

Climates and climate zonality of the Vendian: geological evidence

N. M. CHUMAKOV

*Geological Institute, Russian Academy of Sciences, 7 Pyzhevsky pereulok,
119017 Moscow, Russia (e-mail: chumakov@ginras.ru)*

Abstract: In view of the difficulties of stratigraphic correlation, the absence of being able to position continents reliably, the scarcity of climate indicators, and the fact that Vendian sequence crops out over a wide area and can be far apart, it has only so far been possible to identify the most general climatic features for three Vendian units. Late Vendian (Nemakit–Daldyn), and possibly Early Tommotian (Early Cambrian), time was characterized by a glacial climate with pronounced climatic zonation. It appears that there were northern and southern cold zones and a low-latitude, possibly mid-latitude warmer zones. Throughout the time the Middle Vendian sequence was being deposited (Redkino–Kotlin), a warm, possibly arid zone was characteristic of low and mid-palaeolatitudes. In southern high latitudes, there is evidence of a warm humid climate at some periods during this time. The Early Vendian (Laplandian or Varangian) time was characterized by a glacial climate. Some palaeocontinental reconstructions based on magnetism suggest that these glaciations affected high, middle and most of the low latitudes, extending to the palaeoequator. The timing of glacial events in the late Neoproterozoic and their extent across the globe and severity is a topic of great debate at the moment—some researchers suggesting glaciations that lasted for millions of years that locked the entire Earth in solid ice ('Snowball Earth'). Others suggest that some ice-free oceans were present even during the most severe of glacial events and certainly some geological evidence seem to fit this latter hypothesis well.

Direct application of palaeoclimatic reconstruction methods developed for the Phanerozoic (Semikhatov & Chumakov 2004), in the Vendian is hampered by several difficulties. The first arises as a result of the lack of resolution of chronostratigraphy when compared with the precision of the Phanerozoic schemes. In some of the best understood sequences the late Neoproterozoic has been divided into up to five widely correlative units based on trace fossils, microfossils, metazoans, radiometric dates, stable isotope signatures and characteristic glacial horizons (Knoll 2000; Walter *et al.* 2000). But in many Vendian sections world-wide, the set of stratigraphic data is insufficient to allow recognition and broad correlation. On the global scale, only three units in time equivalent sequences can currently be distinguished and correlated.

The second difficulty in studying Vendian palaeoclimates arises from the lack of general agreement on continental reconstructions, with available reconstructions differing greatly. It would be of great value, as has been suggested by many researchers, to cross-check reconstructions arrived at by use of palaeomagnetic evidence, with palaeoclimatic indicators (Khain & Yasamanov 1987; Smith 2001; amongst many others).

The third difficulty affecting the reconstruction of Precambrian climatic zones is that, with increased age, the number of lithological and palaeontological climate indicators vanish and geochemical indicators decrease, through alteration, recycling and thus resetting of the 'climate-signal'. The principle lithological indicators useful for Vendian/Ediacaran palaeoclimate reconstruction are tillites,

evaporites (gypsum and salts) and carbonate platform sediments. Red beds, especially those lacking carbonate cement, are more ambiguous in their climate signal (unless, of course, there are additional indicators: mineralogical, structural, etc.). Indicators of humidity levels are particularly scarce in the Vendian. Bauxites occur only in exceptional cases and their origin is frequently unclear. Grey, terrigenous rocks are generally not reliable as indicators of humid conditions, though some researchers have invoked such. Grey colour is often of secondary origin in these ancient rocks. So, in practice, palaeoclimatic reconstructions are mainly based on indicators such as tillites, evaporites and carbonate platforms. This can lead to an exaggerated estimate of glacial and arid zone distribution at the expense of humid zones. Bio-lithological indicators are primarily limited to the occurrence of stromatolitic reefs, which occur occasionally as thick sequences, indicative of a warmer climate.

Finally, present-day outcrop areas of Late Precambrian deposits are separated by considerable distance. This also limits the accuracy of reconstructions.

These restrictions allow only the most general conclusions on global climates of the Vendian to be drawn.

Stratigraphic and palaeogeographic framework

The stratigraphic distribution of climatic indicators in some of the key sections of the Vendian System on five continents is summarized in Figure 1.

