Integrated chronostratigraphy of Proterozoic–Cambrian boundary beds in the western Anabar region, northern Siberia

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Abstract – Carbonate-rich sedimentary rocks of the western Anabar region, northern Siberia, preserve an exceptional record of evolutionary and biogeochemical events near the Proterozoic/Cambrian boundary. Sedimentologically, the boundary succession can be divided into three sequences representing successive episodes of late transgressive to early highstand deposition; four parasequences are recognized in the sequence corresponding lithostratigraphically to the Manykai Formation. Small shelly fossils are abundant and include many taxa that also occur in standard sections of southeastern Siberia. Despite this coincidence of faunal elements, biostratigraphic correlations between the two regions have been controversial because numerous species that first appear at or immediately above the basal Tommotian boundary in southeastern sections have first appearances scattered through more than thirty metres of section in the western Anabar. Carbon- and Sr-isotopic data on petrographically and geochemically screened samples collected at one- to two-metre intervals in a section along the Kotuikan River, favour correlation of the Staraya Reckha Formation and most of the overlying Manykai Formation with sub-Tommotian carbonates in southeastern Siberia. In contrast, isotopic data suggest that the uppermost Manykai Formation and the basal 26 m of the unconformably overlying Medvezhya Formation may have no equivalent in the southeast; they appear to provide a sedimentary and palaeontological record of an evolutionarily significant time interval represented in southeastern Siberia only by the sub-Tommotian unconformity. Correlations with radiometrically dated horizons in the Olenek and Kharaulakh regions of northern Siberia suggest that this interval lasted approximately three to six million years, during which essentially all 'basal Tommotian' small shelly fossils evolved.

1. Introduction

During the past three decades, the general pattern of Early Cambrian faunal succession has been established (Rozanov *et al.* 1969; Qian & Bengtson, 1989; Repina & Rozanov, 1992; Lipps & Signor, 1992); however, the biostratigraphic detail necessary for precise interbasinal correlation remains a subject for debate, especially for the uppermost part of the Vendian System and the lowermost Cambrian Nemakit-Daldynian and Tommotian stages. Traditionally, the correlation of Proterozoic/Cambrian boundary successions has centered on skeletonized invertebrates, especially archaeocyathids and the small shelly fossils (SSF) common in carbonate facies, but problems of taxonomy, taphonomy and facies control hamper biostratigraphic interpretation (Rozanov, 1982; Qian & Bengtson, 1989; Repina & Rozanov, 1992; Landing, 1992; Khomentovsky & Karlova, 1993, 1994). In the absence of unambiguous global zonation and correlations, a detailed reconstruction of evolutionary pattern during the early part of the Cambrian explosion remains beyond our grasp.

Given continuing disagreement about zonation and correlations and the need of a framework for ordering evolutionary events that is independent of the organisms under consideration, there has been growing interest in additional means of correlating latest Proterozoic and basal Cambrian successions. Trace fossils have loomed large in some zonations, especially in siliciclastic successions (Crimes, 1987; Narbonne & Myrow, 1988; Fedonkin, 1990), and ichnostratigraphy attained critical importance in the choice of a global stratotype section and point (GSSP) for the initial boundary of the Cambrian Period (Narbonne *et al.* 1987; Landing, 1994; Brasier, Cowie & Taylor, 1994). Although trace fossils are made by metazoans, the animals that make them are not well represented by skeletons. Thus, terminal Proterozoic/basal Cambrian zonation based on ichnofaunal succession fulfills the criterion of essential independence from the SSF record; however, early ichnofossils share with skeletons unresolved problems of taxonomy, taphonomy and facies dependence.

Acritarchs diversified across the Proterozoic/Cambrian boundary in concert with invertebrates, providing the potential for a biostratigraphic zonation that is truly independent of animal fossils (Volkova, 1968; Volkova *et al.* 1979, 1983; Moczydłowska, 1991). Basal Cambrian acritarch zones were developed in siliciclastic succes-
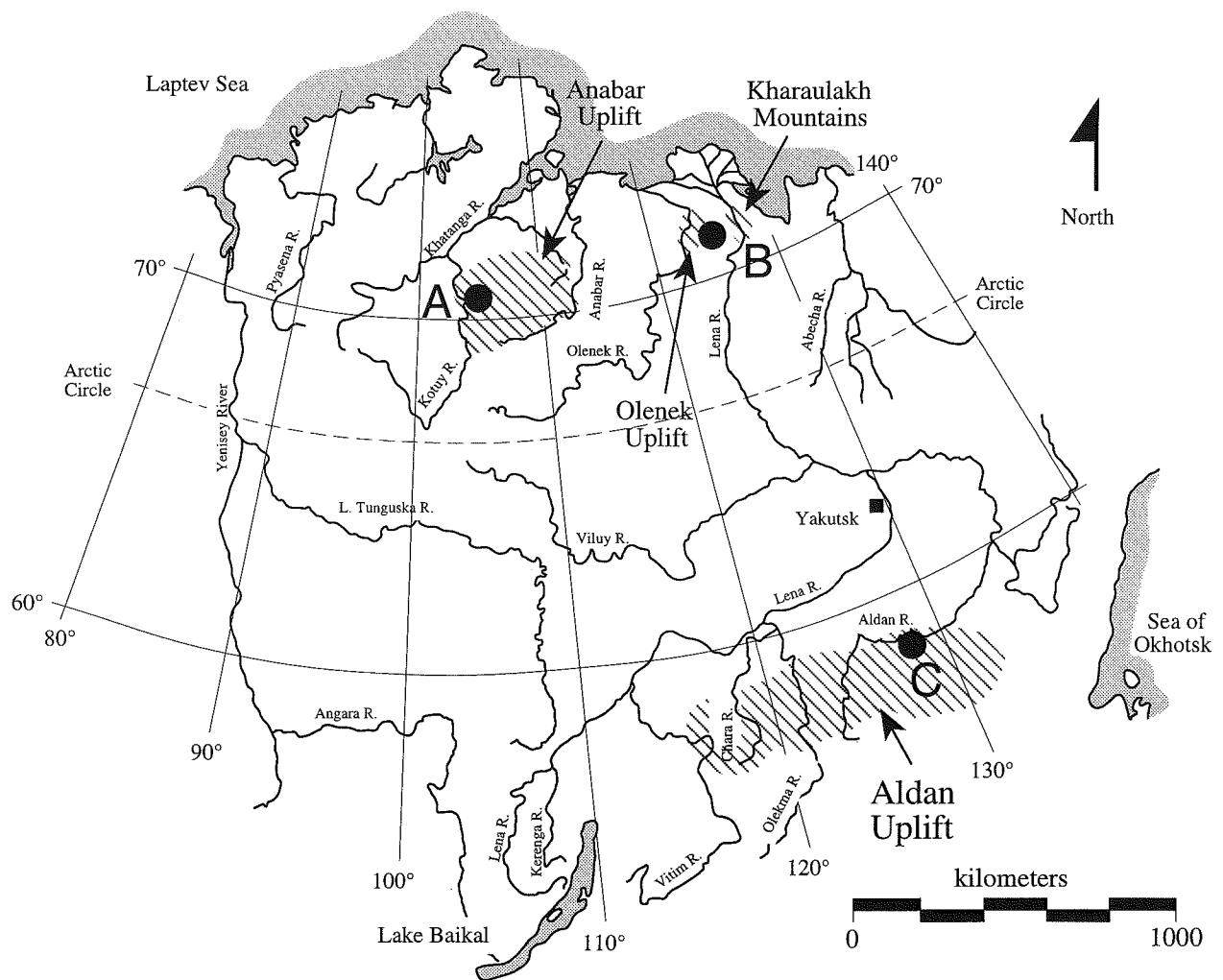
Figure 1. Map showing the locations of successions mentioned in the text. A denotes the Kotuikan River section; B marks the Olenek Uplift section measured along the Khorbusuonka River (site of the U–Pb date on a basal Nemakit-Daldyn volcanic breccia reported by Bowring *et al.* 1993); C marks the basal Tommotian stratotype section and point.

sions of the East European Platform, but they have been difficult to apply in the carbonate-dominated standard sections of the Lower Cambrian in Siberia, where acritarchs occur sporadically and, with few exceptions, display limited diversity (Rozanov *et al.* 1969). Recent discoveries of diverse Early Cambrian acritarchs in Siberian sections point the way toward interfacies correlation (Vidal, Moczydłowska & Rudavskaya, 1995). Palaeomagnetic reversal stratigraphy may also prove important in boundary correlations (e.g. Kirschvink *et al.* 1991), but available data are limited.

Chemostratigraphy based on the isotopic compositions of carbon and (to a lesser extent) strontium in marine carbonates has been shown to be effective in the correlation of terminal Proterozoic (Kaufman & Knoll, 1995, and references cited therein) and Early Cambrian (Kirschvink *et al.* 1991; Magaritz *et al.* 1991; Brasier, Khomentovsky & Corfield, 1993; Brasier *et al.* 1994b) carbonate-bearing successions. Given their amplitude and repeated occurrence, C-isotopic excursions, in particular, show great potential for resolving important questions of correlation

among successions that document the initial diversification of animals. Reliable stratigraphic (or biogeochemical) interpretation of isotopic data requires that samples be collected at small stratigraphic intervals and evaluated using a battery of petrographic and geochemical techniques designed to detect diagenetic alteration. In the absence of such tests, the relationship between measured isotopic abundances and depositional values that have stratigraphic significance cannot be known. The problem is significant in terminal Proterozoic successions (Kaufman & Knoll, 1995) and is exacerbated in Cambrian carbonates, which are bioturbated and contain skeletons not necessarily precipitated in isotopic equilibrium with sea-water (Grant, 1992). Because the terminal Proterozoic and Early Cambrian C-isotopic record contains repeated excursions of broadly similar magnitude, chemostratigraphic interpretation must be anchored by biostratigraphy.

The terminal Proterozoic/basal Cambrian section exposed along the Kotuikan River in the Anabar Uplift, northern Siberia, provides a good test of the capacity of

isotopic data to resolve problems of boundary-interval correlation (Fig. 1). This largely carbonate section preserves an exceptionally complete sedimentary record of terminal Proterozoic (Upper Vendian) and basal Cambrian time, contains diverse SSF assemblages, includes the stratotype of the pre-Tommotian Nemakit-Daldynian Stage, was never deeply buried (based on the colour of organic-walled microfossils), and can be correlated by means of bio-, chemo- and lithostratigraphy to other northern Siberian sections that contain well-dated volcanic rocks (Bowring *et al.* 1993). The western Anabar section has also played an important role in the development of the concept of the Yudomian as the Siberian correlative of the Vendian System (Zhuravleva & Komar, 1962; Komar, 1966; Semikhatov, Komar & Serebryakov, 1970).

Despite these features, divergent correlations have been proposed between the western Anabar and the type sections of the Yudomian, Tommotian and Atdabanian intervals in southeastern Siberia. SSFs have been used to support three strikingly different placements of the Nemakit-Daldynian/Tommotian boundary within the Anabar succession (see Section 3.b), and the pre-Tommotian succession in this region has variously been correlated with the whole type Yudomian or a limited part of the Upper Yudomian (Komar, 1966; Rozanov *et al.* 1969; Semikhatov, Komar & Serebryakov, 1970; Savitsky, 1975; Khomentovsky, 1976, 1986; Shishkin, 1978; Rozanov, 1982; Semikhatov & Serebryakov, 1983; Khomentovsky & Karlova, 1992, 1994). These differing correlations have important implications for the chronostratigraphic resolution of Proterozoic/Cambrian boundary beds and, hence, for understanding both Siberian basin development and the early evolution of animals.

Reconnaissance C-isotopic data for the Anabar succession were published by Pokrovsky & Vinogradov (1991) and Pokrovsky & Missarzhevsky (1993); stratigraphic sampling intervals are large, and isotopic determinations were made on whole-rock samples unsupported by geochemical or petrographic data. During a joint expedition in 1992, we measured and sampled the well-studied section near the mouth of the Kotuikan River. Previously, we reported preliminary C-isotopic data and interpretations (Knoll *et al.* 1995*b*). Here we present new lithostratigraphic data and sequence stratigraphic interpretations, details of C- and Sr-isotopic analyses, and a discussion of the chronostratigraphic implications of integrated sequence stratigraphic, palaeontological and chemostratigraphic data.

2. Lithostratigraphy and sequence stratigraphy

2.a. Staraya Rechka Formation

Along the Kotuikan River, the Staraya Rechka Formation is approximately 40 m thick (Fig. 2). Separated from underlying Riphean units by an angular unconformity (Komar, 1966; Khomentovsky, 1986, 1990), the formation comprises a lithologically complex interleaving of peritidal to shallow subtidal dolostones, evaporites and siliciclastic beds, with no evidence of cyclicity. The formation begins with 0–15 cm of laterally discontinuous carbonate–pebble conglomerate and minor quartz sandstone (Fig. 2, section 4), overlain successively by stromatolitic dolostone and laminated to rippled dolosiltite and dololutite that grade upward into oolitic grainstone. A small fault juxtaposes rippled dololutite in the hanging wall against the ooid grainstones in the footwall (Fig. 2, sections 3 and 4). The dolosilites are succeeded, in turn, by thickly laminated dololutite containing abundant nodules and lozenge-shaped moulds filled with gypsum (Fig. 2, section 3), capped by ooid grapestone/packstone with small, symmetrical stromatolites and ripple cross-lamination.

The middle part of the formation consists of interbedded green shale and shaley dololutite, rippled dolosiltite, stromatolitic dolostone and rare quartz sandstone (Fig. 2, section 2). These beds additionally contain an unusual facies consisting of massive dololutite that forms thin beds with tops characterized by 'ridge and furrow' structures. In plan view, these closely resemble strongly elongate stromatolites (see, e.g. Hoffman, 1974), but they show no evidence of lamination in cross-section. Their origin is unclear. The upper Staraya Rechka Formation contains a thick unit of stromatolites overlain by microbially laminated dolostone, a 4 m unit of massive dololutite containing 'ridge and furrow' structures, and massive dololutite containing abundant gypsum pseudomorphs (Fig. 2, sections 1 and 2).

