoids and the demise of olenellids) between levels M and N. This turnover coincided with a peak in the diversity of archaeocythans (Fig. 4). Archaeocyath extinction rates then began to rise sharply through the B. asiaticus Zone (near level O). While this might be attributed to unsuitable facies in Siberia, this decline in diversity was clearly global and culminated in their virtual extinction at the end of the Toyonian (Fig. 4; Zhuravlev, 1986; Debrenne, 1991).

9. Conclusion
The following conclusions are drawn from this study:

(1) Eleven carbon isotope cycles (Z and I to X) are recognized between the Nemakit–Daldynian and Amgan on the Siberian Platform. Of these, six carbon isotope cycles (V to X) are described in detail for the first time, spanning mid-Atdabanian to early Amgan. A diagenetic origin for these new cycles can be discounted, implying that they have great significance for high resolution global stratigraphy of the early Cambrian.

The discovery of so many isotopic cycles is a mixed blessing for chronostratigraphy. It implies that correlation cannot be achieved with carbon isotopes alone, nor in sole combination with the magnetostratigraphic record. The latter holds great potential but is currently limited in scope by uncertain continental reconstructions (Dalziel, 1991), the effects of widespread dolomitization, and thermal resetting (Kirschvink et al. 1991). High resolution stratigraphy can only be achieved at present where these techniques are anchored to a secure biostratigraphic base.

(2) In some cases, these isotopic excursions coincided with the regional appearance of new invertebrate body plans during the ‘Cambrian explosion’. An abrupt shift to negative $\delta^{13}$C during the late Botomian to late Toyonian broadly coincided with the Botomian–Toyonian crisis, during which metazoan biota suffered mass extinction on a global scale.

For the present we must accept that the connection between particular innovations and carbon cycles is interesting, but to be conclusive it requires more data and analysis. It would imply a certainty about stratigraphic first appearances which few could accept at our current state of knowledge. So far as we know, several carbon cycles (V and VIII) do not coincide with major innovations. In addition, the spread of the Tommotian fauna, and other pandemic marker fossils at E, I, L and M, occurred during negative $\delta^{13}$C excursions.

(3) Oscillating levels of $\delta^{13}$C from Nemakit–Daldynian to late Botomian suggest multiple and dramatic fluctuations in the fraction of carbon buried as organic matter.

While the driving force for these oscillations conceivably involved productivity and nutrient cycles, models for the early Phanerozoic carbon-nutrient cycle are in their infancy. The common assumption (e.g. Magaritz et al. 1991; Grant, 1992) that biomineralization events themselves affected the carbon isotope excursions is interesting but needs more rigorous investigation; early biominerals are often sparse, and perhaps represented only a minor proportion of the carbon budget at this time. The oscillatory patterns in $\delta^{13}$C must also be sought in fluctuations in weathering rate and $p$CO$_2$, sedimentation rate, primary productivity, heterotrophy (e.g. sulfate-reduction), bioturbation, and microbial carbonate precipitation (see, e.g. Berner, 1990; Derry, Kaufman & Jacobsen, 1992; Brasier, 1992). It follows that the cause for the negative $\delta^{13}$C shift associated with the B–T crisis is still elusive.

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