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Andrew H. Knoll, Alan J. Kaufman, Mikhail A. Semikhatov, John P. Grotzinger and William Adams

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Notes

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Andrew H. Knoll
Alan J. Kaufman
Botanical Museum, Harvard University, Cambridge, Massachusetts 02138
Mikhail A. Semikhatov Geological Institute, Russian Academy of Sciences, Moscow 109107, Russia
John P. Grotzinger Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
William Adams Department of Earth Sciences, Dartmouth College, Hanover, New Hampshire 03755

ABSTRACT

Sedimentary rocks in the western Anabar region, northwestern Siberia, preserve an exceptional record of evolution and biogeochemical events near the Proterozoic-Cambrian boundary. Carbon isotopic data on petrographically and geochemically screened samples collected at 1 to 2 m intervals support correlation of the lower Anabar succession (Staraya Reckha and lower Manykai Formations) with sub-Tommotian carbonates of the Ust'-Yudoma Formation in southeastern Siberia. In contrast, the upper Manykai and most of the overlying Medvezhya Formation appear to preserve a sedimentary and paleontological record of an evolutionarily important time interval represented in southeastern Siberia only by the sub-Tommotian unconformity. Correlation of the Anabar section with other northern Siberian successions that contain well-dated volcanic rocks permits the estimate that the sub-Tommotian unconformity in southeastern Siberia spans approximately 3 to 6 m.y. Diverse small shelly fossils (but not archaeocyathans) previously thought to mark the base of the Tommotian Stage evolved sequentially throughout this earlier interval.

INTRODUCTION

Darwin (1859) described the geologic record as "a history of the world imperfectly kept" in which "only here and there a short chapter has been preserved; and of each page only a few lines." In terms of this metaphor, the Tommotian stratotype area of southeastern Siberia (Fig. 1) has long been interpreted as an unusually complete manuscript of one critical chapter in life's history, the beginning of the Cambrian explosion (Rozanov et al., 1969). Here, more than 100 species of small shelly fossils and the first archaeocyathans enter the record at the base of the Tommotian Stage. Regionally, an unconformity marked by karst formation and erosional downcutting separates these fossils from low-diversity assemblages in the immediately underlying Ust'-Yudoma Formation (Semikhatov and Serebryakov, 1983; Khomentovsky and Karlova, 1992; Landing, 1992, 1994). Nonetheless, many syntheses of basal Cambrian paleontology (e.g., Missarzhevsky, 1989; Repina and Rozanov, 1992; Khomentovsky and Karlova, 1992, 1993, 1994) and isotopic chemostratigraphy (Magaritz et al., 1986, 1991; Kirschvink et al., 1991; Brasier et al., 1993, 1994) treat the sub-Tommotian unconformity as a minor hiatus in an otherwise complete succession (Rozanov, 1995).

Proterozoic-Cambrian boundary strata exposed near the mouth of the Kotuikan River in the western Anabar region, northwestern Siberia (Fig. 1), provide a means of evaluating both the time span of the sub-Tommotian unconformity in southeastern Siberia and the pattern of evolution that inaugurated the Cambrian explosion.

SUB-TOMMOTIAN UNCONFORMITY IN SOUTHEASTERN 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 (Fig. 1; Rozanov et al., 1969; Rozanov, 1984). This stratigraphic placement is misleading, however; Khomentovsky (e.g., Khomentovsky and Karlova, 1992) recognized that basal Tommotian taxa in this bed are restricted to karst-filling glauconitic lenses emplaced during subsequent Pestrotsvet transgression. Although a limited diversity of small shelly fossils occurs lower in the section, this topologically complex boundary coincides regionally with the first appearance of diverse invertebrate skeletons. Some 30 taxa occur in the lenses of glauconitic carbonate that penetrate downward to bed 8; an additional 70 or more species of small shelly fossils and archaeocyathans first appear regionally in basal argillaceous limestones of the immediately overlying Pestrotsvet Formation (Repina and Rozanov, 1992). When the first beds above the definitional base of the Tommotian Stage accumulated, all of the taxa that typify the early Tommotian *Nochoroicyathus sunnaginicus* zone were present.