The Staraya Rechka Formation is interpreted to represent a range of shallow, restricted subtidal to intertidal depositional environments. The presence of evaporites, abundant fine carbonate and siliciclastic sediments, and general lack of stromatolite elongation all support deposition in shallow water devoid of strong currents (Grotzinger, 1986). The presence of thin oolitic beds is consistent with this interpretation; in modern settings like the Persian Gulf, oolites form in restricted peritidal environments where currents are just strong enough to entrain the grains (Freeman, 1962). The Staraya Rechka oolites formed in protected, shallow epicratonic seas located far from the margins of the Siberian craton, in environments of negligible depositional slope. Water depth probably never exceeded a few metres, and the seascape was likely a complex mosaic of shoals and intervening broad lagoons similar to modern Florida Bay (Enos & Perkins, 1979).

2.b. Manykai Formation

The Manykai Formation is 88 m thick along the north bank of the Kotuikan River (Fig. 3). In general, the formation comprises a basal interval of mixed siliciclastic and carbonate rocks that grades upward into relatively pure limestones (and uncommon dolostones). The entire formation is interpreted as a single depositional sequence, bounded by unconformities that coincide with prominent flooding surfaces. The sequence has been sub-
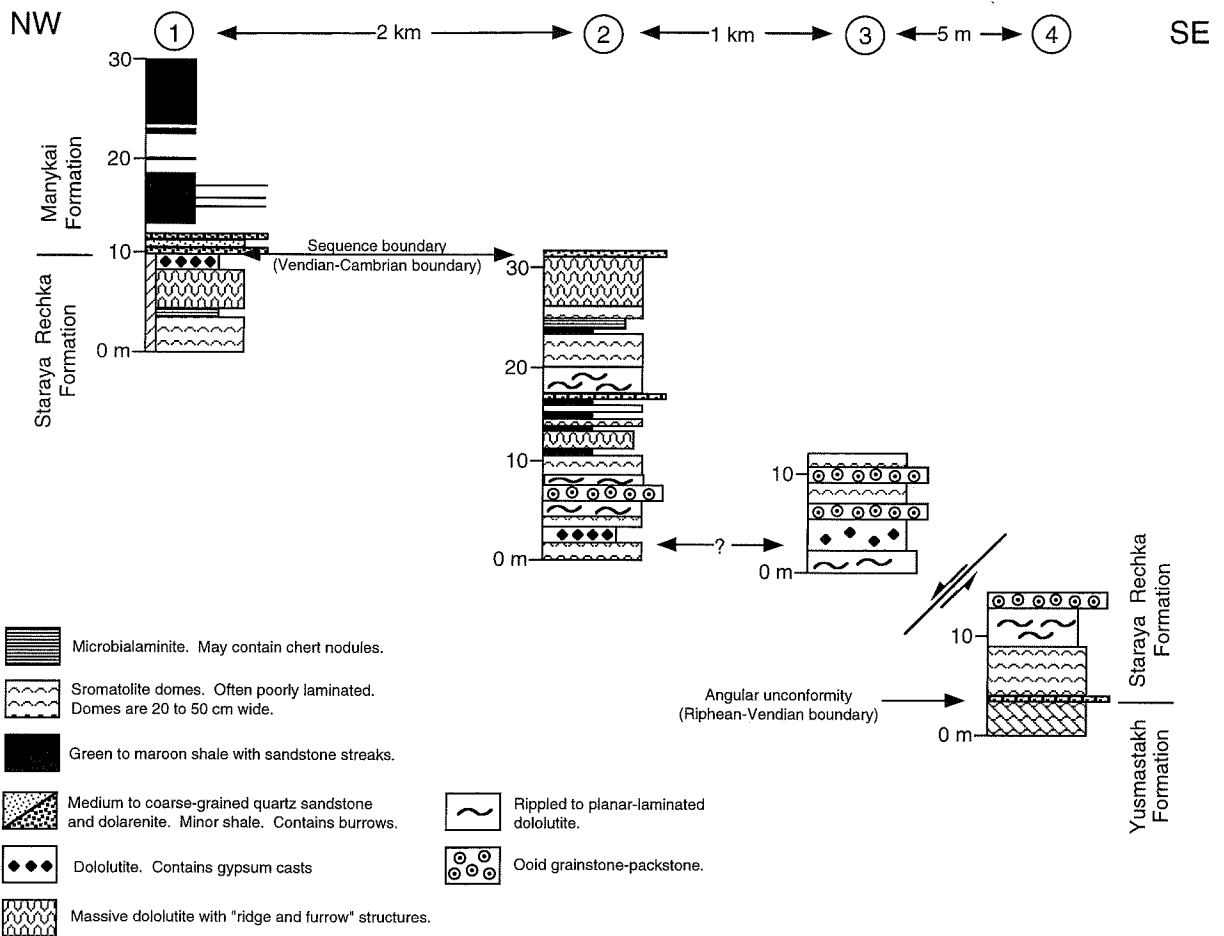
Figure 2. Stratigraphic sections of the Staraya-Rechka Formation along the Kotuikan River. Question mark denotes an uncertainty of c. ± 2 m in correlation between sections 2 and 3.

divided into four parasequences defined by systematic changes in facies and the partitioning of siliciclastic detritus (Fig. 4).

Parasequence 1 (22 m, Fig. 4) contains a basal unit (1.8 m) of medium- to coarse-grained sandstone interbedded with minor shale, dolarenite and microbial laminite (= Bed I of Khomentovsky & Trofimov, 1980; see also Khomentovsky, 1990). A middle unit, which coincides with Khomentovsky & Trofimov's Bed II, comprises 18 m of variegated shale with thin beds and lenses of glauconitic sandstone or dolosiltite in the lower third of the unit. The upper unit (2 m thick; = basal Bed III of Khomentovsky & Trofimov, 1980) is a distinctive interval of ripple-laminated calcarenite and calcisiltite that grades upward into trough cross-bedded *Anabarites* grainstone/packstone. The base of the grainstone has scoured relief of up to 50 cm. Parasequence 1 is interpreted as a late transgressive or early highstand system tract.

Siliciclastic sediments form only a minor component of parasequence 2 (24 m; Fig. 3). A basal 5 m unit consists of thin-bedded lime mudstone and calcisiltite, with abundant flat-pebble and edgewise conglomerate. The unit is bioturbated, and its upper part contains nodules

developed as diffuse zones of early diagenetic cement around individual burrows. A middle unit, 6 m thick, comprises a heterogeneous assemblage of interstratified grey shales and thin-bedded lime mudstones. Carbonates contain distinct beds with quasi-planar to hummocky stratification; the bases of these beds may contain intraclasts or resedimented nodules developed as lag deposits. An upper unit, 13 m thick (Khomentovsky & Trofimov's Bed IV), is dominated by thick-laminated to thin-bedded calcisiltite and calcarenite with ripple- and small-scale hummocky cross-stratification. Trough cross-bedding is locally developed. As in parasequence 1, the basal unit of parasequence 2 is interpreted as a transgressive unit deposited during progressive deepening, as shown by the upward increase in shale layers and glauconite. The middle unit records maximum submergence, with mixed shale–carbonate deposition, followed in the upper part by progradation and shallowing to above wave base. These facies are identical to Middle and Upper Cambrian 'ribbon' limestones described from shallow subtidal depositional settings (Demicco, 1983; Markello & Read, 1981).

Parasequence 3 (20 m) begins with a 3.5 m unit of wavy-bedded lime mudstone with thin shale seams that decrease in abundance upward. Thrombolitic bioherms
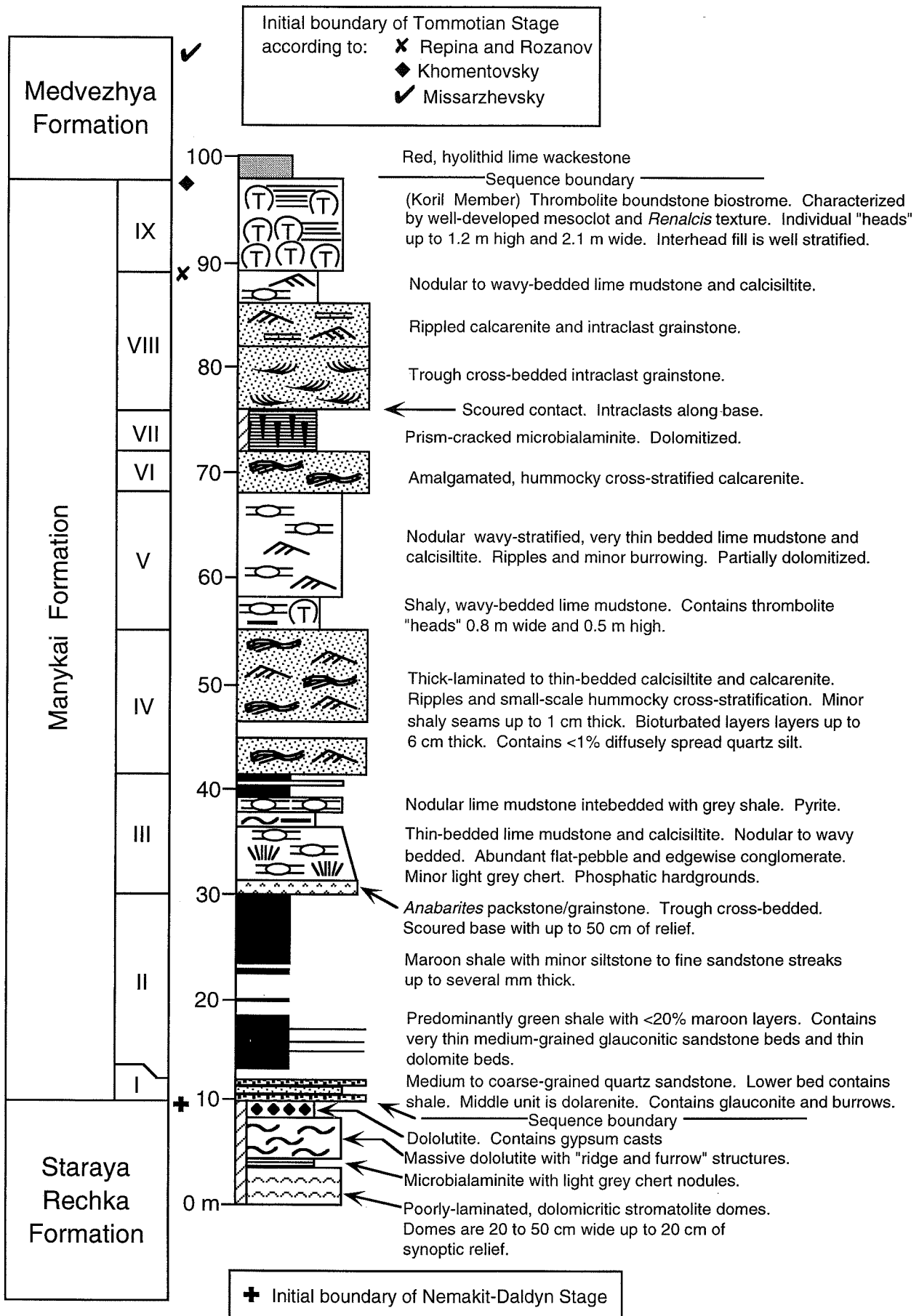
Initial boundary of Tommotian Stage
according to: ✗ Repina and Rozanov
◆ Khomentovsky
✔ Missarzhevsky

Medvezhya Formation

Manykai Formation

Staraya Rechka Formation

IX
VIII
VII
VI
V
IV
III
II
I

100
90
80
70
60
50
40
30
20
10
0 m

Red, hyolithid lime wackestone
———————Sequence boundary———————
(Koril Member) Thrombolite boundstone biostrome. Characterized by well-developed mesoclot and *Renalcis* texture. Individual "heads" up to 1.2 m high and 2.1 m wide. Interhead fill is well stratified.

Nodular to wavy-bedded lime mudstone and calcisiltite.

Rippled calcarenite and intraclast grainstone.

Trough cross-bedded intraclast grainstone.

◄——— Scoured contact. Intraclasts along base.
Prism-cracked microbialaminite. Dolomitized.

Amalgamated, hummocky cross-stratified calcarenite.

Nodular wavy-stratified, very thin bedded lime mudstone and calcisiltite. Ripples and minor burrowing. Partially dolomitized.

Shaly, wavy-bedded lime mudstone. Contains thrombolite "heads" 0.8 m wide and 0.5 m high.

Thick-laminated to thin-bedded calcisiltite and calcarenite. Ripples and small-scale hummocky cross-stratification. Minor shaly seams up to 1 cm thick. Bioturbated layers layers up to 6 cm thick. Contains <1% diffusely spread quartz silt.

Nodular lime mudstone intebedded with grey shale. Pyrite.

Thin-bedded lime mudstone and calcisiltite. Nodular to wavy bedded. Abundant flat-pebble and edgewise conglomerate. Minor light grey chert. Phosphatic hardgrounds.

Anabarites packstone/grainstone. Trough cross-bedded. Scoured base with up to 50 cm of relief.

Maroon shale with minor siltstone to fine sandstone streaks up to several mm thick.

Predominantly green shale with <20% maroon layers. Contains very thin medium-grained glauconitic sandstone beds and thin dolomite beds.

Medium to coarse-grained quartz sandstone. Lower bed contains shale. Middle unit is dolarenite. Contains glauconite and burrows.
—————————Sequence boundary —————————
Dololutite. Contains gypsum casts
Massive dololutite with "ridge and furrow" structures.
Microbialaminite with light grey chert nodules.
Poorly-laminated, dolomicritic stromatolite domes. Domes are 20 to 50 cm wide up to 20 cm of synoptic relief.

✚ Initial boundary of Nemakit-Daldyn Stage

Figure 3. Lithostratigraphy of the Manykai Formation section exposed along the north bank of the Kotuikan River, *c.* 1 km above its confluence with the Kotui River. Roman numerals mark the Beds defined by Khomentovsky & Trofimov (1980; see also Khomentovsky, 1990).
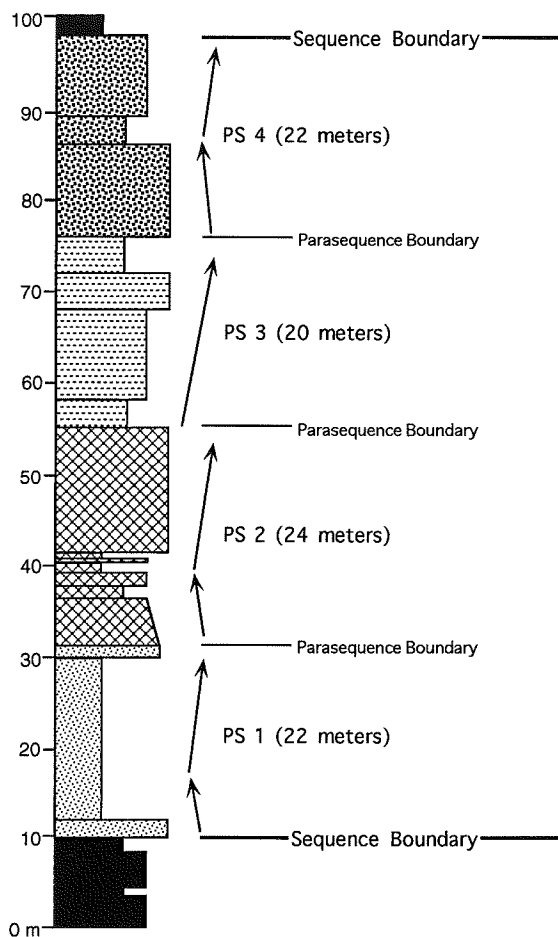
Figure 4. Sequence stratigraphic interpretation of the Manykai Formation, showing the four parasequences identified within the sequence corresponding lithostratigraphically to the formation.

