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ABSTRACT

New and revised Early Cambrian biostratigraphic data allow a quantitative analysis of changes in biotic diversity and extinction rate. The mid-Early Cambrian extinction can now be resolved into two distinct events: the well-known early Toyonian Hawke Bay regression event, and a newly observed but more severe disruption during the early Botomian, here named the Sinsk event. During the Sinsk event, the shallow-water benthos of the so-called Tommotian fauna, together with archaeocyaths and some trilobites, underwent a rapid decline. The Sinsk event is characterized by the significant accumulation of nonbioturbated laminated black shales in tropical shallow waters. Lamination is due to the fine alternation of clay- and organic-rich laminae with calcite-rich laminae containing abundant monospecific acritarchs. These shales are enriched by pyrite and elements typical of anoxic conditions and support a benthic biota of dysaerobic character. Our observations suggest that the extinction during the early Botomian was caused by extensive encroachment of anoxic waters onto epicontinental seas, associated with eutrophication and resultant phytoplankton blooms.

INTRODUCTION

The timing and pattern of the Cambrian "explosion" that marked the rapid appearance of many invertebrate groups is now relatively well established. Yet what is less-well documented is that only some 15 m.y. after the beginning of the Cambrian many of these groups were decimated by a major extinction event. This event preferentially eliminated elements of the "Tommotian fauna" (sensu Sepkoski, 1992), including the archaeocyaths, other reef-associated fauna, and many trilobites. In contrast, most elements typical of the "Cambrian fauna" (sensu Sepkoski, 1992), including some trilobites, lingulate brachiopods, and echinoderms, continued to proliferate.

Although this Early Cambrian extinction has long been recognized as the first of the Phanerozoic (Newell, 1972; Signor, 1992), poorly constrained stratigraphic correlation and systematic uncertainties have hindered its detailed study. We present here an analysis of both lithological and quantitative palaeontological data to detail the exact timing of, and possible processes responsible for, this extinction.

METHODS

A new integrated Early Cambrian stratigraphic framework has been assembled from recent biostratigraphic correlations (Zhuravlev, 1996). We have calculated global generic diversity for the following major Early Cambrian invertebrate groups: archaeocyaths, trilobites, brachiopods, hyoliths, mollusks, and small shelly fossils. They compose a total of 1617 genera (data are available from the authors on disk).[1] From these we derive extinction rates (Fig. 1). Diversity data have also been assembled on a regional basis from the well-documented faunas of Mongolia, the Siberian Platform, and Gondwana (Australia, Antarctica, south China, Spain, France, Sardinia, and Morocco) (Fig. 2). All regional data consist of species diversity plots, except for the small shelly fossils and mollusks of the Siberian Platform, where generic data were used. Trilobite genera data from a black shale facies on the Siberian Platform (Kuonamka Group) were also assembled to demonstrate the absence of taphonomic and collection biases in the data set (Fig. 2B).

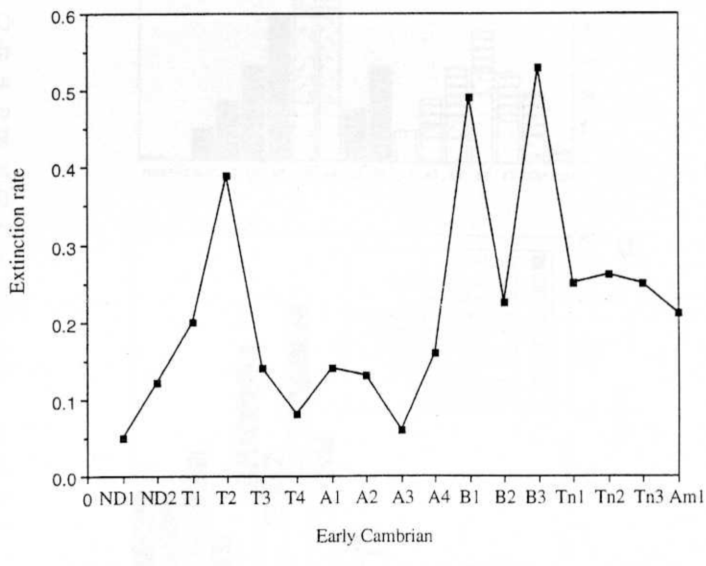

Figure 1. Extinction rate (extinct genera/total genera per stratigraphic interval) of Early-Middle Cambrian metazoans. ND = Nemakit-Daldynian; T = Tommotian; A = Atbadanian; B = Botomian; Tn = Toyonian; Am = Amgan.