ANABAR LITHOSTRATIGRAPHY AND BIOSTRATIGRAPHY

Along the Kotuikan River, the terminal Proterozoic through Tommotian succession comprises 180 m of shallow-marine carbonates and subordinate siliciclastic lithologies (Khomentovsky, 1990) divided into three principal sequences, each representing late transgressive to early highstand accumulation (Fig. 2; Kaufman et al., 1995). The 88-m-thick Manykai Formation is interpreted as a single depositional sequence, bounded by unconformities that coincide with prominent flooding surfaces. A regional uncomformity between the Manykai and underlying Staraya Rechka Formations is marked by breccia clasts and solution features (Khomentovsky, 1990); this flooding surface marks the beginning of the basal Cambrian Nemakit-Daldynian Stage (Savitsky, 1975).

The unconformably overlying Medvezhya Formation comprises argillaceous, heavily bioturbated lime mudstone and wackestone deposited during regional onlap across the Anabar platform. Along the Kotuikan River, only the basal 27 m of this formation were examined in detail. Shortly above this level, Medvezhya limestones grade into diagenetically altered, sugary dolomites of the Kyndyn Formation. The first appearance of trilobites and index archaeocyathans some 13 m higher in sections 150 km to the northeast of the Kotuikan locality marks the Tommotian-Atdabanian boundary; correlations with southeastern Siberia (see below) indicate that the Kyndyn Formation is either condensed or marked by at least one cryptic unconformity.

Khomentovsky and Karlova (1992, 1993) listed 86 invertebrate taxa found in the western Anabar succession. Of these, 65 are in southeastern Siberia, including the Tommotian stratotype section (Fig. 3). Despite faunal similarities between the two regions, biostratigraphic correlation has been contented, principally because some 50 small shelly fossil taxa that have simultaneous first appearances in basal beds of the Tommotian stratotype and associated sections enter the record sequentially through more than 30 m of section in the Anabar region.

The initial Tommotian boundary is defined in southeastern Siberia, but its placement in the Anabar region depends on how one views the sub-Tommotian unconformity. If the massed first appearances of small shelly fossils in the stratotype area represent a true evolutionary burst whose stratigraphic relation to the sub-Tommotian unconformity is fortuitous, the basal Tommotian boundary in the Kotuikan River section is logically placed at the point where the *low-*