Figure 5. Lithostratigraphy of Medvezhya carbonates sampled in exposures along the Kotuikan River.

are present in the upper part of the unit (Luchinina, 1989). A second unit, 10 m thick, consists of nodular to wavy stratified, thin-bedded lime mudstone and calcisiltite. Current and wave-ripple cross-stratification is well developed, and scattered burrows are present. The unit is partially replaced by fine-grained dolomite. The first two units correspond to Bed V of Khomentovsky & Trofimov (1980), while the third unit, an amalgamated, metre-scale hummocky cross-stratified calcarenite, coincides with Bed VI. The uppermost unit (= Khomentovsky and Trofimov's Bed VII) consists of prism-cracked, microbially laminated dololutite. This parasequence is systematically different from the underlying intervals in that it contains very little siliciclastic detritus, is depositionally asymmetric (lacks transgressive deposits), and shows evidence of shallowing completely to sea-level. The lack of any indicators of extreme exposure (e.g. tepees, karst) is consistent with regional platform aggradation in a highstand system tract.

The uppermost parasequence (parasequence 4; 22 m) contains no siliciclastic rocks. A basal 10 m unit consists predominantly of intraclast grainstone, overlying a well-
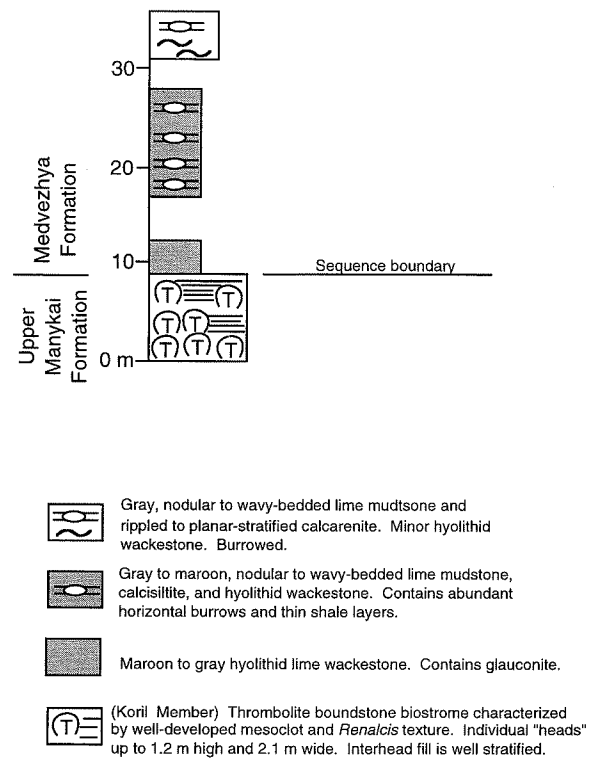
developed scoured base. Fine- to medium-grained calcarenites are interstratified with coarser grainstones toward the top. The lower half of the unit is dominated by trough cross-bedding, which is replaced by ripple cross-stratification in the upper half. This grades up into a second unit (4 m) of nodular to wavy-bedded lime mudstone and calcisiltite. The uppermost unit comprises a distinctive thrombolitic boundstone biostrome (8 m) known as the Koril Member (Bed IX). Thrombolitic textures consist of well-developed mesoclots associated with *Renalcis* (Luchinina, 1989). Where not amalgamated, bioherms are separated by well-stratified calcarenite and intraclast grainstone. The top of parasequence 4 is marked by a sharp contact with the overlying Medvezhya Formation.

The abundance of grainstone in parasequence 4 suggests deposition in broad shoals swept by strong daily currents (Hine, Wilber & Neumann, 1981). The lower unit gives way to finer-grained sediments of the middle unit, although deposition is still inferred to have taken place in relatively shallow subtidal conditions, as shown by the abundance of symmetrical, wave-produced ripples (de Raaf, Boersma & Van Gelder, 1977). Shallowing is supported by the development of the massive, thrombolite biostrome at the top of the parasequence. The sharp contact at the top of parasequence 4 is interpreted as a sequence boundary and flooding surface.

Overall, the Manykai Formation is interpreted as a single, unconformity-bounded depositional sequence con-

taining four aggradationally-stacked parasequences. Late transgressive to early highstand deposition is favoured by: (1) the lack of systematic changes in parasequence thickness that would accompany long-term changes in accommodation rate; (2) the depositional symmetry in three of the four parasequences, which indicates that parasequence-scale flooding events were not amplified by high long-term accommodation rates; and (3) the absence of tidal flat sediments in three of the four parasequences and/or indicators of subaerial exposure along parasequence boundaries. Finally, late transgressive to early highstand deposition is supported by the upward decrease in the quantity of siliciclastic detritus, which supports progressive coastal onlap.

The unconformable relationship between the Manykai and Staraya Rechka formations, interpreted as a type-II sequence boundary, is regional, extending at least as far as the eastern Anabar Uplift (Khomentovsky, 1990). In contrast, local evidence (exposures along the Kotuikan River) for a sequence boundary at the top of the Manykai Formation is less dramatic. Identification of these surfaces in carbonate-dominated strata typically depends on (1) interpretation of parasequence stacking patterns (Grotzinger, 1986; Montanez & Osleger, 1993; Read *et al.* 1986), (2) the presence of indicators of subaerial exposure (Montanez, 1992), and (3) the juxtaposition of palaeoenvironmentally discordant facies (Sarg, 1988). Along the Kotuikan River, the upper boundary of the Manykai Formation lacks strong indications of subaerial exposure; the actual contact is sharp, but no evidence of karst, mouldic porosity or brecciation is seen (Fig. 5). Here, red hyolithid wackestones and mudstones of the basal Medvezhya Formation – which lack evidence for frequent current activity – are juxtaposed against grey, thrombolite biostromes and associated well-stratified, channel grainstones. This suggests a significant flooding event at the top of the Manykai Formation and, at least, a type-II unconformity (cf. Sarg, 1988). Regional observations (Fedorov & Shishkin, 1984; Missarzhevsky, 1989) show that the Medvezhya Formation and its equivalents form a transgressive blanket over the entire Anabar region, systematically overstepping older strata on the northern slope of the Anabar Uplift. For this reason, we interpret the Manykai/Medvezhya contact as a regionally-extensive type I unconformity (cf. Sloss, 1963).

2.c. The Medvezhya Formation

In our measured section, typical Medvezhya strata comprise 28 m of monotonous, maroon to mauve, argillaceous, fossiliferous lime mudstone and wackestone. Locally, SSFs are abundant enough to form packstone lags. Bioturbation is characteristic, and large, simple, bedding-parallel traces are particularly common. These strata represent deposition on an open, shallow-marine carbonate platform. The considerable bioturbation prevents detailed analysis of fairweather stratification, but it

is likely that storms resulted in significant reworking of the sea-floor such that fossils were concentrated as lag deposits by winnowing. The Medvezhya Formation represents regional onlap of the Anabar platform, following possible subaerial exposure at the top of the Manykai Formation. Medvezhya carbonates probably accumulated during a highstand in relative sea-level.

Elsewhere in the western Anabar region, comparable Medvezhya facies are up to 60 m thick (Missarzhevsky, 1989), but in our measured section, sugary, yellow dolostones occur above the 28 m mark. These dolostones are conventionally assigned to the Kyndyn Formation, but Missarzhevsky (1989) shows that they are a regionally variable product of facies and diagenetic change that truncates Medvezhya limestones at different levels in different locations (see also Khomentovsky & Karlova, 1992). It is, thus, hazardous to think of the Medvezhya–Kyndyn boundary as a time horizon that can be correlated even locally. In the following discussion, we locate fossiliferous and isotopically important horizons in terms of their vertical distance above the base of the Medvezhya Formation.

3. Biostratigraphy

Palaeontological investigations over a period of thirty years have provided detailed data on faunal distributions within the Manykai and Medvezhya formations (see references in Missarzhevsky, 1989; Repina & Rozanov, 1992; Khomentovsky & Karlova, 1992, 1993, 1994). Critical monographic accounts are not yet available for all of these assemblages, but the present discussion only requires taxonomic consistency between regions.

Khomentovsky & Karlova (1992, 1993) listed the occurrences of 86 invertebrate taxa found regionally in the western Anabar succession[1]. Of these, 65 occur in southeastern Siberian sections, including the Tommotian stratotype. Figure 6 shows the first appearances of these taxa in the western Anabar, along with the zone in which they first occur in the Aldan and/or Uchuro-Maya regions and the summary biostratigraphic interpretations of Khomentovsky & Karlova (1992, 1993), Repina & Rozanov (1992) and Missarzhevsky (1989).

All parties agree that the lower Manykai Formation should be assigned to the pre-Tommotian *Anabarites trisulcatus* zone. There is also agreement that Medvezhya lithologies extend as high as the Atdabanian *Pagetiellus anabarus* zone some 70 m above the base of the formation in sections along the Fomich River, 150 km northeast of our field area. Regionally, trilobites and archaeocyathans indicate that Atdabanian strata begin 40–45 m above the Manykai/Medvezhya boundary – well above

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[1] Khomentovsky & Karlova (1994) also provide species lists for the eastern Anabar region, but as these are ordered by zone and not by position within measured sections, they comprise biostratigraphic *interpretations* and cannot be plotted in the same manner as faunal distributions in the western Anabar region and southeastern Siberia.
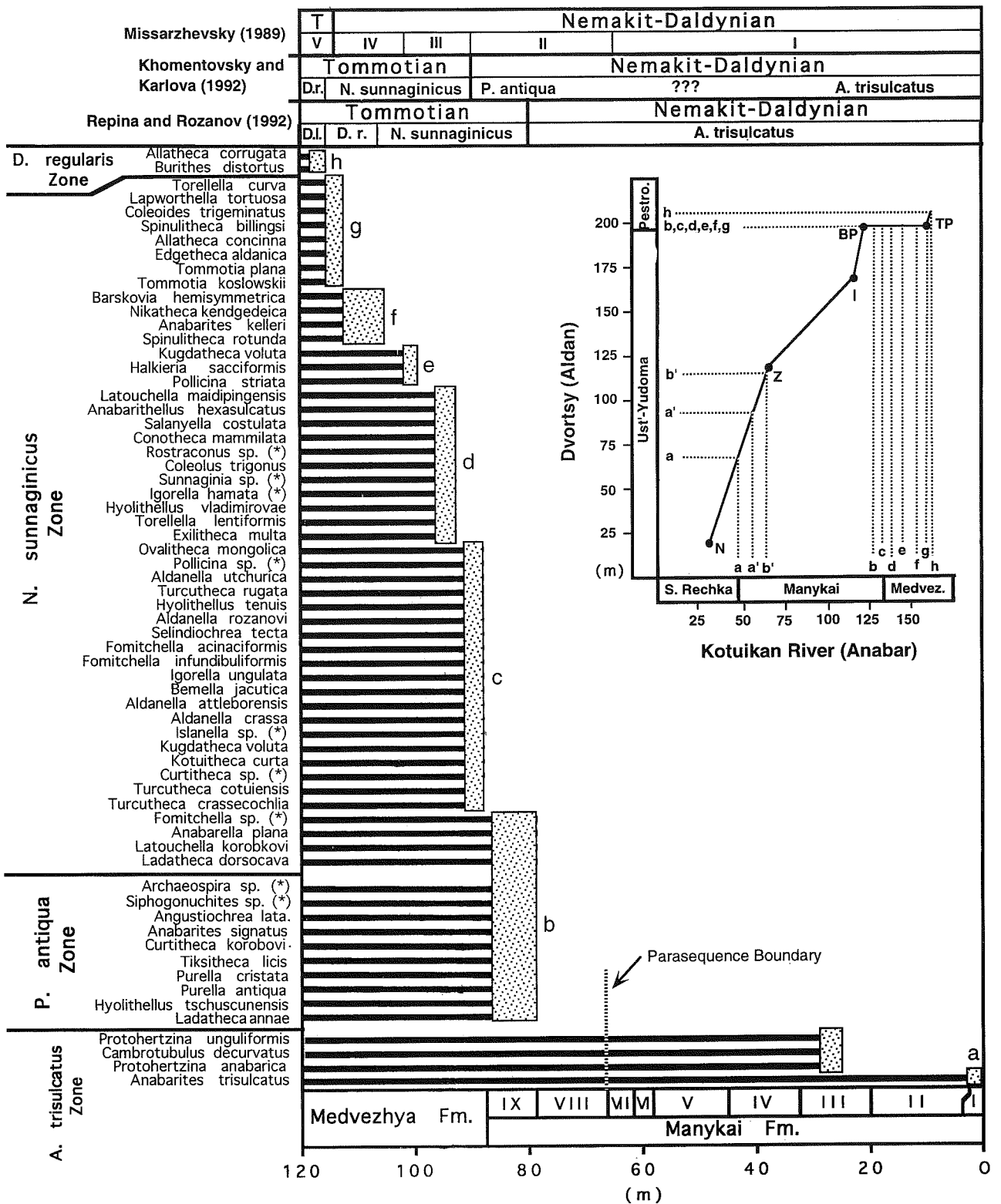
	Nemakit-Daldynian				
Missarzhevsky (1989) T / V	IV	III	II	I

Khomentovsky and Karlova (1992)

Tommotian		Nemakit-Daldynian	
D.r.	N. sunnaginicus	P. antiqua	???	A. trisulcatus

Repina and Rozanov (1992)

Tommotian		Nemakit-Daldynian
D.l.	D. r.	N. sunnaginicus	A. trisulcatus

D. regularis Zone

Allatheca corrugata
Burithes distortus
Torellella curva
Lapworthella tortuosa
Coleoides trigeminatus
Spinulitheca billingsi
Allatheca concinna
Edgetheca aldanica
Tommotia plana
Tommotia koslowskii
Barskovia hemisymmetrica
Nikatheca kendgedeica
Anabarites kelleri
Spinulitheca rotunda
Kugdatheca voluta
Halkieria sacciformis
Pollicina striata
Latouchella maidipingensis
Anabarithellus hexasulcatus
Salanyella costulata
Conotheca mammilata
Rostraconus sp. (*)
Coleolus trigonus
Sunnaginia sp. (*)
Igorella hamata (*)
Hyolithellus vladimirovae
Torellella lentiformis
Exilitheca multa
Ovalitheca mongolica
Pollicina sp. (*)
Aldanella utchurica
Turcutheca rugata
Hyolithellus tenuis
Aldanella rozanovi
Selindiochrea tecta
Fomitchella acinaciformis
Fomitchella infundibuliformis
Igorella ungulata
Bemella jacutica
Aldanella attleborensis
Aldanella crassa
Islanella sp. (*)
Kugdatheca voluta
Kotuitheca curta
Curtitheca sp. (*)
Turcutheca cotuiensis
Turcutheca crassecochlia
Fomitchella sp. (*)
Anabarella plana
Latouchella korobkovi
Ladatheca dorsocava

N. sunnaginicus Zone

Archaeospira sp. (*)
Siphogonuchites sp. (*)
Angustiochrea lata.
Anabarites signatus
Curtitheca korobovi·
Tiksitheca licis
Purella cristata
Purella antiqua
Hyolithellus tschuscunensis
Ladatheca annae

P. antiqua Zone

Protohertzina unguliformis
Cambrotubulus decurvatus
Protohertzina anabarica
Anabarites trisulcatus

A. trisulcatus Zone

Medvezhya Fm.	IX	VIII	VII	VI	V	IV	III	II	I
	Manykai Fm.								