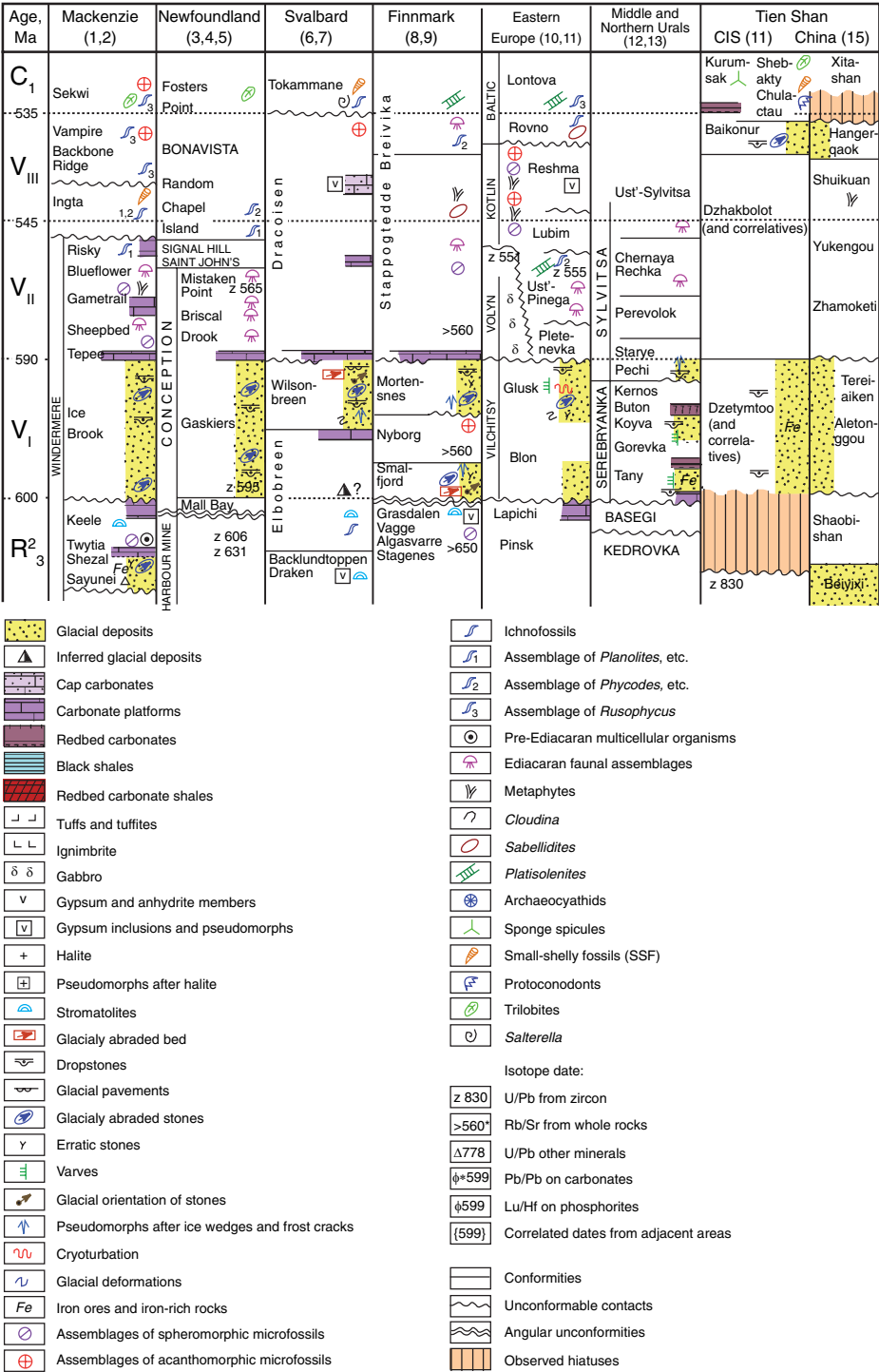


Fig. 1. Attempt at correlation of glacial horizons and other climatic indicators in key sections of the Vendian. The names of supergroups, groups, and subgroups are in capital letters, and those of formations and smaller stratigraphic units are in lower case. V_I, V_{II}, and V_{III} denote the 'Early,' 'Middle,' and 'Late Vendian'—informal units used in this paper. References: 1, Narbonne & Aitken 1995; 2, Walter *et al.* 2000; 3, Myrow 1995; 4, Myrow & Kaufman 1999; 5, Narbonne & Gehling 2003; 6, Chumakov 1978*b*; 7, Harland *et al.* 1993; 8, Vidal 1981; 9, Gorokhov *et al.* 2001; 10,

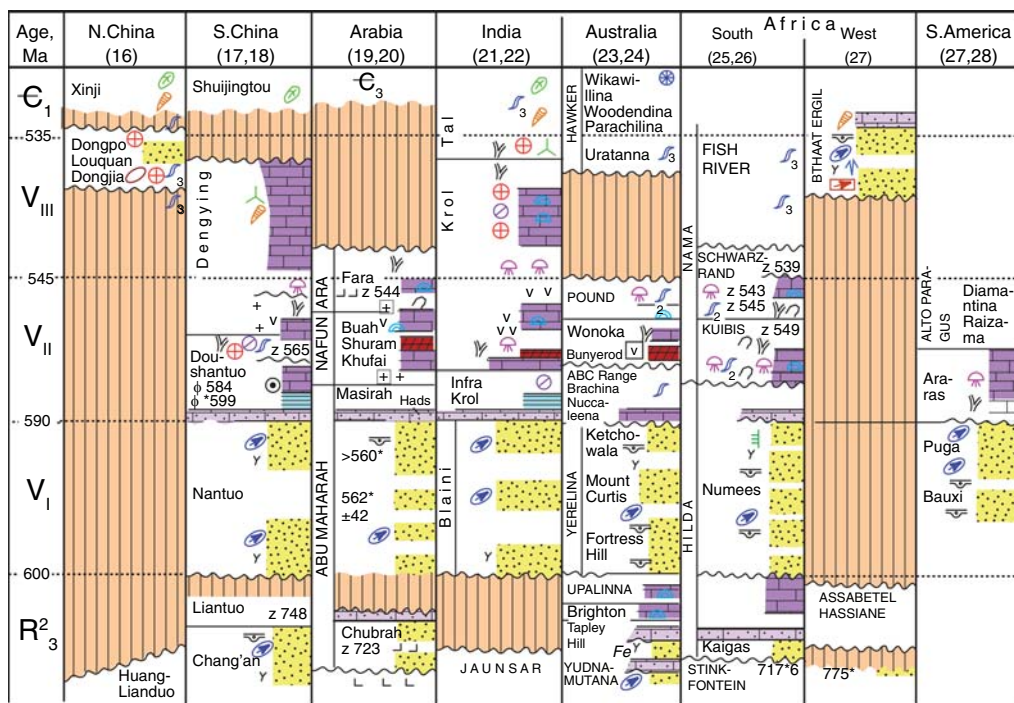


Fig. 1. (Continued) Aksenov 1990; 11, Vidal & Moczydlowska 1995; Martin *et al.* 2000; 12, Bekker 1992; 13, Chumakov 1998; 14, Kiselev & Korolev 1981; 15, Hambrey *et al.* 1981; 16, Bobrov 1965; Chumakov 1993; Pokrovsky *et al.* 2005. 17, Wang *et al.* 1998; 18, Zhang *et al.* 1998; Barfod *et al.* 2002; Condon *et al.* 2005; Yin *et al.* 2005; 19, Brasier & McCarron 2000; 20, Leather *et al.* 2002; 21, Tiwari & Knoll 1994; 22, Tiwari 1999; 23, Preiss 2000; 24, Walter 2000; Calver 2000; 25, Germs 1995; 26, Walter *et al.* 2000; 27, Trompette 1994, 1996; 28, Alvarenga & Trompette 1998, 1992.

Suggested correlations between Vendian and Ediacaran Systems are shown in Table 1. Based on the distribution of Small Shelly Fossils (SSF) and other metazoans, multicellular algae, trace fossils and microfossils, glacial horizons and radiometric dating, it is possible to define three divisions of the Vendian, which are loosely referred to here as 'Early,' 'Middle,' and 'Late' Vendian and are designated V_I, V_{II}, and V_{III} in Figure 1. The Early Vendian contains one or, in some regions, two glacial horizons (one at the base—Lower Blon' Subformation, Smalfjord Formation etc.; another at the top—Glusk and Mortensnes formations, etc.), and is characterized by a significant negative $\delta^{13}\text{C}$ at the base and the top. New data provide some evidence of correlation of the upper glacial formations of the Lower Vendian with the Gaskiers Formation of Newfoundland, dated at *c.* 580 Ma (Knoll *et al.* 2004). The base of lower glacial formations of the Lower Vendian may be correlated to the base of the glacial Nantuo Formation *sensu stricto* (age between 635 and 663 Ma; Zhou *et al.* 2004; Condon *et al.* 2005) or to the base of Nantuo Formation *sensu*

lato (including Gucheng Formation; Evans 2000) of age >663 Ma (Zhou *et al.* 2004). The Middle Vendian contains primitive ichnofossils, specific assemblages of acanthomorphic acritarch, metaphytes and Ediacaran metazoans and is radiometrically dated at between 580 Ma and *c.* 545 Ma (Semikhatov 2000). The Late Vendian is characterized by the Nemakit–Daldyn assemblage of small shell fossils, complex ichnofossils, at the top by a significant negative $\delta^{13}\text{C}$ and glacial horizons in some regions, along with radiometric dates between 545 and 535 Ma (Semikhatov 2000).