[1]Data Repository item 9616, the genera data set and references, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

Data Repository item 9616 contains additional material related to this article.

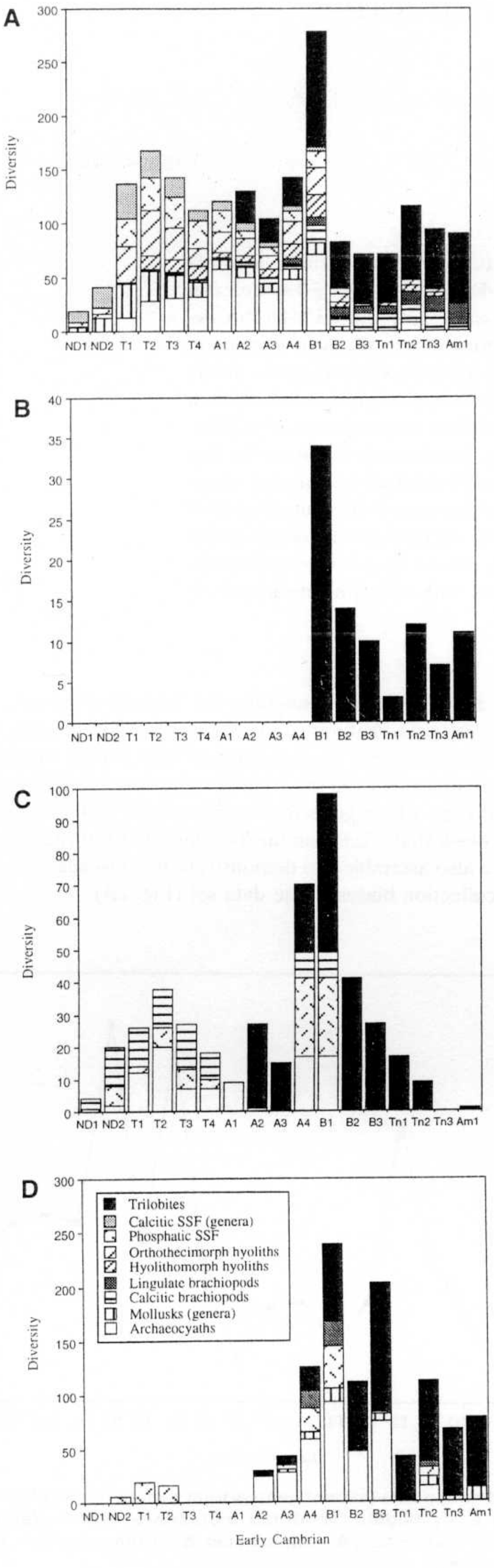

Figure 2. Early Cambrian species diversity for (A) Siberian Platform, (B) Siberian Platform Kuonamka Black Shale trilobites, (C) Mongolia, (D) Gondwana. ND = Nemakit-Daldynian; T = Tommotian; A = Atbadanian; B = Botomian; Tn = Toyonian; Am = Amgan.