120   100   80   60   40   20   0
(m)

Inset (Shaw-type diagram):

Dvortsy (Aldan) — Pestro. / Ust'-Yudoma
200 — h / b,c,d,e,f,g ... BP / TP
175 — I
125 — b'
100 — a'
75 — a
N
(m)

a a'b'   b d f h
c e g

S. Rechka | Manykai | Medvez.
25   50   75   100   125   150

Kotuikan River (Anabar)

Parasequence Boundary

Figure 6. Stratigraphic first appearances in the western Anabar region for taxa that also occur in southeastern Siberia (after Khomentovsky & Karlova, 1992, 1993). Zone of first appearance in southeastern Siberia is shown on the left; all taxa listed as occurring in the N. sunnaginicus Zone have regional first appearances in the southeast that coincide with basal Tommotian onlap. Boxes show interval of first appearance in the western Anabar succession; black lines indicate that taxa persist into younger rocks, though they may not have western Anabar occurrences throughout their known stratigraphic ranges. Biostratigraphic interpretations of Missarzhevsky (1989), Khomentovsky & Karlova (1992, 1993) and Repina & Rozanov (1992) are shown across the top. The inset shows a Shaw-type diagram of the Kotuikan River and composite southeastern Siberia sections. N, Z, and I are named C-isotopic peaks (Brasier, Khomentovsky & Corfield, 1993), as discussed in the text; BP and TP are, respectively, the bottom and top of the Kotuikan interval interpreted as corresponding to the sub-Tommotian unconformity; a and a' indicate first appearances of A. trisulcatus Zone faunas in southeastern Siberia and the western Anabar, respectively; b and b' indicate the first appearance of P. antiqua Zone faunas in southeastern Siberia and the western Anabar, respectively (with projections onto the other section); c–h indicate the successive horizons at which taxa that first appear in basal Tommotian strata in southeastern Siberia are introduced in the western Anabar area (see main part of diagram); i indicates the first appearance of Burithes distortus, considered an index for the Tommotian D. regularis Zone. Southeastern Siberian data from Khomentovsky & Karlova (1992, 1993), Repina & Rozanov (1992), and Brasier, Khomentovsky & Corfield (1993).

the top of the interval considered in this paper (Repina & Rozanov, 1992; Khomentovsky & Karlova, 1992). In the intervening part of the succession, there is disagreement about placement of the Nemakit-Daldynian/Tommotian boundary and the zonation of boundary beds by means of SSFs (Fig. 6).

Calcified microbes, a limited acritarch flora and scattered trace fossils also occur in the western Anabar succession (Luchinina, 1989; Volkova *et al.* 1980), but these do not resolve the problems raised by conflicting interpretations of the invertebrate record. Komar (1966), Golovanov (1970) and Semikhatov, Komar & Serebryakov (1970) used stromatolites in the broad correlation of Staraya Rechka carbonates with other Yudomian deposits, but microbialites do not provide good tests for more refined correlations of terminal Proterozoic rocks.

3.a. Biostratigraphic placement of the initial Tommotian boundary in the western Anabar region: logic

Any correlation proceeds from a fixed point, defined as a stratigraphic horizon in a type section, to sections distant from the stratotype. In Siberia, the initial boundary of the Tommotian Stage is defined by a point at the base of Bed 8 of the Ust'-Yudoma Formation in the Ulakhan Sulugur section along the Aldan River (Rozanov *et al.* 1969; Rozanov, 1984). This stratigraphic placement of the boundary is misleading, however; Khomentovsky, Valkov & Karlova (1990; Khomentovsky & Karlova, 1992) recognized that the glauconitic lenses in Bed 8 that contain basal Tommotian taxa are karst-filling sediments emplaced during subsequent Pestrotsvet transgression. Regionally, this topologically complex boundary surface (Semikhatov & Serebryakov, 1983, fig. 41; Khomentovsky & Karlova, 1993, figs 11, 12) coincides with the first appearance of a diverse invertebrate fossil assemblage. Some 30 taxa occur in lenses of fine-grained glauconitic carbonate that penetrate downward to Bed 8; an additional *c.* 70 species of archeocyathans and SSFs occur regionally in basal Pestrotsvet carbonates (Rozanov *et al.* 1969; Repina & Rozanov, 1992). In terms of time, then, more than 100 species appear more or less simultaneously in basal Tommotian rocks of southeastern Siberia.

These diverse skeletal assemblages are considered to typify the *Nochoroicyathus sunnaginicus* Zone (Rozanov *et al.* 1969; Rozanov, 1984; Repina & Rozanov, 1992; Khomentovsky & Karlova, 1992, 1993); however, the base of the Tommotian is not defined by these fossils, and their point of first appearance in a distant section does not by definition indicate precise correlation with the boundary in the stratotype. This consideration is especially important in the case of the Tommotian, because its definitional lower boundary is associated with a karsted unconformity and major facies change (Rozanov *et al.* 1969; Semikhatov & Serebryakov, 1983; Moczydłowska & Vidal, 1988; Khomentovsky & Karlova, 1992, 1993; Repina & Rozanov, 1992; Landing, 1994).

In the Aldan region, underlying Ust'-Yudoma strata are dominated by sugary dolostones that (with the exception of the glauconitic lenses of Bed 8 at Ulakhan Sulugur) contain only scattered occurrences of poorly-preserved SSFs in the uppermost few metres of the sections. Better fossil preservation is found in Ust'-Yudoma sections along the Uchur and Dzhanda rivers, some 100 km east of the Tommotian GSSP (Semikhatov & Serebryakov, 1983; Khomentovsky & Karlova, 1992, 1993, 1994), but most published sections for the region show *no* SSF occurrences in the *c.* 25 m immediately below basal Tommotian beds (Khomentovsky & Karlova, 1993, 1994). Only along the Dzhanda and Selinde rivers do well-preserved SSFs occur within a few metres of the basal Tommotian (basal Pestrostvet) boundary, and these assemblages are of limited diversity (Khomentovsky & Karlova, 1992, 1993, 1994).

The 65 taxa that both (1) appear first at or near the base of the Tommotian in southern Siberia and (2) occur in the western Anabar have first appearances spread through more than 30 m of section in the latter (Fig. 6). Clearly, most taxa did not appear simultaneously in the two areas. If the clustered first appearances in southeastern Siberia are interpreted as a record of simultaneous evolution, then the base of the Tommotian in western Anabar can be no higher than the lowermost point of occurrence for any 'basal Tommotian' species. A necessary corollary of this view is that the stratigraphic coincidence, in the Aldan region, of massed fossil appearances, marked facies change, and subtending unconformity is fortuitous.

Biostratigraphic experience in better known parts of the geological record indicates that first appearances distributed through a more-or-less continuous section are more likely to approximate evolutionary pattern than are those clustered at a major facies change or unconformity (e.g. Shaw, 1964). Considering the sedimentological realities of southeastern Siberian sections, all that really can be said of the stratotype region is that when the first beds above the definitional boundary point of the Tommotian Stage accumulated, *all c.* 100 taxa that typify the *N. sunnaginicus* Zone were already present (Landing, 1994). In this view, the initial Tommotian boundary in western Anabar can be as high as the point at which the *last* 'basal Tommotian' taxon appears. (Note that this horizon is *c.* 25–27 m above the base of the Medvezhya Formation whether or not one considers the fossiliferous lenses in Ust'-Yudoma Bed 8 to be karst-fill; *Edgetheca aldanica*, *Coleoloides trigeminatus* and *Torellella curva* all have first appearances in Bed 8 lenses in the GSSP and > 25 m above the base of the Medvezhya Formation in the Kotuikan area (Fig. 6).)

Intermediate boundary placements are possible, but any such placement requires that one accept some taxa as having synchronous first appearances in the two regions while rejecting synchrony in others. This necessitates arbitrary assumptions about individual taxa that cannot be justified on the basis of existing palaeontological data.

3.b. Biostratigraphic placement of the initial Tommotian boundary in the western Anabar region: practice

In the Manykai–Medvezhya interval under consideration, Missarzhevsky (1989) recognized five SSF zones (Fig. 6). His lower two zones, encompassing the Manykai Formation, are approximately equivalent to the Nemakit-Daldynian *Anabarites trisulcatus* and *Purella antiqua* zones recognized by Khomentovsky & Karlova (1992, 1993); however, Missarzhevky (1989) considered that the Nemakit-Daldynian Stage includes two additional zones that extend upward 25–30 m into the Medvezhya Formation. He placed the beginning of the Tommotian Stage at the base of his zone V, marked, in his view, by the first appearance of 20 taxa. Many of the taxa that Missarzhevsky (1989) used to define the lower boundary of his zone V are now known to occur in the lower part of the Medvezhya Formation, where they are associated with other SSF taxa (Khomentovsky & Karlova, 1992, 1993). None the less, the initial Tommotian boundary favoured by Missarzhevsky (1989) corresponds to the point in the western Anabar section where the *last* taxa appear that mark the beginning of the Tommotian in its stratotype area.

Khomentovsky & Karlova (1992, 1993, 1994), in accordance with earlier publications by Khomentovsky, place the base of the Tommotian in western Anabar sections at the lower boundary of the Medvezhya Formation (Fig. 6). Basal Medvezhya beds contain diverse SSFs, most of which have been reported from the *N. sunnagini-cus* zone in Aldan and Uchuro-Maya sections. Although this correlation places the base of the Tommotian at the point in the western Anabar succession where the *most* 'basal Tommotian' taxa first appear, it marks neither the horizon at which the *first* 'basal Tommotian' fossils enter the record nor the point where the *last* ones appear.

Repina & Rozanov (1992) place the lower Tommotian boundary at the point where the first 'basal Tommotian' taxa appear – at the base of Manykai Bed IX (Fig. 6). Thus, as conceived by Repina & Rozanov (1992), the Tommotian in western Anabar includes strata placed in the Nemakit-Daldynian *Purella antiqua* Zone (or Zone II) by the preceding authors. Twenty-seven taxa have regional first appearances at this level (Khomentovsky & Karlova, 1993, 1994), and of these, 14 occur in southeastern Siberia (Fig. 6). Of those that occur in both regions, ten have first appearances in the south that underlie the basal Tommotian boundary by 25 m or more; four first appear in the southeast in lowermost type Tommotian beds (Repina & Rozanov, 1992; Khomentovsky & Karlova, 1993, 1994). Repina & Rozanov's (1992) preferred correlation receives logical support if the clustered first appearances in the Aldan region are interpreted as evolutionary first appearances unrelated to associated sedimentological changes.

Thus, the three divergent placements of the initial Tommotian boundary in western Anabar reflect the three logical possibilities outlined in the preceding section. Independent means of correlation are necessary to evaluate these alternatives.

3.c. A note on the Nemakit-Daldynian Stage

Savitsky (1962, 1975) was the first to delimit the Nemakit-Daldynian 'horizon' as 'the beds with small hyolithellids' that underlie diverse SSF assemblages in the basal Medvezhya Formation and regarded it as Early Cambrian in age. Later, Khomentovsky (1976) reconsidered the rank of that unit and described it as belonging to the Nemakit-Daldynian Stage, thus assigning it to the uppermost Vendian (Yudomina) in accordance with the view that the Tommotian was the first stage of the Cambrian System (see Rozanov & Sokolov, 1984, for references). No initial boundary stratotype has been formally defined, and the term has variously been used with reference to time (stage) or lithostratigraphy (horizon). Recent trends in the Russian literature lean towards regarding this unit as a stage.

In so far as the recently-defined base of the Cambrian Period appears to be significantly earlier than the beginning of the Tommotian Stage (see, e.g. Grotzinger *et al.* 1995), there is a recognized need to establish a pre-Tommotian basal Cambrian stage, and Nemakit-Daldynian has increasingly been pressed into service for this purpose. In Savitsky's original usage, the Nemakit-Daldynian 'horizon' was locally coextensive with the Manykai Formation; however, as a stage the Nemakit-Daldynian must be defined as beginning at a GSSP and ending at the defined initial boundary of the succeeding Tommotian Stage.