Early, Middle and Late Vendian correspond, on the Russian Platform, to: (a) the Laplandian glacial horizon (comprising the Glusk and Blon' formations); (b) the Redkino and Kotlin horizons; and (c) the Rovno horizon of B. S. Sokolov (1998). In Siberia, a likely stratigraphic correlative of the Rovno horizon is the Nemakit–Daldyn stage. Outside Russia, these three parts of the Vendian are usually referred to as Varangerian (comprising Smalfjord, Nyborg and Mortensnes formations), Ediacaran, and pre-Tommot Cambrian.

Table 1. Accepted correlation between Vendian and Ediacaran Systems

		Vendian System Sokolov 1998 (with some additions)	Ediacaran System Knoll <i>et al.</i> 2004	
Lower Cambrian	Tommotian Stage $\approx$ 535 Ma		Lower Cambrian 543 Ma	
Vendian System	V _{III}	Nemakit-Daldyn Stage		
	V _{II}	Kotlin Horizon Redkino Horizon	Ediacaran System 620 Ma	Gaskiers Glaciation
	V _I	Laplandian Horizon (Varangerian)		
		>635–<660/ >660 Ma		
Upper Riphean			Cryogenian	

Thus, the intervals for which Vendian palaeoclimatic reconstructions might be possible are comparable in duration to long stages in the Phanerozoic (V_{III}) or to the longest Phanerozoic periods (V_I).

The use of palaeogeography as a basis for palaeoclimatic reconstruction is more complex than it might seem (Chumakov 1992; Kirschvink 1992a; Scotese & McKerrow 1990; Dalziel *et al.* 1994; Young 1995; Mossakovsky *et al.* 1996; Piper 2000; Scotese 2000; Dalziel & Soper 2001; Smith 2001; Kheraskova *et al.* 2003; Smith & Pickering 2003; and many others). Many of these reconstructions are similar with regard the positioning of the main continents, but differ significantly with respect to location of microcontinents. This situation reflects the vigorous effort being made to refine such reconstructions—and, indeed, many of these are beginning to converge. In this paper, the palaeoclimatic schemes are based on the palaeogeographic reconstructions proposed by Smith & Pickering (2003) for the Early Vendian (600 Ma), and on tentative ones proposed by Smith (2001) for the Middle Vendian (580 Ma) and the earliest Cambrian Period (540 Ma). Following recommendations of the International Stratigraphic Commission, Smith assigned the Nemakit–Daldyn stage to the earliest Cambrian. In this paper and in Russia generally, this stage is regarded as Late Vendian. Smith's reconstructions were based on the most reliable palaeomagnetic and palaeotectonic data available at the time of publication, placing early Vendian tillites in high and middle latitudes. This may not now always be the case. In

this paper, Smith's reconstructions are used with insignificant changes, as explained below.

Climatic zonation of the Late Vendian (Nemakit–Daldyn, 'V_{III}')

Climatic indicators of the V_{III} (Fig. 1) were plotted on Smith's (2001) palaeogeographical reconstruction for 540 Ma. These indicators suggest the existence of three roughly east–westwardly trending climatic zones during the Late Vendian (possibly earliest Cambrian): two zones of cold climate (northern and southern), delimited by glacial deposits, and a third zone with evidence of a warm, locally arid zone (Fig. 2c). The northern zone includes glacial deposits deposited near end of Vendian time on the Tarim and North China blocks (Hambrey *et al.* 1981; Yin & Guan 1999). A glacially-striated basement occurs locally in sequences on the North China block beneath glacial deposits (Guan *et al.* 1986). According to Smith's (2001) reconstruction, at the peak of this glaciation, terrestrial ice sheets in the northern hemisphere could have reached a palaeolatitude of 45° north. The southern cold zone, developed during Early Cambrian or Late Vendian times, is exemplified by glacial deposits in north and west Africa (West African Glacial Horizon—Chumakov 1993; Bertrand–Sarfati *et al.* 1995; Trompette 1997), which may have been limited to the high southern palaeolatitudes (approximately 75° S). The original geographical positions of Late Vendian glacial deposits in Kazakhstan and Tien