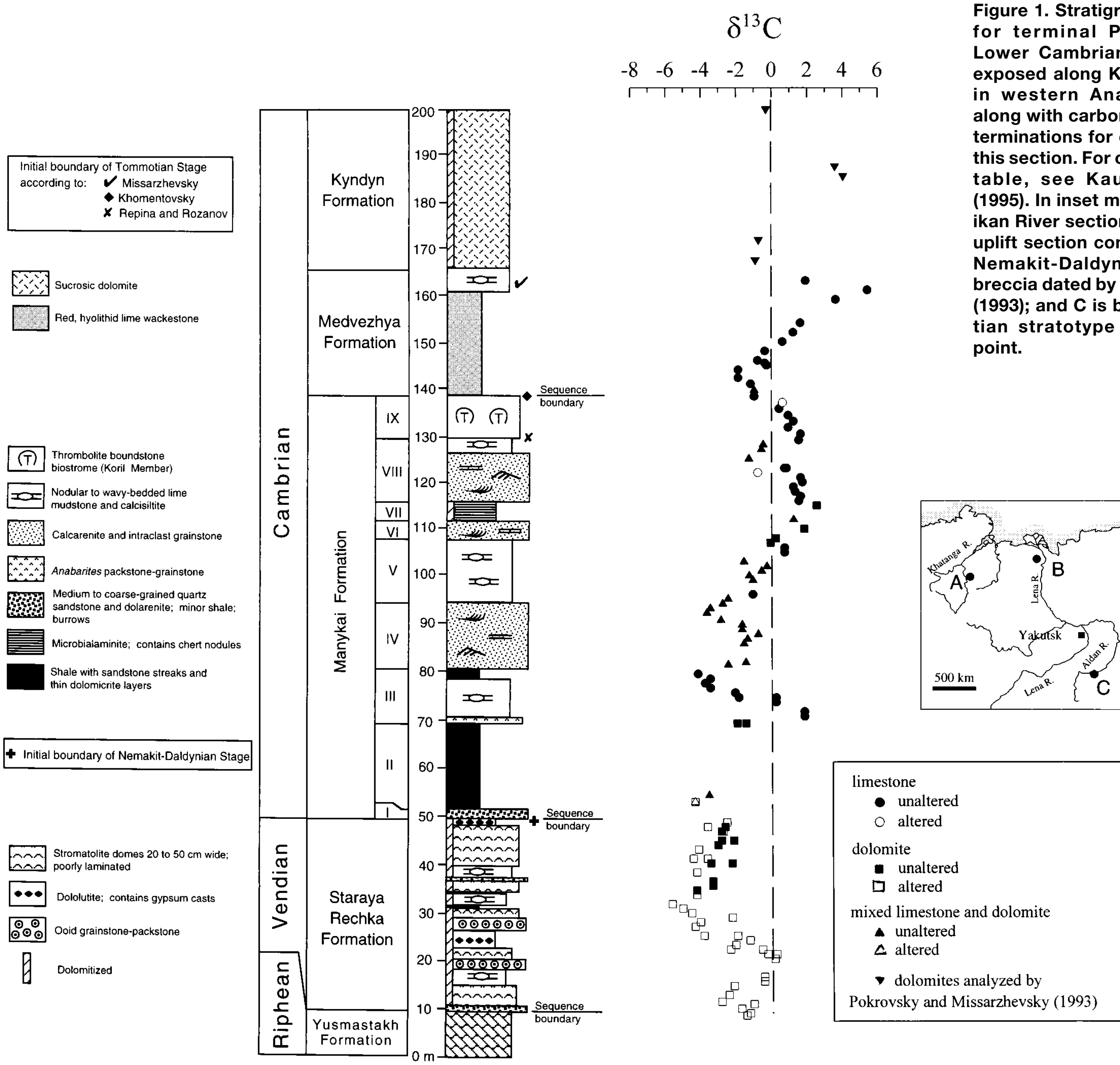

Figure 1. Stratigraphic section for terminal Proterozoic–Lower Cambrian succession exposed along Kotuikan River in western Anabar region, along with carbon isotopic determinations for carbonates in this section. For complete data table, see Kaufman et al. (1995). In inset map, A is Kotuikan River section; B is Olenek uplift section containing basal Nemakit-Daldynian volcanic breccia dated by Bowring et al. (1993); and C is basal Tommotian stratotype section and point.

ermost "basal Tommotian" species appear (Fig. 3; Repina and Rozanov, 1992). In contrast, if the abrupt appearance of diverse faunas in southeastern Siberia is interpreted as a stratigraphic consequence of the unconformity, the Nemakit-Daldynian-Tommotian boundary can be placed as high as 25–30 m above the base of the Medvezhya Formation—the point at which the *last* "basal Tommotian" taxa appear (Missarzhevsky, 1989; Fig. 3). A third alternative is to place the boundary where the *most* "basal Tommotian" taxa first appear—at the base of the Medvezhya Formation (Fig. 3; Khomentovsky and Karlova, 1992, 1993, 1994). This placement, however, requires an arbitrary choice of selected "basal Tommotian" species as "true" time indicators.

Published correlations concur in treating successions in the two regions as essentially complete records of terminal Proterozoic and basal Cambrian time, the Ust'Yudoma-Pestrotsvet and Manykai-Medvezhya unconformities representing evolutionarily insignificant breaks in sedimentation.

CHEMOSTRATIGRAPHIC CORRELATION

Chemostratigraphy based on the isotopic compositions of carbon and (to a lesser extent) strontium has been shown to be effective in the correlation of terminal Proterozoic (Kaufman and Knoll, 1995) and Early Cambrian (Kirschvink et al., 1991; Brasier et al., 1993, 1994) carbonate-bearing successions. Given their magnitude and frequency, C isotopic excursions in particular show great potential for resolving 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. Because the terminal Proterozoic and Early Cambrian C isotopic record contains repeated excursions of broadly similar magnitude, chemostratigraphic interpretation must be anchored by biostratigraphy.