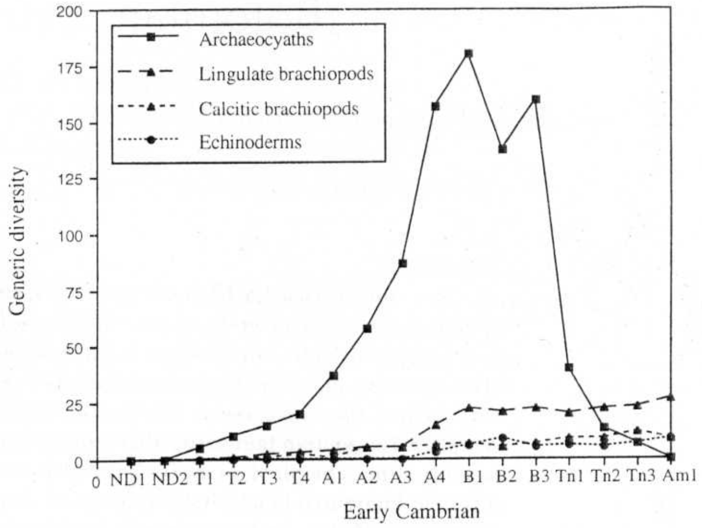

Figure 3. Early Cambrian generic diversity of archaeocyaths, calcitic brachiopods, lingulate brachiopods, and echinoderms. ND = Nemakit-Daldynian; T = Tommotian; A = Atbadanian; B = Botomian; Tn = Toyonian; Am = Amgan.

RESULTS

Quantitative analysis of global generic diversity and extinction rate show marked changes in diversity through the Early Cambrian (Figs. 1, 2, and 3). First, a peak in extinction rate is noted in the mid-Tommotian (Fig. 1), which is expressed regionally on the Siberian Platform, in Mongolia, and on Gondwana (Fig. 2). This extinction reflects mainly the decline of the orthothecimorph hyoliths and some small shelly fossils. However, the severity of the extinction is likely to be exaggerated due to taxonomic oversplitting.

More striking are two further major extinction events noted in the mid-Early Cambrian, in the early Botomian and early Toyonian. The latter event is related to the well-known Hawke Bay regression (Palmer and James, 1979). This regression alone was previously thought to be responsible for the Early Cambrian extinction, but our analysis reveals that most of the extinctions took place during an earlier event. The most pronounced extinction occurred in the early Botomian (approximately at the *micmacciformis–Erbiella-gurarii* zone boundary) and is noted on all major continents and terranes of the Early Cambrian world (Fig. 2). This event follows a prolonged period of rapid diversification and is here named the Sinsk event after the section on the Siberian Platform where the event is most prominent. The Sinsk event is responsible for a severe reduction of the "Tommotian fauna," and a marked reduction in trilobite and archaeocyath global diversity. In contrast, echinoderms and lingulate brachiopods appear to be unaffected (Fig. 3).

The data concerning Laurentia are not presented here, although analyses of key areas (Sonora: Stewart et al., 1984; Great Basin: Onken and Signor, 1988; Mackenzie Mountains: Voronova et al., 1987) show a reduction in overall diversity during the Sinsk event.

SEDIMENTOLOGICAL OBSERVATIONS

Stratigraphic successions worldwide indicate the deposition of sediments under lowered oxygen conditions during the early Botomian (Fig. 4). Varved black shale facies are present within the Sinsk Formation and its coeval strata on the Siberian Platform (Bakhturov et al., 1988), the Parara Limestone in South Australia (Clarke, 1990), and the Qiongzhussi Formation and coeval strata on the Yangtze Platform (Coveney and Nansheng, 1991). In addition, sim-