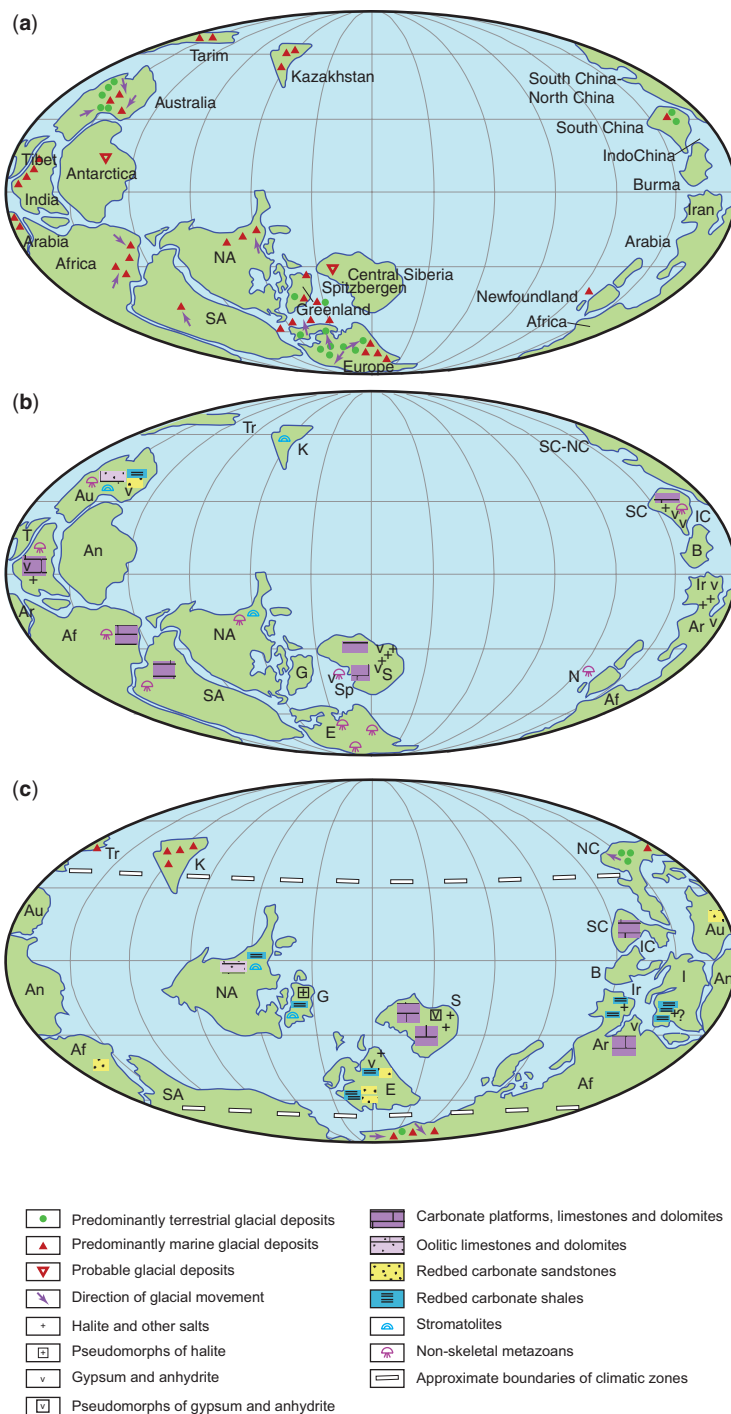


Fig. 2. Schemes of the Vendian zonation (palaeogeographic basis is modified after Smith (2001) and Smith & Pickering (2003): (a) Early Vendian (Laplandian or Varangian time); (b) Middle Vendian (Redkino–Kotlin time); (c) End of the Vendian—? beginning of the Early Cambrian (Nemakit–Daldyn, ? early Tommotian time). Au, Australia; An, Antarctica; Ar, Arabia; Af, Africa; B, Burma; G, Greenland; E, North-eastern Europe; I, India; IC, Indo-China; Ir, Iran; K, Kazakhstan blocks; N, Newfoundland; S, Central Siberia; NA, North America; NC, North China; T, Tibet; Tr, Tarim; Sp, Spitsbergen; SA, South America; SC, South China.

Shan (Baikonur Glacial Horizon—Chumakov 1978) are not well defined. Smith (2001) associated these tectonic blocks with the Siberian block, all located in low latitudes of the southern hemisphere. Considering the similarity of Vendian to Cambrian sequences (in particular their glacial deposits) of the Tien Shan, Kazakh blocks, Tarim blocks, and taking into account minimal subsequent movement, it seems most logical that the Kazakh, Tien Shan and Tarim blocks were relatively close to each other in the northern hemisphere. This positioning of the Kazakh, Tien Shan and Tarim blocks is more consistent with the tectonic ideas about make-up of the Central Asian fold belt (Mossakovsky *et al.* 1996; Kheraskova *et al.* 2003). Separating the cold zones during Nemakit–Daldyn time, was a warmer belt in which predominantly stromatolitic and oncolitic carbonate platforms were forming (northwestern North America, Siberia, Arabia and South China). Much of this zone was arid, as indicated by extensive deposits of salt, gypsum and anhydrite in Siberia (Zharkov 1981; Khomentovsky 1990), Arabia (Brasier *et al.* 2000; Walter *et al.* 2000), Iran and northwestern India (Strauss *et al.* 2001). Sabkha-type gypsum-bearing deposits and imprints of salt and gypsum crystals and anhydrite nodules are known outside these basins as well. All attest to a warm to hot arid climate in low and some middle latitudes in Nemakit–Daldyn time. Carbonate red beds of this age are known from South Africa (Germs 1995) and Australia (Walter *et al.* 1995). Non-carbonate red beds, showing evidence of aridity gypsification, halite films and desiccation cracks (Aksenov 1990) occur in the Reshma Formation in the East European Craton and in north India (Tiwari 1999; Kumar *et al.* 2000). These terrigenous red beds, including carbonate-bearing sediments, were deposited at midlatitudes between cold and warm zones and may have formed in semi-arid climate. According to the reconstruction used in this paper, the southernmost occurrence of polymict red bed lay at palaeolatitude of 60° south (Suvorovo Formation in the southwestern Ukraine). All of the above data give some support for the cold zone of the southern hemisphere being restricted to high latitudes, with the midlatitudes hosting a semi-arid or arid belt. Of course, all of these reconstructions depend heavily on precise dating of the sediments so that climatic events are contemporaneous and at the moment there is lively discussion and disagreement that may lead to quite different conclusions in the future.

Analysis of the palaeoclimatic reconstruction for the Nemakit–Daldyn stage leads to three essential conclusions. First, the latitudinal positions of two

cold and warm climatic belts are consistent with the principal climatic trends on Earth and, hence, Smith's (2001) palaeoclimatic reconstruction at the moment appears consistent with observed palaeoclimatic indicator distribution. The second conclusion is no less important: the climate during the Late Vendian times was glacial. The existence of an extensive Late Vendian glaciation is consistent with a large negative anomaly of $\delta^{13}\text{C}$ at the Vendian–Cambrian boundary (Knoll 2000) and deposition of cap carbonates signalling the end of the glaciation (Kazakhstan and Tien Shan: Chumakov 1978, 1992; West Africa: Trompette 1997). Lastly, the climatic zoning at the end of the Vendian was asymmetrical, a pattern similar to such zonation during Phanerozoic glacial episodes.

Climatic zonation of the Middle Vendian (Kotlin–Redkino; Ediacaran; 'V_{II}')

Smith's reconstructions for the Middle Vendian (Fig. 2b) are consistent with the distribution of carbonate platforms at low and middle latitudes (deposits currently found in Australia, Kazakhstan, North India, Arabia, South Africa, South America, Siberia and South China). Deposition of salts and gypsum in North India, Siberia, South China and in the region of the present-day Persian Gulf testifies to the wide distribution of arid environments within this climatic zone. The evaporite basins of the south Siberian and Iranian–Arabian regions are of enormous proportions. The latter probably included northwestern Hindustan. To the south of this warm zone, in high latitudes in the East European craton and in the Cis-Ural region, the sediments that accumulated in the seas invading the shallow Valdai Basin were dominated by bluish-grey, fine-grained, thin-bedded clays and siltstones, some enriched in organic matter, which preserved the characteristic Ediacaran metazoans along with metaphytes. In the marginal parts of the Valdai Basin, fine-grained and thin-bedded rocks graded into coarser grained non-carbonate, variegated red beds containing an admixture of kaolinite; indicative of erosion under humid conditions. This suggests that the land adjacent to the Valdai Basin was under the regime of a warm and humid climate. Thus, the climate in the high latitudes during the Middle Vendian times was humid and relatively warm, consistent with the lack of glacial indicators preserved in Middle Vendian deposits.

Climatic zonation of the Early Vendian (Laplandian or Varangian, 'V_I')

Evidence of glaciation is widespread in Lower Vendian deposits. There are two glacial units in

the Lower Vendian: one in the lower part and one in the upper part (Fig. 1). These lower glacial unit occurs on many large continents, and on some microcontinents as well. These units are located on the northeastern European craton with adjacent orogenic zones (Chumakov 1990, 1992; Harland *et al.* 1993), South Africa (Germs 1995), the Lesser Himalayas (Tiwari & Knoll 1994; Kumar *et al.* 2000), Australia (Preiss 1987, 2000; Walter 2000), and South China (Wang *et al.* 1998), as well as some other regions (Figs 1, 2a). In addition to those mentioned above, there are numerous occurrences of Lower Vendian diamictites whose age or origin is not well constrained (for a review see Evans 2000). The diversity of published continental reconstructions suggest that many of these glacial deposits were formed at low latitudes, some on the Equator. Such a wide latitudinal distribution indicates a profound glacial climate at beginning of the Early Vendian. Non-glacial facies of this time have not been identified. They may have been removed by the glacio-eustatic subaerial exposure of the continental shelves and inland basins.