In this paper, we follow Savitsky's intent and subsequent convention in placing the initial boundary of the Nemakit-Daldynian Stage at the base of the Manykai Formation in the section sampled along the Kotuikan River. Here, the initial Nemakit-Daldynian boundary corresponds to the first appearance of SSFs of the *Anabarites trisulcatus* Zone (Savitsky, 1975; Khomentovsky, 1976; Missarzhevsky, 1989; Khomentovsky & Karlova, 1992, 1993). This does not necessarily mean, however, that the boundary can be recognized elsewhere by the lowermost occurrences of SSFs. Should the fossils be shown to occur earlier somewhere else – as they do in the Olenek region of northern Siberia (Karlova, 1987; Khomentovsky & Karlova, 1992, 1993; Knoll *et al.* 1995a; see also the placement of the lowermost SSFs in Iran and Kazakhstan by Brasier *et al.* 1990, fig. 1) – this does not change the definition of the boundary; it simply means that improved tools are necessary for precise correlation.

4. Chemostratigraphy of the western Anabar

4.a. Methods

Except where precluded by thick siliciclastic units, carbonate samples were collected at 1 m intervals throughout the Staraya Rechka and Manykai formations and at 2 m intervals through 28 m of the Medvezhya Formation. Samples were prepared, screened and analysed according to the procedures described in detail in Kaufman & Knoll (1995).

4.b. Elemental and oxygen-isotopic results

The results of elemental and oxygen-isotopic analyses of carbonate micro-samples are presented in Table 1. All Staraya Rechka carbonates are dolomites, and most have elevated Mn/Sr. Lower Staraya Rechka carbonates, in particular, are partially silicified and have very high Mn/Sr; C-isotopic compositions of these samples should be viewed with caution.

Manykai and Medvezhya carbonates are predominantly calcitic, although several samples in the interval between the top of Bed II and the upper Bed VII contain both calcite and dolomite. Within the upper formations, dolomitization is most pronounced immediately adjacent to thick shales or silty/intraclastic horizons. Siliciclastic horizons may have acted as fluid conduits, channelling diagenetic waters through the succession. Mn/Sr in the dolomitic samples is slightly higher than in adjacent calcites (which contain virtually no Mn and have very low Mn/Sr) and oxygen-isotopic compositions are altered to variable extent. There is, however, no systematic relationship between ^{18}O abundances (Table 1) and Mn/Sr or Mg/Ca in the Manykai carbonates. Evidently dolomitization did not result in the systematic resetting of $\delta^{18}O$ values of these limestones; indeed, with few exceptions, $\delta^{18}O$ values of the Kotuikan carbonates are remarkably constant. Manykai and Medvezhya carbonate $\delta^{18}O$ values are remarkably constant while Staraya Rechka dolomites are, on average, enriched in ^{18}O by 2 ‰.

On balance, the degree of alteration determined by elemental and O-isotopic compositions of carbonates in the Manykai and Medvezhya formations is minimal, suggesting that near primary $\delta^{13}C$ values are retained in most samples. Neither are skeletons abundant in these rocks, minimizing the possibility that 'vital effects' played a significant role in determining C-isotopic compositions (Grant, 1992). Moderately elevated Mn/Sr values (5–9) characterize a few dolostones, especially near the base of the section and in parasequence 3; however, experience elsewhere indicates that moderate Mn enrichment is not commonly associated with C-isotopic alteration (Derry, Kaufman & Jacobsen, 1992; Kaufman & Knoll, 1995; Knoll, Kaufman & Semikhatov, 1995). Moreover, stratigraphic trends in this interval are defined by samples that pass all of our screening tests. In the entire Manykai–Medvezhya interval, only four samples are marked by strong ^{18}O depletion; these are interpreted as altered and are not considered further.

4.c. Carbon-isotopic results

Carbon-isotopic data for the Anabar section are presented in Table 1 and shown graphically in Figure 7. As originally reported by Pokrovsky & Vinogradov (1991), $\delta^{13}C$ values for Staraya Rechka dolomites are consistently negative. Values in the lower 22 metres range between +0.1 and –2.9 ‰, above which they decrease to values as low as –5.7 ‰; these are the most ^{13}C-depleted carbonates in the entire section and, as noted in the previous sec-

tion, must be interpreted with caution. However, less altered dolostones in the upper part of the formation also record negative $\delta^{13}C$ values that increase up-section. Within the upper member, altered and unaltered samples show comparable stratigraphic trends, with altered samples offset toward more negative values (Fig. 7).

The lowermost carbonates in the Manykai Formation are thin dolomicrites interbedded with shale in Bed II. Pokrovsky & Missarzhevsky (1993) recorded values as low as –6 ‰ in these dolomites, above which they show a strong increase to values a bit below +2 ‰ in the lower part of Bed III. Our data also show that Bed II dolomicrites are isotopically light (–3.6 to –4.4 ‰); however, the low $\delta^{18}O$ values associated with the more extreme $\delta^{13}C$ values (Table 1) and a high potential for early diagenetic incorporation of isotopically light carbon urges caution in interpretation. Regardless of possible alteration in Bed II dolomites, the unaltered carbonates in lowermost Bed III also have negative $\delta^{13}C$ values (–2.0 to –1.5 ‰). Thus, the isotopic excursion to moderately positive values (a prominent peak of +1.8 ‰) occurred *within* Bed III, coincident with the boundary between parasequences 1 and 2, and well above the base of the Nemakit-Daldynian Stage.

As shown in Figure 7, C-isotopic values show an oscillating but generally increasing trend from the top of Bed III through upper bed VII, where $\delta^{13}C$ values as high as +2.5 ‰ form the second largest peak in the succession. This peak is preceded by two troughs with values as low as –4.2 and –3.7 ‰ confined to the top of Bed III and IV, respectively, and separated by a relatively higher $\delta^{13}C$ value lower in Bed IV. Within Bed VIII $\delta^{13}C$ values gradually decrease to –1.3 ‰ and then increase again toward the top of the bed. A sharp increase to moderately positive values (+1.6 ‰) coincides with the Bed VIII/IX boundary. The sequence boundary that separates Bed IX and the Medvezhya Formation is also marked by a sharp offset in $\delta^{13}C$ values.

Limestones of the Medvezhya Formation document a significant $\delta^{13}C$ excursion. From a moderate trough (–1.9 ‰) 3–5 m above the base of the formation, C-isotopic values rise continuously to the most prominent peak in the entire data set (+5.4 ‰), 26 m above the base of the unit. The peak is defined by a single point – a sample just 2 m higher has a $\delta^{13}C$ of +1.9 ‰. With the exception of methanogenesis, which is unlikely in this context, all principal processes known to alter the $\delta^{13}C$ of carbonates do so by *lowering* it (Grossman, 1994; Scholle, 1995). Thus, we interpret the Medvezhya peak as genuine but stratigraphically narrow.

Pokrovsky & Missarzhevsky (1993) provide scattered data on carbonates higher in the succession, suggesting that the drop hinted at in our uppermost sample culminates in a trough of –0.9 to –0.7 ‰ *c*. 8 m above the C-isotopic peak; this trough is located in the Medvezhya-Kyndyn formation boundary beds. Above this point, they record further positive values +3 to +4 ‰ in Kyndyn facies *c*. 55 m above the base of the

Table 1. Elemental and isotopic compositions of late Vendian and Lower Cambrian carbonates, Anabar Massif, northwest Siberia

Sample	Depth*	Formation/bed	Mn/Sr	Mg/Ca	δ^{13}C	δ^{18}O
					(‰, PDB)	
139	0.5	Staraya Rechka	21.70	0.545	-1.5	-2.4
140	1.0	"	29.29	0.512	-1.3	-4.9
141	2.0	"	44.20	0.535	-1.8	-3.7
142	3.0	"	31.11	0.537	-1.1	-1.1
143	4.0	"	14.73	0.554	-2.9	-3.9
144	5.0	"	17.76	0.576	-2.5	-3.8
145	6.0	"	21.97	0.535	-2.4	-14.8
146	7.0	"	19.86	0.547	-2.2	-17.3
147	8.0	"	18.95	0.552	-0.5	-15.2
148	9.0	"	16.74	0.522	-0.5	-4.0
149	10.0	"	25.00	0.548	n.d.	n.d.
150	13.0	"	14.07	0.579	n.d.	n.d.
151	14.0	"	23.99	0.515	n.d.	n.d.
152	15.0	"	16.36	0.556	-2.9	-11.8
153	16.0	"	21.38	0.535	-2.4	-13.7
154	17.0	"	29.52	0.519	-1.5	-7.9
155	18.0	"	24.74	0.498	-0.6	-4.7
156	19.0	"	16.28	0.532	-0.1	-5.3
157	20.0	"	18.52	0.529	-0.3	-3.5
158	21.0	"	22.41	0.522	-0.6	-3.4
160	23.0	"	21.76	0.515	-1.3	-6.0
161	24.0	"	26.60	0.508	-2.0	-2.9
164	n.d.	"	n.d.	n.d.	-2.5	-15.5
165	19.0	"	14.93	0.542	0.1	-4.0
166	20.0	"	15.20	0.517	0.2	-3.8
167	21.0	"	15.03	0.527	-2.4	-3.2
168	22.0	"	17.14	0.485	-2.1	-3.1
170	24.0	"	11.42	0.547	-3.9	-3.9
171	25.0	"	12.37	0.476	-4.4	-15.7
172	26.0	"	23.76	0.539	-4.4	-3.5
173	27.0	"	13.64	0.557	-4.1	-3.5
174	28.0	"	16.60	0.556	-2.3	-4.0
175	29.0	"	13.66	0.536	-4.6	-3.5
176	30.0	"	10.05	0.493	-5.1	-2.7
177	31.0	"	11.01	0.514	-5.7	-3.2
178	32.0	"	16.74	0.548	-6.2	-3.2
179	33.0	"	10.32	0.520	-4.3	-3.1
180	34.0	"	8.86	0.536	-4.3	-2.8
181	35.0	"	7.61	0.525	-3.4	-2.9
182	36.0	"	8.06	0.512	-3.4	-2.3
184	38.0	"	13.04	0.556	-4.3	-3.3
73	38.0	"	n.d.	n.d.	-2.0	-7.1
185	39.0	"	9.71	0.521	n.d.	n.d.
74	39.0	"	n.d.	n.d.	-1.1	-5.7
186	40.0	"	8.55	0.537	-2.3	-3.4
75	40.0	"	9.66	0.632	-3.5	-3.3
76	41.0	"	16.32	0.634	-4.5	-4.9
187	41.0	Staraya Rechka	11.30	0.556	-3.7	-3.5
78	43.0	"	16.97	0.631	-4.2	-2.4
190	44.0	"	9.18	0.532	-3.1	-3.1
79	44.0	"	11.24	0.619	n.d.	n.d.
191	45.0	"	7.20	0.552	-2.9	-2.8
80	45.0	"	9.33	0.643	-2.2	-3.8
192A	46.0	"	n.d.	n.d.	-3.7	-0.8
192B	46.0	"	n.d.	n.d.	-3.3	-2.8
81	46.0	"	4.83	0.652	n.d.	n.d.
193	47.0	"	7.60	0.512	-2.9	-2.7
82	47.0	"	11.50	0.652	-2.8	-5.1
194	48.0	"	8.78	0.527	-2.7	-3.0
83	48.0	"	13.85	0.622	-3.7	-16.4
195	49.0	"	11.36	0.495	-2.6	-2.0
85	50.0	"	31.60	0.578	-1.9	-9.4
87	53.5	Manykai/II	3.37	0.425	-4.4	-11.0
88	55.0	"	2.59	0.404	-3.6	-7.5
89A	68.5	Manykai/III	7.38	0.613	-2.0	-8.8
89B	68.5	"	6.87	0.571	-1.5	-6.2
222	70.0	"	2.70	0.089	1.8	-6.1
91	71.0	"	1.66	0.065	1.8	-5.3
93	73.0	"	0.15	0.016	0.2	-5.4
94	74.0	"	0.87	0.012	-1.9	-9.0
210	74.0	"	0.08	0.015	0.2	-5.6
95	75.0	"	1.10	0.016	-2.1	-6.2

Sample	Depth*	Formation/bed	Mn/Sr	Mg/Ca	δ¹³C	δ¹⁸O
					(‰, PDB)	
213	76.0	"	1.53	0.015	-3.5	-6.9
96	77.0	"	1.60	0.019	-3.8	-6.8
97	78.0	"	0.94	0.011	-3.5	-6.4
214	79.0	"	1.22	0.023	-4.2	-6.2
215	80.0	"	0.77	0.018	n.d.	n.d.
216	81.0	"	2.13	0.278	-2.5	-5.5
98	81.5	Manykai/IV	1.56	0.293	-1.5	-6.9
100	85.5	"	1.44	0.236	-1.6	-7.1
101	86.5	"	1.27	0.226	-1.4	-6.6
102	87.5	"	1.01	0.148	-0.8	-6.4
103	88.5	"	1.87	0.387	-1.7	-6.7
104	89.5	"	1.65	0.347	-1.7	-5.7
105	90.5	"	2.07	0.187	-2.9	-6.9
217	92.0	"	1.62	0.482	-3.7	-5.2
218	93.0	"	2.19	0.481	-3.5	-4.7
219	94.0	"	1.52	0.444	-2.8	-5.2
220	95.0	Manykai/V	3.13	0.445	-2.5	-4.8
221	96.0	"	0.60	0.018	-1.1	-5.5
107	99.0	"	1.28	0.129	-1.1	-5.8
108A	100.0	"	1.74	0.338	-1.3	-6.6
108B	100.0	"	1.80	0.355	-1.3	-6.7
109	101.0	"	0.96	0.123	-0.6	-6.0
110	102.0	Manykai/V	0.94	0.214	-0.3	-6.6
111	103.5	Manykai/VI	2.22	0.466	-1.6	-5.8
112	105.0	"	0.55	0.069	0.7	-6.2
113	106.0	"	0.77	0.069	0.7	-6.3
114	107.0	"	2.67	0.528	-0.1	-5.9
115	108.0	"	5.39	0.623	0.2	-7.9
116	109.0	Manykai/VII	5.29	0.543	0.0	-6.5
117	110.0	"	8.65	0.566	1.8	-5.0
118	111.5	"	5.17	0.558	n.d.	n.d.
119	112.0	"	2.14	0.427	1.2	-5.7
120	115.0	"	1.42	0.525	2.5	-4.7
121	116.0	Manykai/VIII	0.35	0.047	1.5	-8.2
122	117.0	"	0.46	0.004	1.6	-7.9
123	118.0	"	0.60	0.009	1.3	-8.4
124	119.0	"	0.42	0.014	1.2	-8.4
125	120.0	"	0.68	0.034	1.7	-8.3
126	121.0	"	0.61	0.007	1.6	-8.0
127	122.0	"	0.38	0.015	-0.8	-11.0
128A	123.0	"	0.10	0.017	0.8	-6.2
128B	123.0	"	0.27	0.020	0.7	-6.6
129	125.0	"	3.28	0.419	-1.3	-6.5
130	127.0	"	3.04	0.393	-0.6	-5.5
131	128.0	"	2.82	0.400	-0.5	-5.5
132	129.0	Manykai/IX	0.67	0.029	1.5	-5.5
133	130.0	"	0.65	0.028	1.6	-5.4
134	131.0	"	0.87	0.008	0.9	-8.5
135	132.0	"	0.56	0.041	1.2	-5.2
136	133.0	"	0.50	0.007	0.9	-8.4
137	134.0	"	0.49	0.008	0.4	-9.8
138	135.0	"	0.34	0.009	0.6	-10.1
199	136.0	Medvezhya	2.59	0.016	-1.0	-6.2
200	137.0	"	1.94	0.134	-1.0	-6.9
224	138.0	"	2.29	0.059	-1.2	-6.2
225	139.0	"	1.73	0.015	-1.9	-6.0
226	141.0	"	1.95	0.030	-1.9	-6.0
227	143.0	"	1.44	0.040	-0.3	-5.6
201	144.0	"	3.44	0.026	-0.4	-5.9
202	146.0	"	1.11	0.019	-0.8	-5.8
203	148.0	"	0.89	0.009	-0.4	-5.8
204	150.0	"	0.64	0.014	-0.6	-5.2
205	152.0	"	0.53	0.015	1.2	-5.3
206	154.0	"	0.91	0.011	1.6	-5.0
207	159.0	"	3.60	0.035	3.6	-4.9
208	161.0	"	0.19	0.015	5.4	-3.7
209	163.0	"	0.64	0.010	1.9	-6.0