Anabar Data

Reconnaissance C isotopic data for the Anabar section were published by Pokrovsky and Vinogradov (1991) and Pokrovsky and Missarzhevsky (1993). In those studies, stratigraphic sampling intervals are large, and isotopic determinations are for whole-rock samples unsupported by geochemical or petrographic data. In this study, carbonates were collected at 1 m intervals throughout the Staraya Rechka and Many-

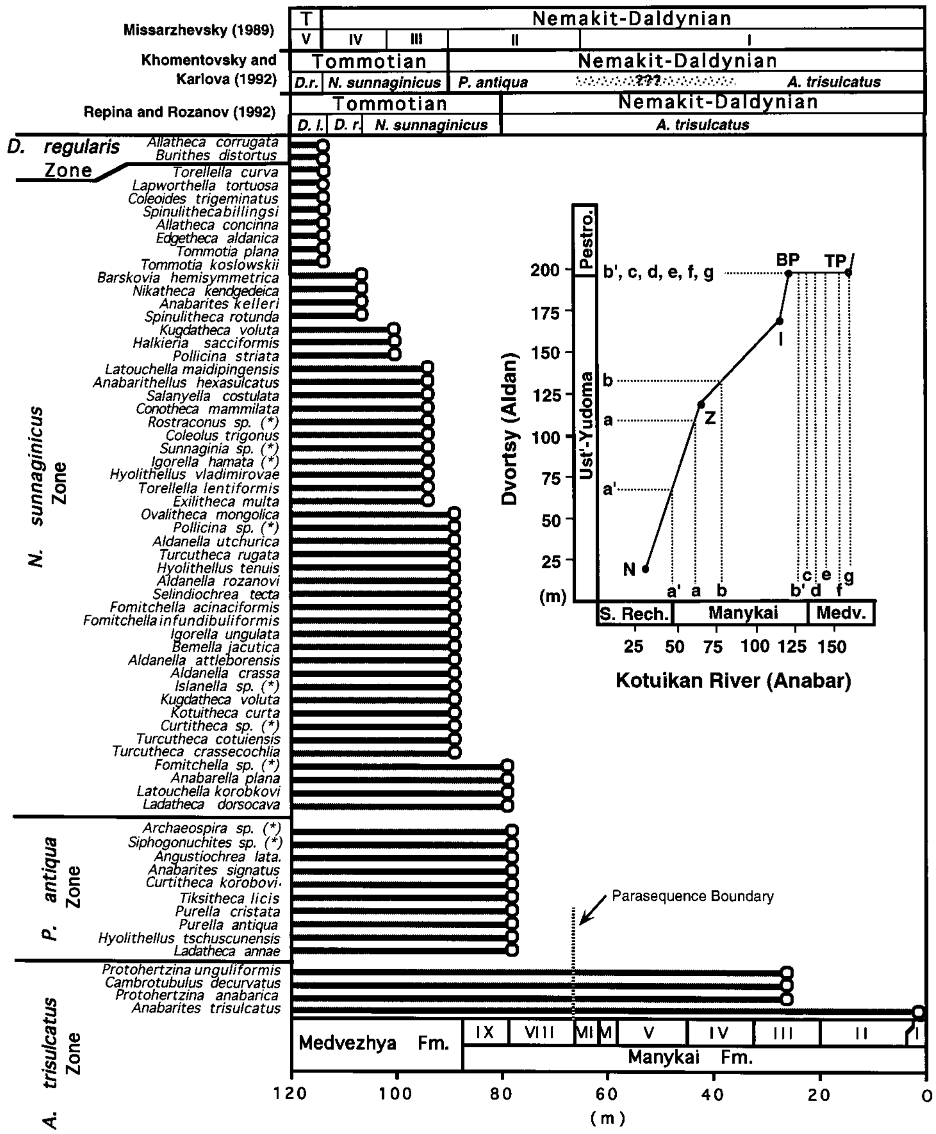

Figure 2. Stratigraphic first appearances in western Anabar region for taxa that also occur in southeastern Siberia. Zone of first appearance in southeastern Siberia is shown on left; all taxa listed as occurring in *N. sunnaginicus* zone have southeastern regional first appearances that coincide with basal Tommotian onlap. Previous biostratigraphic interpretations are shown across top. Inset shows Shaw-type diagram of Kotuikan River and composite southeastern Siberia sections (N, Z, and I as in Fig. 3; BP and TP are bottom and top of Kotuikan interval corresponding to sub-Tommotian unconformity; a and a′ indicate first appearances of multispecies *A. trisulcatus* zone faunas and monospecific *A. trisulcatus*; b indicates first appearance of *P. antiqua* zone faunas in southeastern Siberia and projection of this horizon on Kotuikan River section; b′ indicates first appearance of *P. antiqua* zone faunas in Kotuikan River section and projection of this horizon on southeastern Siberia composite section: c–g indicate successive horizons at which new taxa are introduced throughout Medvezhya Formation in western Anabar area and their projections on southeastern Siberian composite section.

kai Formations and at 2 m intervals in the Medvezhya Formation. Samples were prepared, screened, and analyzed according to protocols reported in Kaufman and Knoll (1995). With the exception of dolomites in the Lower Member of the Staraya Rechka Formation and thin dolomicrites within the predominantly siliciclastic succession of Manykai bed II, petrographic and geochemical data indicate that Anabar samples preserve little-altered C isotopic signatures. Neither are skeletons abundant in these rocks, minimizing the possibility that "vital effects" played a significant role in determining C isotopic compositions. Isotopic data for the Anabar section are shown in Figure 1 (see Kaufman et al., 1995, for complete data tables).