This rock-record points to a severe glacial event on Earth at the beginning of the Early Vendian. Some authors supposed that this glaciation was global (Harland 1964; 'Snowball Earth' of Kirschvink 1992b; Hoffman & Schrag 2002 and others). Although there are currently no compelling counter-arguments against the 'Snowball Earth' hypothesis, which suggests that the entire Earth was covered by ice—serious doubts as to its validity do exist. There are a number of reasons for these doubts.

1. There are numerous indications of frequent glacial oscillations within the Lower Vendian and Upper Riphean sequences (Chumakov 1992, 1998, 2004; Condon *et al.* 2002; Hambrey *et al.* 1981; Leather *et al.* 2002 etc.). Typical examples are the glacial sequences of Belarus (Chumakov 1992) and of the Middle and South Urals (Chumakov 1998). The Vil'chitsy Group of Belarus consists of two units; the lower Blon' Formation and the unconformably overlying Glusck Formation (Fig. 3). The Blon' Formation is composed of glacial sediments at the base and interglacial sandstones and sandy dolomites in its upper part. In the most complete sections, the Glusck Formation includes three till members separated by varved clays with dropstones, and by well sorted, likely fluvial and aeolian sands with thin clay intercalations, rare ripple marks, and desiccation cracks (Fig. 3b). The uppermost layers of interglacial members reveal glacial deformations. Each till member has an intricate structure and consists

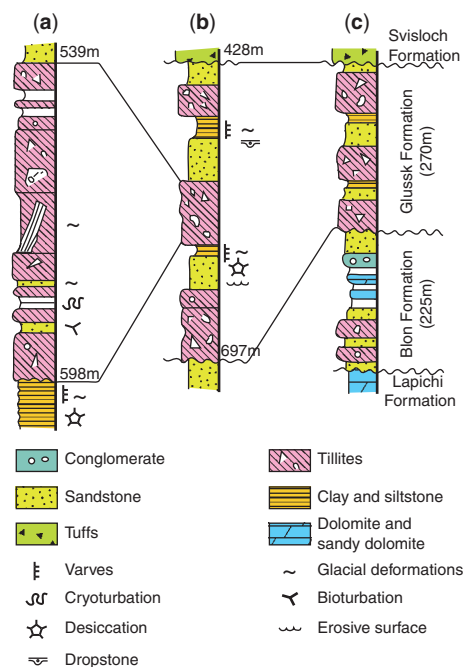


Fig. 3. Cyclic structure of the glacial Vil'chitsy Group in the Vil'chitsy drill hole, Lower Vendian sequence, Belarus: (a) middle member of the Glusck Formation; (b) Glusck Formation; (c) Vil'chitsy Group.

of several layers of differing composition and facies, usually separated from each other by thin-bedded clay with glacial deformations (Fig. 3a). This complicated structure of the Vil'chitsy Group is related to the number glacial oscillations of different scale. The Vil'chitsy Group is much thicker than all Pleistocene glacial sequences at platforms and is similar to Permian glacial sequences. It is difficult therefore to suggest that the Vil'chitsy Group was deposited during deglaciation of ice sheet only, as suggested by some authors. Another typical example of glacial oscillations occurs in the Lower Member of the Kurgashlya Formation. This member consists of an alternation of tillites, cap dolomites and laminated siltstones containing dropstones (Fig. 4). The 'Snowball Earth' requires the stable existence of each global ice cover for several million years. A marked increase in the heat balance of the planet's surface would be required for the termination of each glaciation. Mechanisms for such dramatic, multiple and rapid warming are unknown and unlikely.

2. Numerical simulations of glacial events carried out for the Late Proterozoic (Jenkins & Frakes 1998; Poulsen *et al.* 2002; Poulsen 2003 and