* Height in metres above the base of the Staraya Rechka Formation.
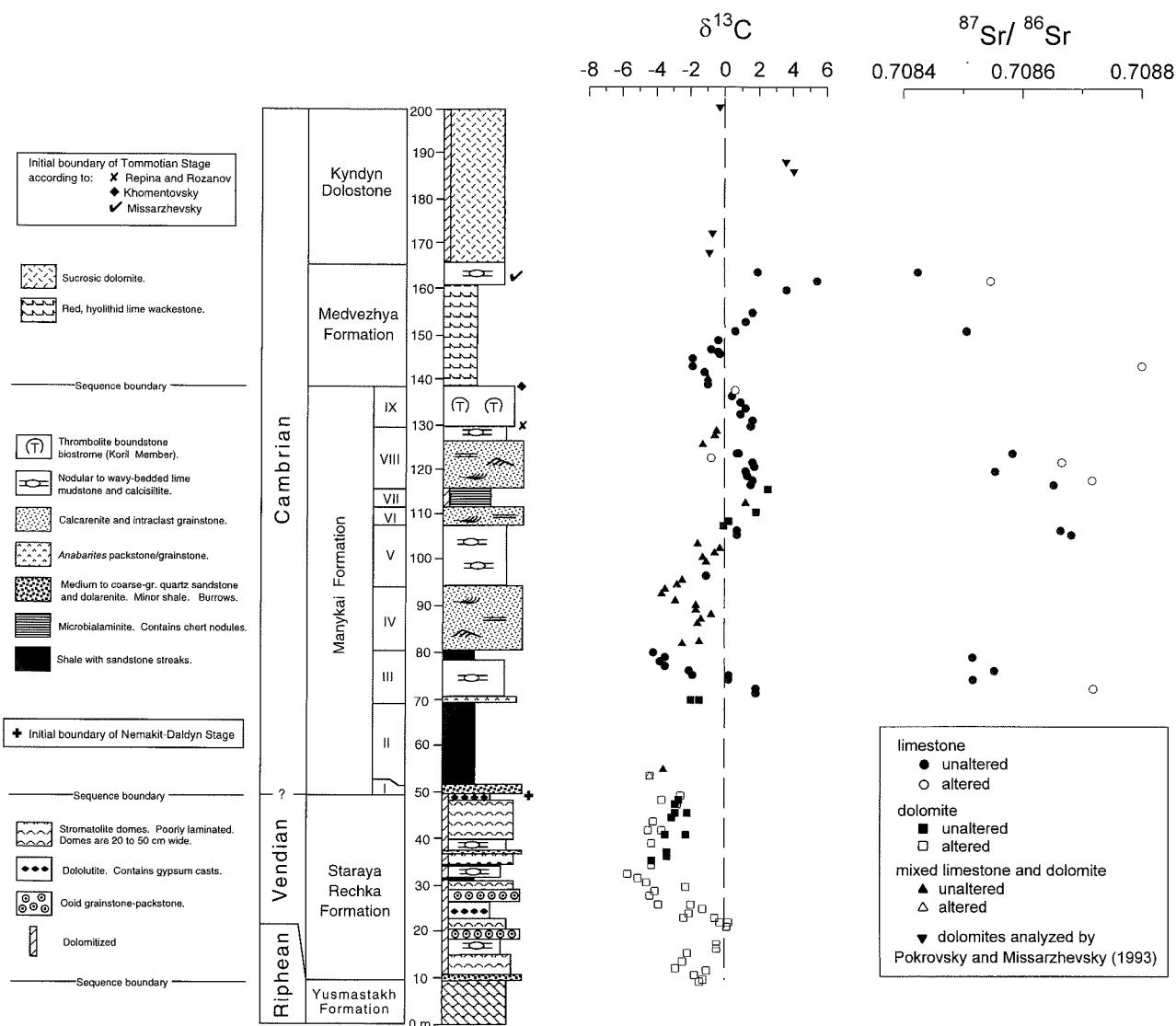
Figure 7. C- and Sr-isotopic determinations for the terminal Proterozoic/Lower Cambrian succession exposed along the Kotuikan River. See also Table 1.

Medvezhya Formation. Their uppermost sample, another c. 14 m above the upper peak, suggests a further interval of values near 0 ‰.

In general, the C-isotopic curve in Figure 7 confirms the findings of Pokrovsky & Missarzhevsky (1993), but our higher sampling density provides more detail in the pattern of secular variation and more pronounced isotopic maxima and minima, whose peaks and troughs occupy only thin intervals of the section. The difference is particularly important in the Medvezhya Formation, for which Pokrovsky & Missarzhevsky (1993) obtained only nine C-isotopic values. Perhaps for this reason, their curve does not show the full amplitude of the most prominent isotopic excursion in the entire section – the sharp, strongly positive peak at the 26 m level.

4.d. Strontium-isotopic results

Results of Sr-isotopic analyses of a selected suite of microsamples from pure limestones with low Mn/Sr are

presented in Table 2 and shown graphically in Figure 7. Isotope dilution analyses indicate relatively low concentrations of Sr (< 200 ppm) and/or high 87Rb/^{86}Sr (> 0.005) in some samples. Our empirical studies (Derry et al. 1989; Derry, Kaufman & Jacobsen, 1992; Kaufman, Knoll & Awramik, 1992; Kaufman, Jacobsen & Knoll, 1993; Narbonne, Kaufman & Knoll, 1994) suggest that samples which have lost Sr due to meteoric diagenesis or have authigenic clays containing Rb will likely have altered Sr-isotopic compositions (see also Veizer, 1983). Therefore, we consider that samples shown as open circles and triangles in Figures 7 and 8 do not retain primary ^{87}Sr/^{86}Sr signatures.

Least-altered samples show a distinct pattern of stratigraphic variation in ^{87}Sr/^{86}Sr through the sampled interval. This trend is anchored in Bed III at a value of slightly greater than 0.7085 by three closely-spaced samples. About 30 m above this level (in Bed V), the curve peaks at values around 0.7087 – again corroborated by closely-spaced samples. Strontium-isotopic compositions drop

Table 2. Sr isotope analyses of Manykai and Medvezhya limestones

Sample	Depth*	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
91	71.0	151	0.009223	0.708719
93	73.0	587	0.001541	0.708517
95	75.0	632	0.000962	0.708553
97	78.0	398	0.002497	0.708516
215	80.0	247	0.015055	n.d.
102	87.5	211	0.011894	0.708992
105	90.5	95	0.012539	n.d.
221	96.0	362	0.007127	n.d.
109	101.0	183	0.015552	n.d.
112	105.0	714	0.005020	0.708682
113	106.0	157	0.007361	0.708664
121	116.0	379	0.002004	0.708652
122	117.0	115	0.008453	0.708717
124	119.0	352	0.001425	0.708554
126	121.0	380	0.000117	0.708666
128A	123.0	1128	0.000012	0.708583
132	129.0	203	0.011126	n.d.
135	132.0	324	0.177953	n.d.
225	139.0	396	0.009838	0.708843
202	146.0	116	0.012568	0.709049
204	150.0	507	0.005993	0.708506
208	161.0	378	0.007598	0.708546
209	163.0	461	0.003471	0.708424

* height in metres above the base of the Staraya Rechka Formation.

steadily through the next 57 m of section to 0.7084 at the top of the Medvezhya limestones.

5. Chemo- and biostratigraphic correlation with southeastern Siberia

The best available C-isotopic record for uppermost Proterozoic and basal Cambrian carbonates comes from the sections along the Aldan and Lena rivers that contain the definitional initial Tommotian boundary, type Tommotian succession and associated fossil assemblages discussed in Section 3 (Magaritz, Holser & Kirschvink, 1986; Magaritz *et al.* 1991; Kirschvink *et al.* 1991; Brasier, Khomentovsky & Corfield, 1993; Brasier *et al.* 1994*b*; Fig. 9). In principle, chemostratigraphic correlation between these sections and the Kotuikan River involves the matching of successive isotopic peaks and troughs. In practice, however, the comparison is straightforward only if the two profiles (1) record basin-wide biogeochemical events, (2) reflect a comparable partitioning of time between sediments and hiatuses, and (3) are equally well sampled and screened for diagenetic alteration. Of these criteria, only the first may be met in this case.

Petrological and geochemical tests indicate that diagenesis did not play an important role in generating the isotopic profile recorded in the western Anabar, and the similarities of the western Anabar and southeastern Siberian curves both to each other and to other sections as distant as Morocco and India suggest that the main determinants of isotopic pattern are global biogeochemical events. The nature of these events remains enigmatic. Stratigraphic variations in the $\delta^{13}C$ of carbonates and co-occurring organic matter record secular change in the
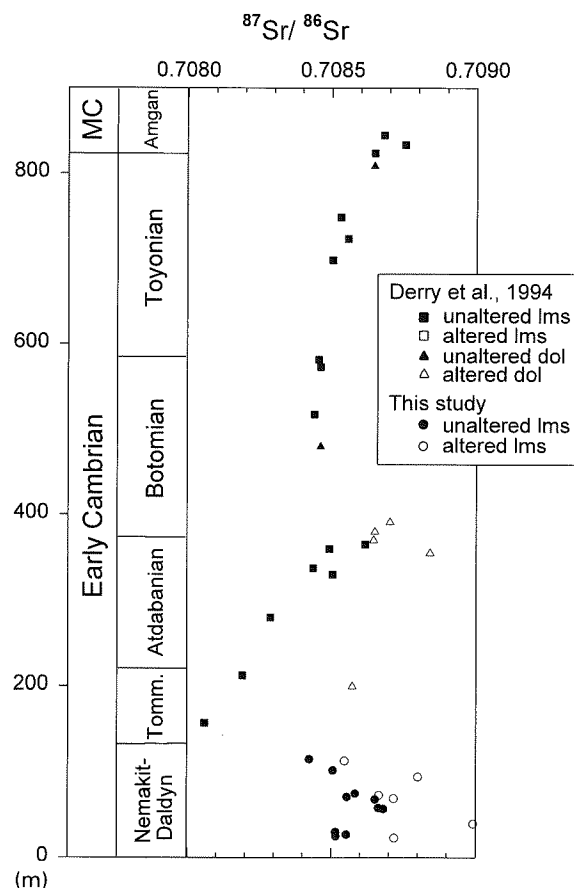
Figure 8. Composite Sr-isotopic profile for Early Cambrian time, based on data reported in Derry *et al.* (1994) and this paper.