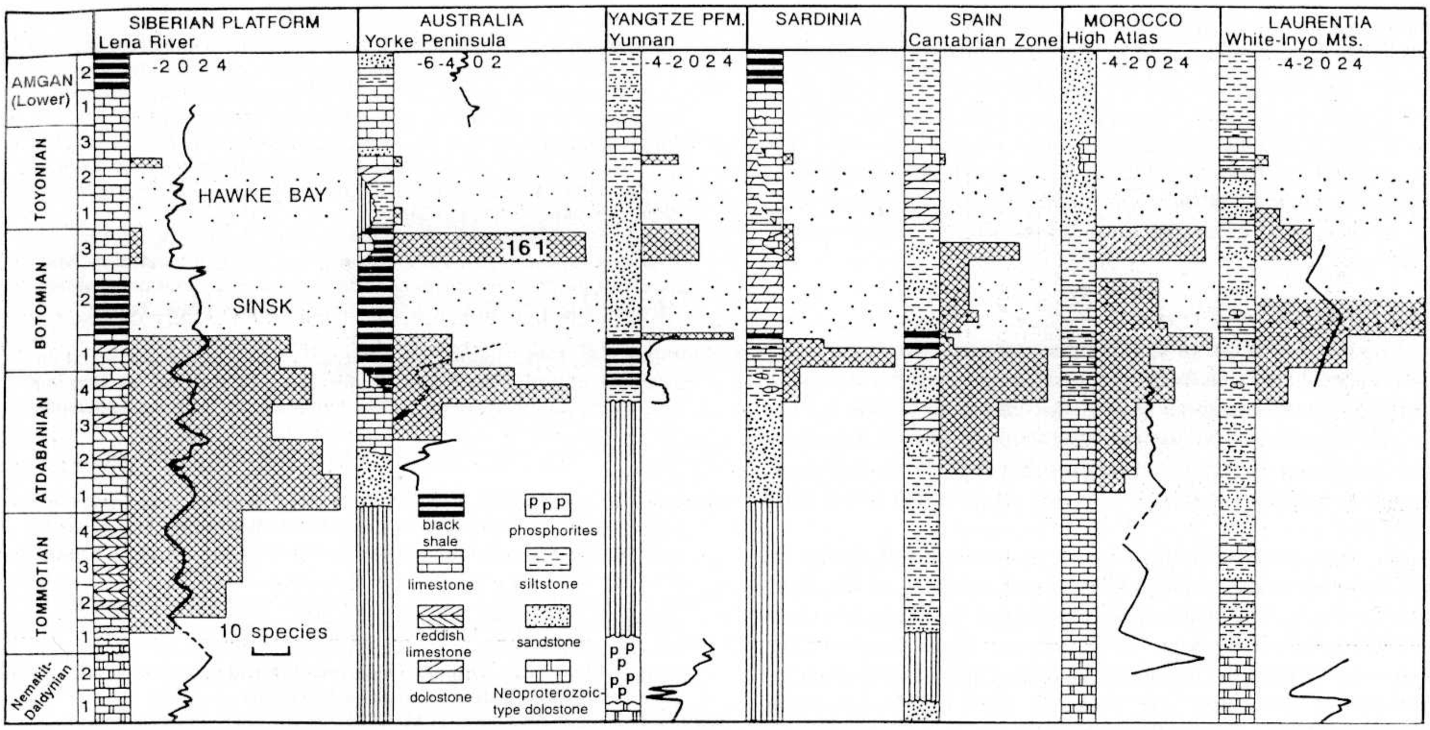

Figure 4. Generalized Early-Middle Cambrian lithological sections, together with regional archaeocyath species diversity and $\delta^{13}C$ curves (from Kirschvink et al., 1991; Brasier et al., 1994). Proposed timings of Sinsk and Hawke Bay extinction events are given.

ilar facies are noted in terranes from the Altay Sayan fold belt, Transbaikalia, the Russian Far East, Kazakhstan, and Mongolia (Astashkin et al., 1995).

The facies of Kuonamka Group on the Siberian Platform, together with coeval organic-rich carbonates, cover more than 750 000 km^2 (Bakhturov et al., 1988). The extent of these facies was probably far greater, because similar organic-rich facies are noted from the East Kolyma uplift and Eastern Transbaikalia. In particular, the Sinsk Formation facies include bituminous limestone, chert, and argillaceous, siliceous, or calcareous sapropelic black shales, all with a high syngenetic pyrite content. The cherts contain up to 4% organic carbon and the shales contain up to 30% (Bakhturov et al., 1988). The shales commonly show well-expressed submillimetric laminations consisting of an alternation of light calcite and brown clay-rich laminae. The calcitic laminae contain pellets, intraclasts, and abundant monospecific acritarchs of the *Micrhystridium* group. The clay-rich layers contain finely disseminated organic matter. X-ray fluorescence spectroscopy indicates enrichment in minor and trace elements corrected by elements Al (10^4) ratio (V = 176, As = 32, Cr = 19, Cu = 67, Ni = 32).