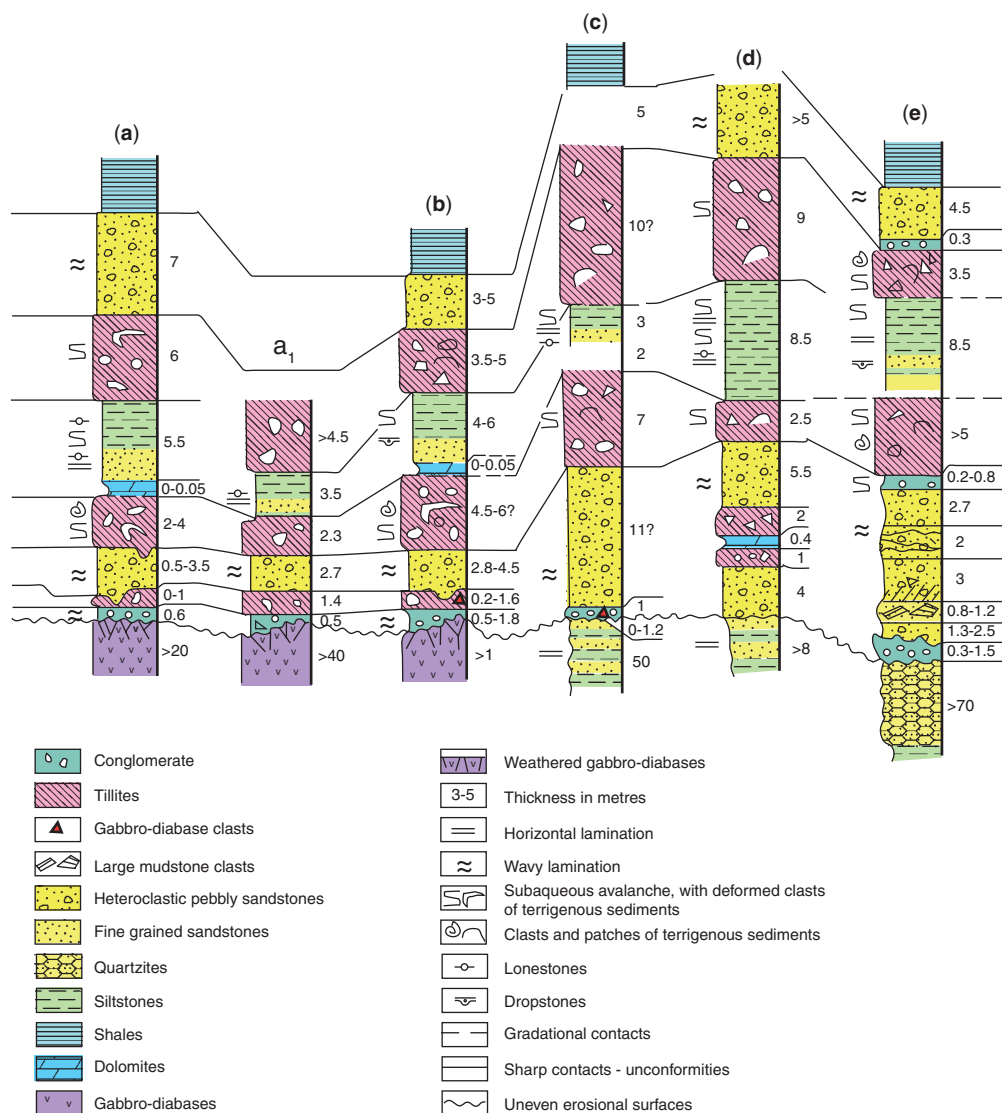


Fig. 4. Cyclic structure of the glacial Lower Member of Kurgashly Formation, Lower Vendian sequence, Belaya River, South Ural. Sections: (a) Krivaya Luka, ridge; (a₁) Krivaya Luka river cuts; (b) 2 km up-stream of Krivaya Luka; (c) 1.5 km NE of Muradymovo village; (d) left side of Belaya River 1.5 km down-stream of Apschak brook; (e) at mouth of Apschak brook.

others) do not support long, uninterrupted total glaciations, such as that required by the 'Snowball Earth' hypothesis.

3. Fossils and biomarkers of phototrophism in glacial deposits provide clear evidence for the continuous existence of phytoplankton and, hence, photosynthesis in the late Precambrian (Fedonkin 2003, and references therein), suggesting that the world ocean was not

completely covered by thick ice as required by the 'Snowball Earth' hypothesis.

4. New data suggest the possibility of underestimating palaeomagnetic latitudes determined from sedimentary rocks, particularly red beds. Original palaeomagnetic directions on Palaeogene red beds of Central Asia were underestimated by 20°–30° due to secondary flattening of the natural remanent magnetism

(NRM) vector (Bazhenov & Mikolaichuk 2002). The possibility of secondary flattening of the NRM in the much older Upper Precambrian sedimentary rocks (in Yrelina Subgroup of Australia, for example) is a real concern due to solution, loss and redistribution of material in the rocks and the reorientation of some clastic grains through long exposure to static load metamorphism (Kholodov 1994).

5. A necessary condition for a 'Snowball Earth' is the tropical position of most continents (Schrage *et al.* 2002). At the same time, according to most reconstructions of continental positions published in recent years, significant landmasses were located in high and middle latitudes during the Vendian (e.g. Scotese & McKerrow 1990; Dalziel 1997; Piper 2000; Scotese 2000; Powell *et al.* 2001—used by Hoffman & Schrage 2002; Dalziel & Soper 2001; Smith 2001; Kheraskova *et al.* 2003; Smith & Pickering 2003).
6. The presence of cap carbonates atop glacial deposits and the occurrence of banded iron formations associated with these sequences is viewed in the 'Snowball Earth' hypothesis as a result of global events related to rapid deglaciation (Hoffman & Schrage 2002). However, even though cap carbonates occurred widely, they do not necessarily occur globally. Cap carbonates are shallow-water, post-glacial sediments demonstrating regional facies changes. The South Australian Nuccaleena Formation, a typical cap carbonate that occurs over a large area, consists of paralic and shallow-water, nearshore dolomites, which grade laterally into shales and sandstones that were deposited in a more open basin (Preiss 1987). Rapid replacement of cap carbonates by sandstones along strike is observable in the Kurgashly Formation of the South Urals (Fig. 4) and in some other regions. In the South (Fig. 4) and Middle Urals, Spitsbergen and in some glacial sequences elsewhere, thin carbonate beds are found within marine glacial deposits. The regional nature of Late Precambrian banded iron formations and manganese occurrences associated with glacial deposits is even more obvious (Chumakov 1992; Young 2002). Almost all occurrences of these ores are confined to volcanic areas, partly those of rift origin: Tien Shan (Dzholdoshev 1964), SW and South Africa (Martin 1965), northwestern Canada (Yeo 1981), Brazil (Ferran 1982), Middle Urals (Chumakov 1992). In some cases, iron-rich rocks and iron ores occur between marine glacial strata (the Tien Shan and Urals) or form the matrix of these strata: the Tien Shan and Canada (Dzholdoshev

1964; Eisbacher 1981; Yeo 1981). These data have led researchers studying Fe and Mn occurrences in glacial sequences to the conclusion that such metals precipitated locally from volcanic fluids in a zone containing a mixture of fresh glacial water and seawater.

Conclusion

Palaeoclimatic reconstructions indicate that, during Vendian time, there were at least two main intervals of glacial climate (V_I and V_{III}), with a non-glacial interval between (V_{II}). This alternation was responsible for the reorganization of climatic zonality, and it changed environments from warm to cold and back, which most certainly would have had significant effects on the biosphere. The Early Vendian 'Snowball Earth' hypothesis needs further critical consideration. At the moment, geological data favours a 'Slushball Earth' hypothesis for this period (Poulsen 2003; Poulsen *et al.* 2002).

The investigations were supported by Project No 05-05-64949 of the Russian Fund of Base Investigations and Programme 18 of Presidium RAS. I appreciate the suggestions by L. A. Frakes and the second anonymous reviewer. This paper was written as a part of UNESCO IGCP493.

References

- AKSENOV, E. M. 1990. The Vendian of the East European platform. In: SOKOLOV, B. S. & FEDONKIN, M. A. (eds) *The Vendian System. Vol. 2. Regional Geology. Processes*. Springer-Verlag, Berlin, 1–37.
- ALVARENGA, C. J. S. & TROMPETTE, R. 1992. Glacially influenced sedimentation in the Later Proterozoic of the Paraguay belt (Mato Grosso, Brazil). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **92**, 85–105.
- BARFOD, G. H., ALBAREDE, F., KNOLL, A. H., XIAO, S. H., TELOUK, P., FREI, R. & BAKER, J. 2002. New Lu–Hf and Pb–Pb age constraints on the earliest animal fossils. *Earth and Planetary Science Letters*, **201**, 203–212.
- BAZHENOV, M. L. & MIKOLAICHUK, A. V. 2002. Paleomagnetism of Palaeogene basalts from the Tien Shan, Kyrgyzstan: rigid Eurasia and dipole geomagnetic field. *Earth and Planetary Science Letters*, **195**, 155–166.
- BEKKER, Yu. R. 1992. The Oldest Ediacaran biota of the Urals (in Russian). *Izvestiya Akademiyies Nauk SSSR, Series Geological*, **6**, 16–24.
- BERTRAND-SARFATI, J., MOUSSINE-POUCHKINE, A., AMARD, B. & AHMED, A. A. K. 1995. 1st Ediacaran fauna found in Western Africa and evidence for an Early Cambrian glaciation. *Geology*, **23**, 133–136.
- BRASIER, M. D., MCCARRON, G. & TUCKER, R. 2000. New U–Pb zircon dates for the Neoproterozoic Ghubrah glaciation and for the top of the Huqf Supergroup, Oman. *Geology*, **28**, 175–178.