instantaneous burial ratio of the two carbon phases, with increases in $\delta^{13}C$ values reflecting higher proportional burial rates of organic carbon (Hayes, 1993). Such variations arise because of secular changes in oceanic circulation patterns, but whether increased proportional fluxes of organic C into sediments reflect increased primary production or enhanced burial at more or less constant production rates is impossible to ascertain from isotopic data alone (Kump, 1991). Large, rapid negative excursions that follow intervals of ^{13}C enrichment in the surface ocean may additionally or alternatively indicate the return to the surface of isotopically light dissolved inorganic carbon generated at depth. Excursions from markedly positive to negative $\delta^{13}C$ values occur in association with both Sturtian and Varangerian glaciogenic rocks (Kaufman & Knoll, 1995), and also accompany Late Ordovician glaciation (Marshall & Middleton, 1990; Long, 1993; Wang *et al.* 1993). The large negative excursion recorded in Medvezhya carbonates (and in other contemporaneous successions, see Sections 6 and 7.c) is consistent with reports of 'Late Sinian' glaciogenic rocks (Chumakov, 1985; Hambrey & Harland, 1985; Bertrand-Sarfati *et al.* 1995); however, age constraints on these tillites require tightening before any association of earliest Cambrian isotopic events and climatic change can be tested.
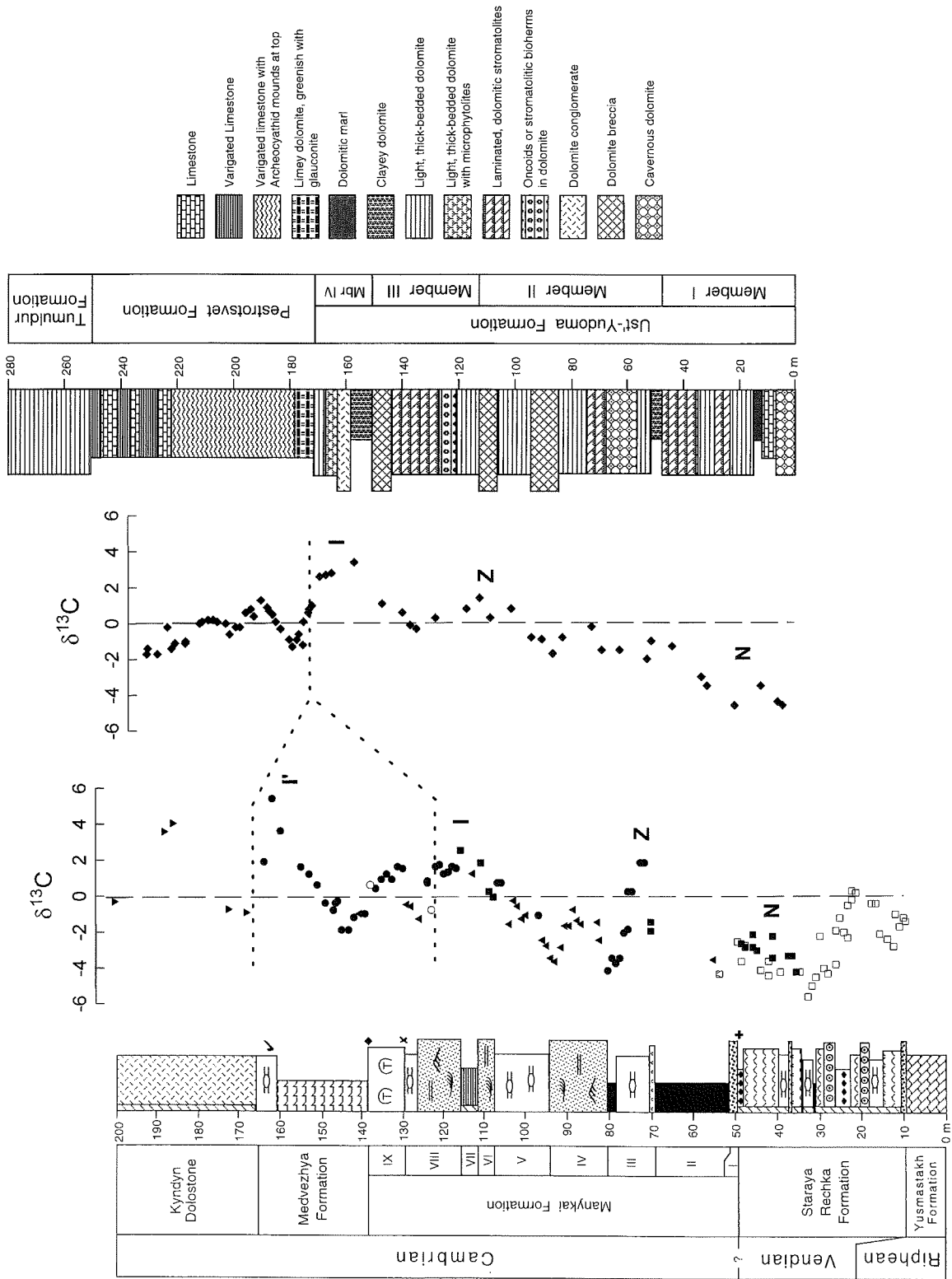
Figure 9. Chemostratigraphic correlation of the Kotuikan River and Dvortsy sections, showing the stratigraphic interval within the Anabar section interpreted as corresponding to the sub-Tommotian unconformity in southeastern Siberia.

5.a. Staraya Rechka and lower Manykai correlation

The strong negative C-isotopic excursion seen near the base of the upper Staraya Rechka Formation (labelled 'N' in Fig. 4) provides a distinctive isotopic datum that can be correlated with a comparably (–4.5 ‰) negative interval at the base of the measured part of the Ust'-Yudoma Formation at Dvortsy, southeastern Siberia (Magaritz, Holser & Kirschvink, 1986; Fig. 9; note that the base of the Ust'-Yudoma Formation is not exposed at Dvortsy and the underlying Aim Formation of the Yudoma Group is missing throughout the Aldan region (Semikhatov & Serebryakov, 1983)).

The isotopic peak in Manykai Bed III (just above the base of parasequence 2) is here correlated with the peak midway through the Ust'-Yudoma section at Dvortsy labelled 'Z' by Brasier, Khomentovsky & Corfield (1993; Magaritz, Holser & Kirschvink, 1986; Kirschvink *et al.* 1991; Fig. 9). Three arguments favour this correlation: (1) the peaks occupy a similar position relative to both the correlated lower Staraya Rechka/basal Ust'-Yudoma troughs and large positive excursions higher in the sections, (2) they are of similar magnitude, and (3) they are both associated stratigraphically with fossils of the *Anabarites trisulcatus* Zone. As noted by Brasier, Khomentovsky & Corfield (1993), *A. trisulcatus* and associated taxa appear to enter the record at slightly different times in different Siberian sections; the multi-species assemblage in Manykai Bed III appears at nearly the same level as its counterpart along the Nemnekey River in southeastern Siberia – well above the first appearance of a monospecific *A. trisuclatus* faunule at the base of the Manykai Formation and still farther above the first appearance of *Cambrotubulus* sp. in the Olenek region (Khomentovsky & Karlova, 1993; Knoll *et al.* 1995a). Correlation of the Manykai Bed III peak with Ust'-Yudoma peak Z also suggests that the lower boundary of the *Purella antiqua* Zone – just above peak Z in Uchuro-Maya sections (Brasier, Khomentovsky & Corfield, 1993) – is located well below the actual first appearance of *P. antiqua* Zone faunas in the Manykai Formation (see also Brasier *et al.* 1994b, who drew a similar conclusion from the data of Pokrovsky & Missarzhevsky, 1993).

A second C-isotopic peak occurs near the top of Manykai Bed VII, just beneath the boundary of parasequences 3 and 4 (Fig. 7). The +3.3 ‰ value of this peak matches precisely that found just beneath the sub-Tommotian unconformity at Dvortsy (Magaritz, Holser & Kirschvink, 1986; Peak 'I' of Brasier, Khomentovsky & Corfield, 1993; Fig. 9). Besides their magnitudes and relative stratigraphic positions, these prominent peaks are tethered by their occurrence in stratigraphic proximity to relatively diverse faunas of the *P. antiqua* Zone. Particularly in sections along the Dzhanda River *c.* 100 km east of the Aldan exposures, uppermost Ust'-Yudoma carbonates contain well-preserved faunas whose taxonomic composition compares closely with assemblages found in Bed IX of the Manykai Formation (Khomentovsky & Karlova, 1993). If this correlation is correct, diverse *P. antiqua* Zone assemblages in the Manykai Formation appear after their counterparts in southeastern Siberia.

5.b. Upper Manykai and Medvezha correlation

At Dvortsy and elsewhere in southeastern Siberia, Peak I is succeeded by an excursion to moderately negative C-isotopic values just above the base of the fossiliferous Pestrotsvet Formation. Above this negative excursion, a peak of magnitude > +2 ‰ occurs in the Aldan–Lena sections only in the mid-Atdabanian *P. anabarus* Zone (Peak V of Brasier *et al.* 1994a). In contrast, in the western Anabar section, the negative isotopic excursion immediately above the correlative of Peak I occurs within Manykai Bed VIII, below the lowermost point at which any stratigrapher has placed the basal Tommotian boundary. The succeeding +5.4 ‰ peak in the upper Medvezhya Formation has a magnitude unmatched anywhere in the Dvortsy profile; it occurs in stratigraphic association with uppermost Nemakit-Daldynian or Tommotian fossils well below the accepted regional base of the Atdabanian Stage.

The simplest explanation for this is that the interval extending from Bed VIII of the Manykai Formation through at least the lower 26 m of the Medvezhya Formation preserves a sedimentary and palaeontological record of the time interval represented in southeastern Siberia by the sub-Tommotian unconformity (Fig. 9). As discussed here, this correlation is consistent with bio-stratigraphic data and potentially resolves outstanding uncertainties in the interregional correlation of earliest Cambrian strata in Siberia.

Sr-isotopic data provide independent support for placement of the basal Tommotian boundary above the 26 m mark of the Medvezhya Formation. The (relatively) low $^{87}Sr/^{86}Sr$ values documented in the type lower Tommotian carbonates by Derry *et al.* (1994) is not seen in the Kotuikan section (Figs 7, 8). Indeed, accepting the stratigraphic interpretation proposed on the basis of C-isotopes, the decrease in $^{87}Sr/^{86}Sr$ documented from Manykai Bed V through the top of the Medvezhya limestones projects smoothly into the relatively low values (*c.* 0.7081) reported by Derry *et al.* (1994) for basal Tommotian limestones in southeastern Siberia (Fig. 8).

Strontium isotope secular variations can also be projected back into the Vendian. Below the Vendian/Cambrian boundary, in unaltered limestones slightly older than those in the Staraya Rechka Formation (the Spitzkopf Formation in Namibia), $^{87}Sr/^{86}Sr$ values match those of the lowermost Nemakit-Daldynian samples analysed here (cf. Kaufman, Jacobsen & Knoll, 1993). The overall rise in $^{87}Sr/^{86}Sr$ inferred for palaeosea-water from basal Vendian to middle Nemakit-Daldynian times (0.7066 to 0.7086) has been attributed to enhanced continental erosion associated with a latter phase of the

Pan-African orogeny (Kaufman, Jacobsen & Knoll, 1993; Gorokhov *et al.* 1994). Derry *et al.* (1994) suggested a similar scenario for the subsequent rise in $^{87}Sr/^{86}Sr$ (0.7081 to 0.7088) from the base of the Tommotian to early Middle Cambrian times. A corollary to these interpretations is that the drop in palaeoseawater Sr-isotopic values from the Nemakit-Daldynian peak to the basal Tommotian valley represents either a transient decline in continental inputs or a significant hydrothermal event.

Above the 28 m level of the Medvezhya Formation, isotopic data are sparse, but they are consistent with both biostratigraphic data and the preceding interpretations. Mildly negative $\delta^{13}C$ values *c.* 34 m above the base of the Medvezhya Formation (Pokrovsky & Missarzhevsky, 1993) are consistent with Tommotian deposition, and according to Repina & Rozanov (1992), *Burithes distortus*, a putative index fossil for the *D. regularis* Zone, first appears 25–30 m above the base of the formation. Khomentovsky & Karlova (1992) place its first appearance above the 30 m mark. The uppermost peak recorded by Pokrovsky & Missarzhevsky (1993) in the Kyndyn Formation is also consistent with biostratigraphic evidence for Adtabanian deposition (Repina & Rozanov, 1992). If these interpretations are correct, the uppermost Medvezhya/lower Kyndyn succession must be condensed relative to southeastern Siberia or marked by cryptic unconformities. Northern Siberia was tectonically active during latest Proterozoic and Early Cambrian times, providing a mechanism for differential uplift and subsidence across the platform (Pelechaty, Kaufman & Grotzinger, 1996).

5.c. Alternative possibilities for correlation

The correlation favoured here is not the only one that could be proposed on the basis of existing data, and it is important to consider alternatives. Perhaps the most obvious alternative is that the pronounced peak 26 m above the base of the Medvezhya Formation correlates directly with Dvortsy peak I (Pokrovsky & Missarzhevsky, 1993). In this alternative, the difference in amplitude between the two peaks must be explained by one of two arguments. The true magnitude of the Dvortsy peak may be underestimated as a result of low sampling density in the critical interval or diagenetic depletion of ^{13}C in the carbonates. Alternatively, one might propose that strong basinal heterogeneity in C-isotopic composition developed within the Early Cambrian seaway covering the Siberian Platform.

In this interpretation, Tommotian strata still begin more than 26 m above the base of the Medvezhya Formation, but Anabar strata record both fossils and isotopic events not reported from correlative beds in southeastern Siberia (Pokrovsky & Missarzhevsky, 1993).

Several arguments militate against this alternative:

(1) A number of prominent C-isotopic excursions are recorded in both older Neoproterozoic and younger Phanerozoic (e.g. Late Cambrian, Late Ordovician, Late Permian, Cenomanian) carbonates, and strong peaks (> +5 ‰) in one region seldom, if ever, match up with relatively minor excursions elsewhere (see, e.g. Smith *et al.* 1994; Erwin, 1993; Pratt, Force & Pomerol, 1991); indeed, in Neoproterozoic basins where strong positive isotopic excursions have been identified in multiple sections, amplitude is consistent among correlative peaks (see, e.g. Knoll *et al.* 1986; Narbonne, Kaufman & Knoll, 1994; Pelechaty, Kaufman & Grotzinger, 1996). Without detailed diagenetic studies of the Dvortsy carbonates, we cannot speculate whether some process may have decreased $\delta^{13}C$ values in these samples.

(2) The principal biostratigraphic corollary of this alternative – that the basal Cambrian fossil distribution in southeastern Siberia faithfully records evolutionary first appearances, whereas the sequential first appearances of taxa in the north reflects episodic migration – is contrary to palaeontological experience in younger rocks.

(3) Among the admittedly small number of Nemakit-Daldynian/Tommotian sections for which C-isotopic data are available, the Dvortsy section is actually unusual in *not* including $\delta^{13}C$ values > +5 ‰ (see Section 7.c).

We cannot rule out the possibility that sampling density at Dvortsy was too low to capture the short-lived maximum of this excursion, but this can, of course, be tested.

Another potential alternative is that the Anabar succession above Manykai Bed VII correlates with the Tommotian to Atdabanian succession in southeastern Siberia, compatible with the biostratigraphic interpretation of Repina & Rozanov (1992). In this case, the small peak in Manykai Bed IX would match up with a minor peak within the *D. regularis* Zone in the southeast, leaving the strong upper Medvezhya peak to correlate with a succeeding Atdabanian excursion. Problems with this alternative include the following:

(1) It does not solve the problem of matching a strong (> +5 ‰) peak in one section with a minor (< +2 ‰ if correlation is made to lower Atdabanian Peak IV of Brasier *et al.* 1994*b*, and *c.* +3 ‰ if one chooses the more prominent Peak V in the *P. anabarus* Zone) excursion in another.

(2) It requires that the lower boundary of the Adtabanian Stage be placed at or below the 27 m mark of the Medvezhya Formation, even though all biostratigraphic interpretations place this level within the Tommotian.

(3) Sr-isotopic data for the upper Manykai and lower Medvezhya formations are not consistent with a Tommotian age for these rocks.

It is possible to articulate a third class of interpretation, in which Kotuikan intervals corresponding to hiatuses in southeastern Siberia are smaller than those suggested in our preferred alternative; however, no alternative in this class escapes the problems noted earlier in this section. The principal correlation proposed in this paper does not suffer from the problems that accompany all other rea-

sonable alternatives, and so we prefer it. Regardless of preference, it can be tested because it makes predictions about (1) the results of denser sampling and more detailed evaluation of diagenesis in southeastern Siberian sections and (2) the stratigraphic relationship between isotopic profiles and SSFs in other sections within and beyond the Siberian Platform.