As originally reported by Pokrovsky and Vinogradov (1991), δ^{13}C values for Staraya Rechka dolomites are consistently negative. The lowermost carbonates in the overlying Manykai Formation are thin dolomicrites interbedded with shale in bed II. Pokrovsky and Missarzhevsky (1993) recorded δ^{13}C values as low as −6‰ in these dolomites, above which they showed a strong increase to values of ~+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 δ^{18}O values associated with the more extreme δ^{13}C values and the high potential for diagenetic incorporation of ^{13}C-depleted carbon indicate the need for caution in interpretation. Regardless of possible alteration in bed II dolomites, little-altered carbonates in the lowermost bed III also have negative δ^{13}C values (−2.0‰ to −1.5‰). Thus, the isotopic excursion to a peak of +1.8‰ occurs within bed III, coincident with a parasequence boundary and well above the accepted base of the Nemakit-Daldynian Stage. A second peak (+2.5‰) occurs near the top of Manykai bed VII, just below another parasequence boundary.

The sequence boundary that separates bed IX and the Medvezhya Formation is marked by a sharp offset in δ^{13}C, above which Medvezhya limestones increase from −1.9‰ to the most prominent peak in the entire data set (+5.4‰), 26 m above the base of the formation. Perhaps because of low sampling density, Pokrovsky and Missarzhevsky's (1993) data miss this maximal excursion. The peak is sharp; a sample just 2 m higher has a δ^{13}C of +1.9‰. Pokrovsky and Missarzhevsky (1993) provided scattered data on carbonates higher in the succession, suggesting that the drop recorded by our uppermost sample culminates in a trough of −0.9‰ to −0.7‰ some 8 m higher (Fig. 1).

Correlations with Southeastern Siberia

The strong negative C isotopic excursion near the base of the Upper Staraya Rechka Formation 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 section at Dvortsy in southeastern Siberia (Magaritz et al., 1986; Fig. 3). Three arguments favor correlation of the isotopic peak in Manykai bed III with peak Z in the Ust'-Yudoma succession at Dvortsy (Brasier et al., 1993): (1) the peaks occupy a similar position relative to both the correlated lower Staraya Rechka–basal Ust'-Yudoma troughs and larger positive excursions higher in the sections; (2) the peaks are of similar magnitude; and (3) they are both associated stratigraphically with fossils of the *Anabarites trisulcatus* zone.