- CHUMAKOV, N. M. 1978. *Dokembriiskie tillity i tilloidy* (Precambrian tillites and tilloids). Moscow, Nauka. [In Russian].
- CHUMAKOV, N. M. 1990. Laplandian glacial horizon and its equivalents. In: SOKOLOV, B. S. & FEDONKIN, M. A. (eds) *The Vendian System. Vol. 2. Regional Geology. Processes*. Springer-Verlag, Berlin, 191–225.
- CHUMAKOV, N. M. 1992. *The problems of old glaciations (pre-Pleistocene glaciogeology in the USSR)*. Harwood Academic Publishers, Pennsylvania.
- CHUMAKOV, N. M. 1993. Riphean Middle Siberian glaciohorizon. *Stratigraphy and Geological Correlation*, **1**, No 1, 17–28.
- CHUMAKOV, N. M. 1998. The key section of Vendian glacial deposits in the South Urals (Kurgashly Formation, Krivoluksky graben). In: KNIPPER, A. L., KURENKOV, C. A. & SEMIKHATOV, M. A. (eds) *Ural: fundamental'nye problemy geodinamiki i stratigrafii (The Urals: Fundamental Problems of Geodynamics and Stratigraphy)*. Nauka, Moscow, 138–153.
- CHUMAKOV, N. M. 2004. Trends in global climatic changes inferred from geological date. *Stratigraphy and Geological Correlations*, **12**, 117–138.
- CONDON, D. J., PRAVE, A. R. & BENN, D. I. 2002. Neoproterozoic glacial-rainout intervals: observations and implications. *Geology*, **30**, 35–38.
- CONDON, D. J., ZHU, M., BOWRING, S., WONG, W., YANG, A. & JIN, Y. 2005. U–Pb ages from the Neoproterozoic Doushantuo formation, China. *Science*, **308**, 95–98.
- DALZIEL, I. W. D. 1997. Neoproterozoic–Paleozoic geography and tectonics: Review, hypothesis, environmental speculation. *Geological Society of America Bulletin*, **109**, 16–42.
- DALZIEL, I. W. D. & SOPER, N. J. 2001. Neoproterozoic extension on the Scottish Promontory of Laurentia: Paleogeographic and tectonic implications. *Journal of Geology*, **109**, 299–317.
- DALZIEL, I. W. D., SALDA, L. H. D. & GAHAGAN, L. M. 1994. Paleozoic Laurentia–Gondwana interaction and the origin of the Appalachian–Andian mountain system. *Geological Society of America Bulletin*, **106**, 243–252.
- DZHDOSHEV, B. 1964. Stratigraphy of the Dzhetyntoo Formation within the Dzhetyntskoe Iron Deposit, Tien Shan (In Russian). In: ANONYM (ed.) *Voprosy stratigrafii dokembriya i nizhnego paleozoya Kirgizii (Issues of Precambrian and Lower Paleozoic stratigraphy of Kirghizia)*. Frunze, Izdatel'stvo Acad. Nauk Kirgizskoy SSR, 23–33.
- EISBACHER, G. H. 1981. Late Precambrian tillites of the northern Yukon–Northwest Territories region, Canada. In: HAMBREY, M. J., HARLAND, W. B. & CHUMAKOV, N. M. (eds) *Earth's Pre-Pleistocene Glacial Record*. Cambridge University Press, Cambridge, 724–727.
- EVANS, D. A. D. 2000. Stratigraphic, geochronological, and palaeomagnetic constraints upon the Neoproterozoic climatic paradox. *American Journal of Science*, **300**, 347–433.
- FEDONKIN, M. 2003. The origin of the Metazoa in the light of the Proterozoic fossil record. *Paleontological Research*, **7**, No 1, 9–41.
- FERRAN, AXEL DE 1982. Vue d'ensemble sur les minéralisations sédimentaires du Tardi-Protérozoïque brésilien. *Chronique de la Recherche Minière*, **466**, 5–39.
- GERMS, G. J. B. 1995. The Neoproterozoic of southwestern Africa, with emphasis on platform stratigraphy and paleontology. *Precambrian Research*, **73**, 137–151.
- GOROKHOV, I. M., SIEDLECKA, A., ROBERTS, D. ET AL. 2001. Rb–Sr dating of diagenetic illite in Neoproterozoic shales, Varangian Peninsula, North Norway. *Geological Magazine*, **138**, 541–562.
- GUAN, B., RUITANG, W. U., HAMBREY, M. J. & WUCHEN, G. 1986. Glacial sediments and erosional pavements near the Cambrian–Precambrian boundary in western Henan Province, China. *Journal of Geological Society, London*, **143**, 311–323.
- HAMBREY, M. J., HARLAND, W. B., CHUMAKOV, N. M. ET AL. (eds) 1981. *Earth's Pre-Pleistocene Glacial Record*. Cambridge University Press, Cambridge.
- HARLAND, W. B. 1964. Critical evidence for a great infra-Cambrian glaciation. *Geologische Rundschau*, **54**, 45–91.
- HARLAND, W. B., HAMBREY, M. J. & WADDAMS, P. 1993. Vendian geology of Svalbard. *Norsk Polar Institut Skrifter*, **193**.
- HOFFMAN, P. F. & SCHRAG, D. P. 2002. The Snowball Earth hypothesis: testing the limits of global change. *Terra Nova*, **14**, 129–155.
- JENKINS, G. S. & FRANKS, L. A. 1998. GCM sensitivity test using increased rotation rate, reduced solar forcing and orography to examine low latitude glaciation in the Neoproterozoic. *Geophysical Research Letters*, **25**, 3525–3528.
- KHAIN, V. E. & YASAMANOV, N. A. 1987. The paradox of Late Proterozoic glaciations and continental drift (in Russian). *Vestnik Moskovskogo Universiteta, Seriya 4 Geologiya*, **1**, 15–25.
- KHERASKOVA, T. N., DIDENKO, A. N., BUSH, V. A., VOLOZH & YU, A. 2003. The Vendian–Early Paleozoic history of continental margin of Eastern Paleogondwana, Paleasian Ocean, and Central Asian Foldbelt. *Russian Journal of Earth Sciences*, **5**, No 3, 165–184.
- KHOLODOV, V. N. 1994. The L. I. Salop–G. Gilluli curve: A reality or an artifact? *Lithology and Mineral Resources*, **2**, 49–65.
- KHOMENTOVSKY, V. 1990. The Vendian of the Siberian platform. In: SOKOLOV, B. S. & FEDONKIN, M. A. (eds) *The Vendian System. Vol. 2. Regional Geology. Processes*. Springer-Verlag, Berlin, 102–183.
- KIRSCHVINK, J. A. 1992a. Paleogeographic Model for Vendian and Cambrian Time. In: SCHOPF, J. W. & KLEIN, C. (eds) *The Proterozoic Biosphere*. Cambridge University Press, New York, 567–582.
- KIRSCHVINK, J. A. 1992b. Late Proterozoic Low-Latitude Global Glaciation: the Snowball Earth. In: SCHOPF, J. W. & KLEIN, C. (eds) *The Proterozoic Biosphere*. Cambridge University Press, New York, 51–52.
- KISELEV, V. V. & KOROLEV, V. G. 1981. *Paleotektonika dokembriya i nizhnego paleozoya Tyan'-Shanya (Precambrian and Lower Paleozoic Paleotectonics of the Tien Shan)*. Frunze, Ilim.
- KNOLL, A. H. 2000. Learning to tell Neoproterozoic time. *Precambrian Research*, **100**, 3–20.