The Sinsk fauna is represented by trilobites, spicular sponges, rare mollusks, hyoliths, palaeoscolecidans, *Margaretia*, *Obruchevella*, and the abundant lingulate brachiopods. Two ecologically distinct groups of monotypic trilobites can be distinguished (Repina and Zharkova, 1974): polymeroids with morphotypes typical of nektobenthic trilobites adapted to dysaerobic conditions (Fortey and Wilmot, 1991), and miomeriods (pagetids and eodiscids) with degenerated eyes. The whole fauna bears features of the dysaerobic fauna.

The Parara Limestone in South Australia is composed of dark gray, argillaceous mottled limestone relatively undisturbed by bioturbation, and has fine-grained organic matter and pyrite concentrations (Clarke, 1990).

On the Yangtze Platform, black shale facies are known from western Yunnan to Zhejiang Province, in a belt more than 2000 km wide. These sedimentary rocks are commonly phosphatic (e.g., the Niutitang Formation, which is also enriched in Mo, V, U, Ag, and Cu), and contain lenses and pellets of organic matter (Coveney and Nansheng, 1991). The Yu'anshan member of the Qiongzhussi Formation exemplifies the early Botomian deposits of this region, consisting of dark, mainly finely laminated and nonbioturbated, carbonate- and pyrite-rich mudstone. It has been proposed that anoxic water repeatedly invaded the area to account for the peculiar preservational mode of much of the Qiongzhussi fauna (Erdtmann et al., 1990).

DISCUSSION

The presence of extensive black shale deposition in early Botomian sections worldwide suggests the occurrence of a widespread anoxic event, which is probably related to the major Early Cambrian transgression (Rowland and Gangloff, 1988). The oceanic anoxic event model however, which requires the migration of anoxia in response to the transgression of oxygen-depleted bottom waters onto shelves, presents a partial explanation only for these Early Cambrian sequences.

Prominent phosphate formation observed globally in early Botomian strata (Shergold and Brasier, 1986; Bakhturov et al., 1988) demonstrates that widespread nutrient-enriched upwelling occurred at this time. Abundant fleshy algae, including chlorophytes such as *Margaretia* and *Yuknessia*, thrived during the Sinsk event on the Siberian and Yangtze platforms. Minor and trace element enrichment characterizing the strata of the Siberian and Yangtze platforms may be due to the presence of high concentrations of organic matter, which can effectively trap metals in euxinic bottom waters (Leventhal, 1991; Calvert and Pedersen, 1993).

Rhythmic laminations of the type observed in the Sinsk Formation are a common result of regular, possibly seasonal, phytoplankton blooms. Such blooms facilitate CO_2 extraction: hence the "summer" precipitation of calcite layers, interleaved with clay-rich layers formed in "winter" seasons (Hollander et al., 1992). Varved microfacies similar to those observed in the Sinsk Formation have been noted from a number of present-day eutrophied marine and lacustrine basins (Brodie and Kemp, 1994; Anderson et al., 1994). Such basins are prone to hypertrophy, which leads to persistent phytoplankton blooms, resulting in anoxic steady states that eliminate much of the benthos. Thus, in the beginning of the transgressive event, a phytoplankton bloom might contribute to the extinction by lowering oxygen levels and hence suppressing certain elements of the biota.

CONCLUSIONS

Major regressions, or severe transgressions, accompanied by anoxic events have been frequently marshalled to explain extinction events. We know little about ancient epicontinental oceans, but perhaps the presence of lamination resembling limnic varving in the Sinsk Formation suggests that lakes rather than modern thalassic basins may be closer analogs to the vast, shallow seas of the Early Cambrian.

We here propose that an anoxic event occurred during the Early Cambrian that preferentially suppressed parts of the Early Cambrian biota. The differential response of the fauna is evident from detailed diversity data, the Tommotian fauna (sensu stricto) undergoing widespread extinction and the Cambrian fauna (sensu stricto) diversifying twice (see Sepkoski, 1992, Fig. 11.4.2) during both the Sinsk and Hawke Bay events.

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