The +3.3‰ C isotopic peak near the top of Manykai bed VII closely matches that found just beneath the sub-Tommotian unconformity at Dvortsy (peak I of Brasier et al., 1993; Fig. 3). In addition to their magnitudes and relative stratigraphic positions,

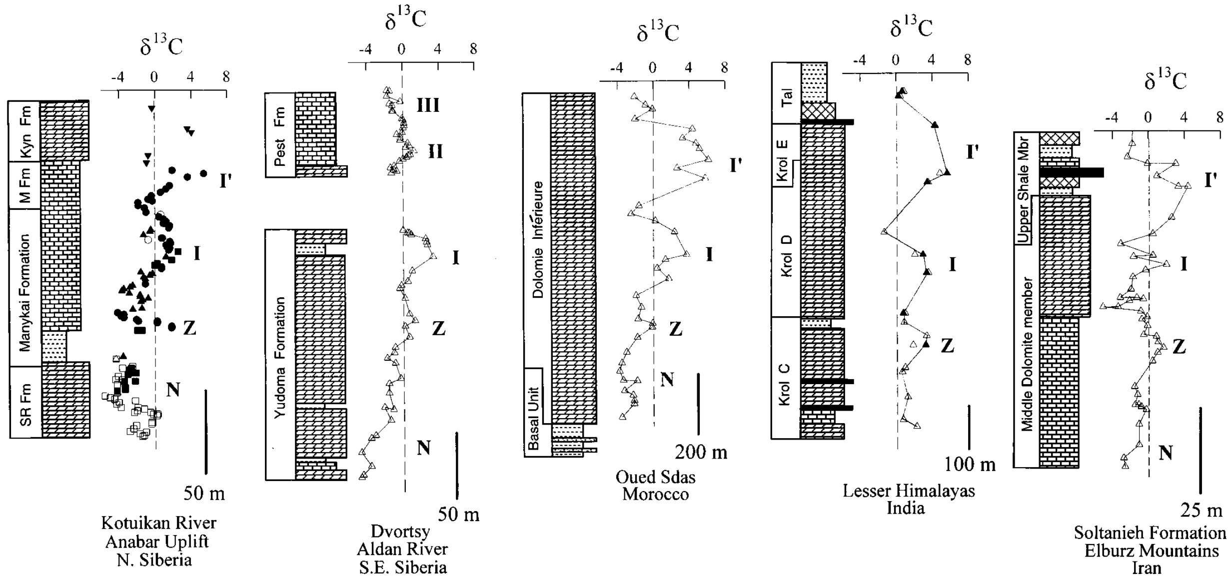

Figure 3. Chemostratigraphic correlations of Kotuikan River and Dvortsy sections with sections in Morocco (Magaritz et al., 1991), India (Aharon et al., 1987), and Iran (Brasier et al., 1990). Sub-Tommotian unconformity at Dvortsy is shown as break in section that spans interval from negative excursion above peak I to point above peak I′. N marks terminal Proterozoic negative excursion; Z, I, I′, II, and III mark successive isotopic peaks (Brasier et al., 1993). Formational names shown for each column; SR = Staraya Rechka, M = Medvyezha, Kyn = Kyndyn, Pest = Pestrotsvet.

these peaks are tethered by their stratigraphic association with relatively diverse faunas of the *Purella antiqua* zone. Particularly in sections along the Dzhanda River, ~100 km east of the Tommotian stratotype section, uppermost Ust'-Yudoma carbonates contain well-preserved faunas whose taxonomic composition compares closely with assemblages found in Manykai bed IX (Khomentovsky and Karlova, 1993).

At Dvortsy, the negative excursion immediately above peak I occurs just above the pre-Pestrotsvet unconformity in richly fossiliferous beds of the basal Tommotian *N. sunnaginicus* zone; the next peak with a magnitude >+2‰ occurs within the middle Adtabanian *Pagetiellus anabarus* zone (Brasier et al., 1993, 1994). In contrast, an uppermost Manykai trough and the strong upper Medvezhya peak both occur in beds that contain only Nemakit-Daldynian and/or Tommotian fossils. Thus, Manykai beds above the parasequence boundary shown in Figure 3 and at least the lowermost 26 m of the Medvezhya Formation have C isotopic signatures unlike anything documented in southeastern Siberia; this succession appears to record a time interval represented in southern Siberia only by the sub-Tommotian unconformity. The scattered data of Pokrovsky and Missarzhevsky (1993) are consistent with biostratigraphic correlations that assign younger Tommotian and Adtabanian ages to uppermost Medvezhya and Kyndyn rocks.