6. Chemo- and biostratigraphic correlation with the Olenek region of northern Siberia

The Staraya Rechka succession can be compared with the latest Proterozoic (Yudomian) succession that underlies Nemakit-Daldynian rocks in the Olenek Uplift, 600 km to the east of the Kotuikan River. Previously, it was broadly accepted (e.g. Semikhatov, Komar & Serebryakov, 1970; Khomentovsky, 1976, 1990; Shpunt, Shapovalova & Shamshina, 1982; Semikhatov & Serebryakov, 1983; Khomentovsky & Karlova, 1994) that the Staraya Rechka Formation correlates with the entire Yudomian succession in the Olenek region (Maastakh, Khatyspyt and Turkut formations) or to its post-Maastakh part. However, C-isotopic data (Knoll *et al.* 1995*a*) preclude such interpretation. In the Olenek section, a negative excursion comparable in magnitude to that recorded in the Staraya Rechka Formation is confined to the thin, upper sedimentary sequence of the Turkut Formation. The mildly negative (0 to −2.5 ‰) $\delta^{13}C$ values seen in the lower Staraya Rechka suggest correlation with some or all of the lower Turkut Formation, but do not support the hypothesis that the underlying Khatyspyt and Maastakh formations have time equivalents in the western Anabar region. This corroborates and refines earlier conclusions that terminal Proterozoic (Yudomian) transgressions flooded different parts of the Siberian Platform at different times (e.g. Semikhatov, Komar & Serebryakov, 1970; Khomentovsky, 1976).

The earliest SSFs of Cambrian aspect recorded in the Olenek region are *Cambrotubulus* sp. found 30 m below the top of the Turkut Formation (Karlova, 1987; Khomentovsky & Karlova, 1993). Carbon-isotopic data demonstrate that this occurrence lies well below the base of the Nemakit-Daldynian Stage in the western Anabar section, at a level equal to or below the lower Staraya Rechka Formation. *Anabarites* sp. occurs in uppermost Turkut carbonates that correlate chemostratigraphically with upper Staraya Rechka or lowermost Manykai strata (Khomentovsky & Karlova, 1993). Shales and carbonates of the overlying Kessyusa Formation contain a succession of skeletal fossils similar to that found in the western Anabar region (Khomentovsky & Karlova, 1993). In the drainage of the Khorbusuonka River, lower Kessyusa rocks assigned to the *A. trisulcatus* Zone do not include carbonates, but middle Kessyusa strata contain both a faunal assemblage referable to the *P. antiqua* Zone and a C-isotopic peak that can be correlated with Peak I in Manykai Bed VII and the uppermost Ust'-Yudoma Formation (Knoll *et al.* 1995*a*).

A sequence boundary separates middle and upper Kessyusa strata (Khomentovsky & Karlova, 1992; Knoll *et al.* 1995*a*). Upper Kessyusa rocks have been assigned to the Tommotian *N. sunnaginicus* Zone (Khomentovsky & Karlova, 1993), but all taxa they share with the western Anabar region have first appearances below the Nemakit-Daldynian/Tommotian boundary. This and a second C-isotopic peak whose magnitude exceeds anything recorded in southeastern Siberia, suggest that the Nemakit-Daldynian/Tommotian boundary may lie at the Kessyusa/Erkeket boundary. An unconformity at this boundary is documented by erosional relief of up to one metre (Grotzinger & Knoll, pers. observation); argillaceous, maroon limestones of the Erkeket Formation record onlap over the previously exposed craton. (As noted in Section 6, the observation that many taxa in the upper Kessyusa Formation occur in rocks of the *N. sunnaginicus* Zone in southeastern Siberia (Khomentovsky & Karlova, 1992) does not provide persuasive evidence for an opposing interpretation.)

7. Discussion

7.a. Biostratigraphy

Previous correlations between northwestern and southeastern Siberia start from the premise that rocks correlate with rocks, rather than with omission surfaces. Our data suggest that this assumption may not be valid. None the less, our preferred placement of the Nemakit-Daldynian/Tommotian boundary in the western Anabar section approximates that of Missarzhevsky (1989) and Khomentovsky & Karlova (1993).

As most or all of the small shelly fossils previously suggested to mark the *N. sunnaginicus* Zone appear to have evolved prior to the beginning of the Tommotian, their use in the unequivocal recognition of this zone or even stage is problematic – this is the argument of Landing (1994, and earlier papers). To date there is no record of archaeocyathids in the sub-Tommotian of the western Anabar; thus, these fossils may provide more robust markers for early Tommotian time. Whether or not a distinct *N. sunnaginicus* Zone can be recognized in Siberia or elsewhere in the absence of archaeocyathans is questionable (Qian & Bengtson, 1989; Landing, 1992, 1994); however, the richness of stratigraphic information recorded by the sequential appearance of SSF taxa in the western Anabar holds the promise that additional zones can be recognized in the upper Nemakit-Daldynian Stage, as suggested by Missarzhevsky (1989). On the other hand, Khomentovsky & Karlova's (1994) comment that even minor environmental fluctuations seem to have affected the local stratigraphic distribution of early shelly fossils is apt.

7.b. The sub-Tommotian unconformity

Previous craton-wide correlations require that unconformities in Proterozoic–Cambrian successions of Siberia be
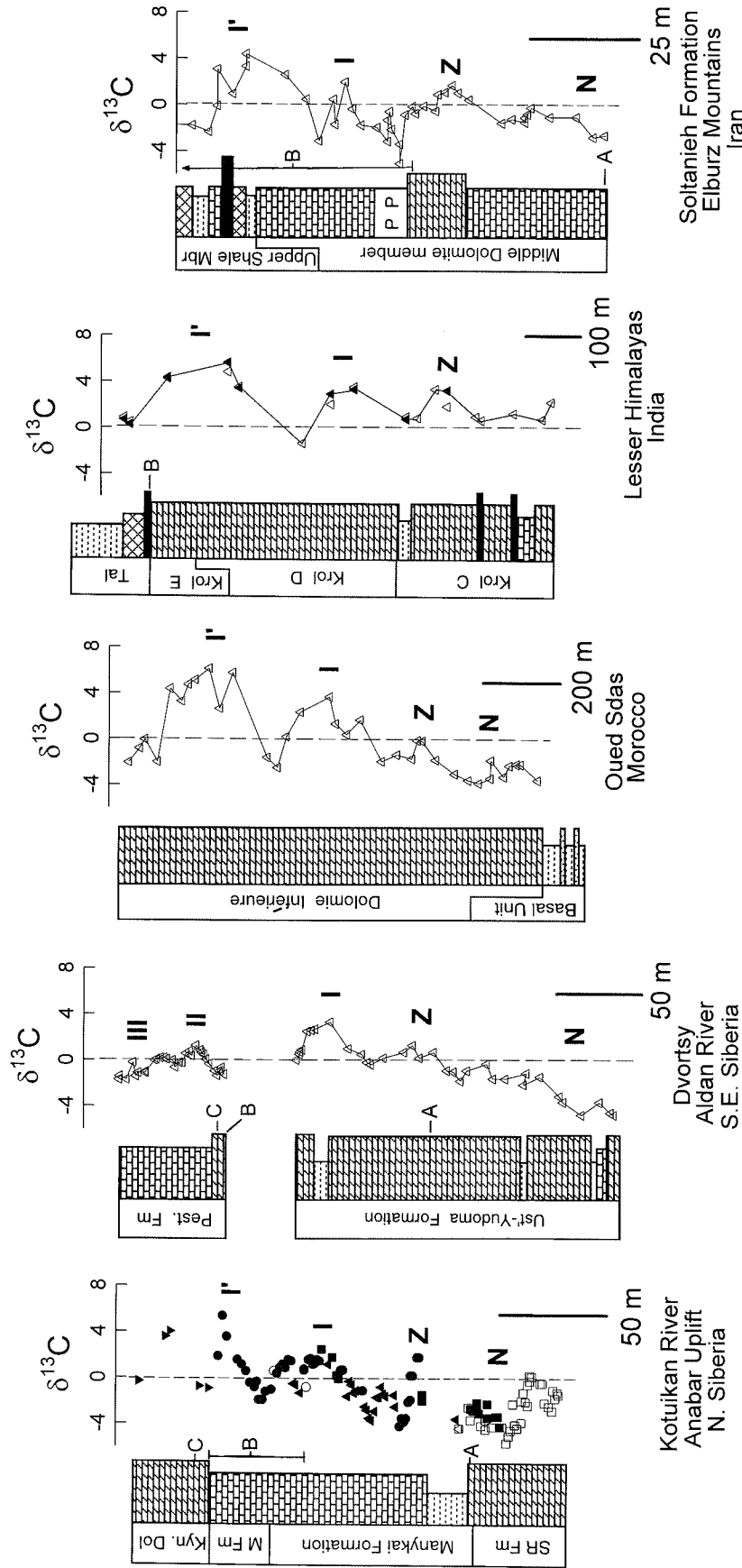
Figure 10. Chemostratigraphic correlations of the Kotuikan River and Dvortsy sections with sections in Morocco (Kirschvink *et al.* 1991), India (Aharon, Schidlowski & Singh, 1987), and Iran (Brasier *et al.* 1990). The sub-Tommotian unconformity at Dvortsy is shown as a break in section that spans the interval from the negative excursion above Peak I to a point above the peak here designated I'. A = first appearance of Nemakit-Daldynian (*A. trisulcatus* Zone) faunas; B = first appearance of 'basal Tommotian' faunas; C = first appearance of *Burithes distortus*.

diachronous among regions. While this is by no means unreasonable, the correlations advocated here encourage a different picture of earliest Cambrian tectonics on the Siberian platform. Unconformities at the Manykai/Medvezhya and Kessyusa/Erkeket boundaries record two distinct regional hiatuses of relatively short duration within the longer time interval encompassed by the Ust'-Yudoma/Pestrotsvet (sub-Tommotian) unconformity in southeastern Siberia.

In our preferred correlation, the unconformity between the Ust'-Yudoma and Pestrotsvet formations corresponds in time to a section of rocks minimally 48 m thick in the Kotuikan River section. Correlation of the Anabar succession with sections that contain volcanic rocks dated by U–Pb geochronometry (Bowring *et al.* 1993), thus, permits us to estimate the duration of the sub-Tommotian hiatus in southeastern Siberia. As noted above, the beginning of Manykai deposition correlates bio- and chemostratigraphically with the lower Kessyusa Formation in the Olenek Uplift (Knoll *et al.* 1995*a*); a basal Kessyusa volcanic breccia has a radiometric age of 543.9 ± 0.3 Ma (Bowring *et al.* 1993). Rhyolite cobbles beneath Tommotian strata assigned to the *D. regularis* Zone (Repina *et al.* 1974) in the nearby Kharaulakh Mountains are 534.6 ± 0.5 Ma old (Bowring *et al.* 1993). Isachsen *et al.* (1994) further considered the stratigraphic position of an ash bed in New Brunswick dated at 530.7 ± 0.9 Ma to be sub-Tommotian. This is consistent with the observation that the 535-Ma-old rhyolites in the Kharaulakh Mountains were deposited, eroded, and redeposited as cobbles before Tommotian transgression, suggesting that the Tommotian Stage began *c.* 530–535 Ma ago.

Taken together, radiometric data suggest that the 114 m interval running from the base of the Manykai Formation to the 27 m level of the Medvezhya Formation lasted 8–14 Ma. The portion of this succession corresponding to the sub-Tommotian unconformity constitutes 42 % of the total section. Recognizing potential problems of equating sediment thickness with time (Sadler, 1981), this suggests that the time interval represented at the sub-Tommotian unconformity in southeastern Siberia is on the order of several Ma. This estimate is probably conservative because the unconformity at the Manykai/Medvezhya boundary may, itself, mark a significant hiatus.

The summary point is that the unconformity beneath the Tommotian in southeastern Siberia represents a time interval whose duration is minimally a significant fraction of and possibly as long as the Tommotian Stage itself.

7.c. Chemostratigraphy

Kotuikan data suggest that a pronounced C-isotopic excursion immediately preceded the beginning of the Tommotian age, but that it was *not* Peak I recorded at Dvortsy. The sub-Tommotian excursion identified here has a much greater amplitude, indicating a distinctive biogeochemical event likely to be recorded globally.

Indeed, Early Cambrian isotopic peaks comparable in magnitude to that seen in the upper Kotuikan succession have been documented in Morocco (Tucker, 1986; Magaritz *et al.* 1991), India (Aharon, Schidlowski & Singh, 1987), and Iran (Brasier *et al.* 1990) – southeastern Siberia is unusual in lacking a comparable C-isotopic excursion.

Our preferred intercontinental correlations are shown in Figure 10. While we suggest that the major peaks and troughs are correlative, we acknowledge that sequence stratigraphy, biostratigraphic data and radiometric analyses of high-precision will be necessary to verify more detailed correlations. Kotuikan results also support the view that Sr-isotopic data provide important constraints on earliest Cambrian correlation (Derry *et al.* 1994); however, the available data base remains small.

7.d. Palaeobiological implications

As noted above, the massed first appearance of many invertebrate taxa above the sub-Tommotian (pre-Pestrotsvet) unconformity in southeastern Siberia has long been cause for concern among both biostratigraphers and evolutionary palaeobiologists. Kotuikan data support the hypothesis that these regional first appearances are controlled by the dynamics of regional sedimentation and do not record an evolutionary burst (Landing, 1994). If so, the Cambrian diversification of animals entered its explosive phase not at the beginning of the Tommotian, as generally accepted, but several million years earlier.

At the species level, the pattern of animal diversification through the Nemakit-Daldynian and early Tommotian ages is cumulative. Such a pattern of faunal addition without replacement lasting for more than ten million years is unusual in a Phanerozoic record more generally marked by faunal overturn every five to seven million years (see, e.g. Brett & Baird, 1990; Morris *et al.* 1995). This may provide evidence that Early Cambrian ecosystems were relatively 'empty' and, therefore, tolerant of new variants or migrants.

8. Conclusion

The western Anabar and other Siberian sections provide an illuminating case study of how sequence stratigraphy, biostratigraphy, chemostratigraphy and geochronometry can be combined to achieve high resolution in the correlation of events and strata near the Proterozoic–Cambrian boundary. The inference that several million years go unrecorded by rocks at the sub-Tommotian unconformity in southeastern Siberia highlights the potential of integrated stratigraphic studies in ordering the biological events that gave rise to Cambrian diversity.

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