STRATIGRAPHIC AND EVOLUTIONARY IMPLICATIONS

Previous correlations between northwestern and southeastern Siberia start from the premise that identical time intervals are represented by sedimentary rocks in both regions. Coupled chemostratigraphic and biostratigraphic data force us to reject this hypothesis; nonetheless, the point in the Kotuikan River section that coincides in time with the definitional base of the Tommotian lies at least 27 m above the base of the Medvezhya Formation, close to the lower Tommotian boundary favored by Missarzhevsky (1989). The sub-Medvezhya unconformity along the Kotuikan River marks a shorter hiatus within the larger interval missing in the southeast.

Our correlation confirms that a pronounced C isotopic excursion immediately preceded the beginning of the Tommotian age, but *it is not the peak I recorded at Dvortsy*. The true sub-Tommotian isotopic peak (labeled I′ in Fig. 3) has a much greater amplitude, indicating a distinctive biogeochemical event likely to be recorded globally. Indeed, Early Cambrian peaks comparable in magnitude and stratigraphic position to that seen in the Anabar succession have been documented in Morocco (Tucker, 1986; Magaritz et al., 1991), India (Aharon et al., 1987), and Iran (Brasier et al., 1990). These have been previously miscorrelated with Dvortsy peak I, on the erronous premise that the Dvortsy section is essentially continuous (see Fig. 3).

If the above conclusion is correct, most or all of the small shelly fossils previously suggested to mark the *N. sunnaginicus* zone evolved prior to the beginning of the Tommotian, making problematic their use in the unequivocal recognition of this zone or even stage. To date there is no record of archaeocyathans in the sub-Tommotian of the western Anabar; these fossils may provide more robust markers for early Tommotian time.

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 allows us to estimate the duration of the sub-Tommotian hiatus in southeastern Siberia. The beginning of Manykai deposition correlates biostratigraphically and chemostratigraphically with the lower Kessyusa Formation in the Olenek uplift (Knoll et al., 1995); a basal Kessyusa volcanic breccia has a radiometric age of 543.9 ± 0.24 Ma (Bowring et al., 1993). Rhyolite cobbles that underlie Tommotian strata of the *Dokidocyathus regularis* zone in the nearby Kharaulakh Mountains are dated at 534.6 ± 0.5 Ma (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.

Taken together, radiometric data suggest that the 114 m interval from the initial deposition of the Manykai Formation to the 27 m level of the Medvezhya Formation lasted 9–14 m.y. The part of this succession corresponding to the sub-Tommotian unconformity composes 42% of the total section. Noting potential problems of equating sediment thickness with time, this suggests that the time interval represented at the sub-Tommotian unconformity in southeastern Siberia is about 3–6 m.y. 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 sub-Tommotian unconformity in southeastern Siberia represents a time interval that lasted at least one-third and possibly fully as long as the Tommotian Stage.

CONCLUSIONS

Our data confirm that regional first appearances of small shelly fossil taxa in southeastern Siberia are controlled by the dynamics of regional sedimentation and do not record an evolutionary burst. The Cambrian diversification of animals entered its explosive phase not at the beginning of the Tommotian, as generally accepted, but several million years earlier, during the Nemakit-Daldynian Stage. Recognition of hiatuses within basal Cambrian successions in Siberia has been hampered by an unusual paleobiological feature of the invertebrate fossil record. For an interval estimated to be as long as 15 m.y. (latest Proterozoic to Tommotian), the invertebrate record is one of continuous accumulation of taxa with no turnover by extinction. This stratigraphic distribution is unusual in terms of the younger record, but it is consistent with the idea that Early Cambrian ecosystems may have been more tolerant of new genetic variants.

Sequence stratigraphy, with its emphasis on unconformities, reinforces Darwin's conviction that geologic history is replete with missing pages; however, sedimentary dynamics require modification of his metaphor. Individual sections may be books with many missing pages, but in different places different parts have been excised. Therefore, by interleaving pages from multiple sections, a more complete history may be recovered. The integration of biostratigraphic, chemostratigraphic, and sequence stratigraphic data with radiometric determinations enables us to recognize a significant and hitherto unrecognized chapter of early animal evolution in the western Anabar region of Siberia, one that fits neatly into the gap marked by the sub-Tommotian unconformity in southeastern Siberia.

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