- KNOLL, A.H., WALTER, M. R., NARBONNE, G. M. & CHRISTIE-BLICK, N. 2004. A new period for the Geological Time Scale. *Science*, **305**, 621–622.
- KUMAR, G., SHANKER, R., MATHUR, V. K., & MAITHY, P. K. 2000. Maldeota Section, Mussoorie Syncline, Krol Belt, Lesser Himalaya, India: A Candidate for Global Stratotype Section and Point for Terminal Proterozoic System. In: ANONYM (ed.) *Terminal Proterozoic System*. Subcommission on terminal Proterozoic System, 9–19.
- LEATHER, J., ALLEN, P. A., BRASIER, M. D. & COZZI, A. 2002. Neoproterozoic snowball earth under scrutiny: Evidence from the Fig glaciation of Oman. *Journal of Geology*, **30**, 891–894.
- MARTIN, H. 1965. *The Precambrian Geology of South West Africa and Namaqualand*. Cape Town University Press, Cape Town.
- MARTIN, M. W., GRAZHDANKIN, D. V., BOWRING, S. A. ET AL. 2000. Age of Neoproterozoic bilarian body and trace fossils, White Sea, Russia: implication for Metazoan evolution. *Science*, **288**, 841–845.
- MOSSAKOVSKY, A. A., PUSHCHAROVSKY, Y. M. & RUZHENTSEV, S. V. 1996. Spatiotemporal relationships of structures of the Pacific and Indo-Atlantic types in the Late Precambrian and Vendian (in Russian). *Doklady Akademiy Nauk*, **350**, 799–802.
- MYROW, P. M. 1995. Neoproterozoic rocks of the Newfoundland Avalon Zone. *Precambrian Research*, **73**, 123–136.
- MYROW, P. M. & KAUFMAN, A. J. 1999. A newly discovered cap carbonate above Varangian-age glacial deposits in Newfoundland, Canada. *Journal of Sedimentary Research*, **69**, 784–793.
- NARBONNE, G. M. & AITKEN, J. D. 1995. Neoproterozoic of the Mackenzie Mountains, northwestern Canada. *Precambrian Research*, **73**, 101–121.
- NARBONNE, G. M. & GEHLING, J. G. 2003. Life after snowball: the oldest complex Ediacaran fossils. *Geology*, **31**, 27–30.
- PIPER, J. D. A. 2000. The Neoproterozoic Supercontinent: Rodinia or Paleopangaea? *Earth and Planetary Science Letters*, **176**, 131–146.
- POKROVSKII, B. G., MELEZHNIK, V. A. & BUYAKAITE, M. I. 2006. C, O, Sr, S isotopic compositions in late Precambrian rocks of the Patom Complex, central Siberia: Communication 1. Results, isotope stratigraphy, and dating problems. *Lithology and Mineral Resources*, **41**, 450–474.
- POULSEN, C. J. 2003. Absence of a runaway ice-albedo feedback in the Neoproterozoic. *Geology*, **31**, 473–476.
- POULSEN, C. J., PIERREHUMBERT, R. T. & JACOB, R. L. 2002. Impact of oceanic dynamics on the simulation of the Neoproterozoic “snowball Earth”. *Geophysics Research Letters*, **28**, 1575–1578.
- POWELL, C. McCA., PISAREVSKY, S. A. & WINGATE, M. T. D. 2001. An animated history of Rodinia. *Geological Society Australia Abstracts*, **65**, 85–87.
- PREISS, W. V. (Compiler) 1987. The Adelaide Geosyncline—Late Proterozoic stratigraphy, sedimentation, palaeontology and tectonics. *Bulletin Geological Survey of South Australia*, **53**.
- PREISS, W. V. 2000. The Adelaide Geosyncline of South Australia and its significance in Neoproterozoic continental reconstruction. *Precambrian Research*, **100**, 21–63.
- SCHRAG, D. P., BERNER, R. A., HOFFMAN, P. F. & HALVERSON, G. P. 2002. On the initiation of a snowball Earth. *Geochemistry, Geophysics, Geosystems*, **3**, 1–21.
- SCOTSESE, C. R. 2000. Paleomap project 2000. <<http://www.scotese.com>>
- SCOTSESE, C. R. & MCKERROW, W. S. 1990. Revised world maps and introduction. *Paleozoic Palaeogeography and Biogeography*, Geological Society, London, *Memoir*, **12**, 1–21.
- SEMIKHATOV, M. A. 2000. Refining radiometric ages for the lower boundaries of the Upper Riphean, Vendian, Upper Vendian, and Cambrian. In: ANONYM (ed.) *Dopolneniya k stratigraficheskemu kodeksu Rossii (Supplements to the Stratigraphic Code of Russia)*, Supplement 4. St. Petersburg, BCEГEИ (All-Russian Geological Institute), 95–107.
- SEMIKHATOV, M. A. & CHUMAKOV, N. M. (eds) 2004. *Klimat v epokhi krupnykh biosfernnykh perestroek (Climate in Epochs of Major Biospheric Reorganization)*. Nauka, Moscow.
- SMITH, A. G. 2001. Palaeomagnetically and tectonically based global maps for Vendian to Mid-Ordovician time. In: ZURAVLEV, A. Yu & RIDING, R. (eds) *The Ecology of the Cambrian Radiation*. Columbia University Press, New York, 11–46.
- SMITH, A. G. & PICKERING, K. T. 2003. Oceanic gateways as a critical factor to initiate icehouse Earth. *Journal of Geological Society, London*, **160**, 337–340.
- SOKOLOV, B. S. 1998. *Ocherki stanovleniya venda (Essays on the Advent of the Vendian System)*. Moscow, KMK Ltd.
- STRAUSS, H., BANERJEE, D. M. & KUMAR, V. 2001. The sulfur isotopic composition of Neoproterozoic to early Cambrian seawater—evidence from the cyclic Hanseran evaporites, NW India. *Chemical Geology*, **175**, 17–28.
- TIWARI, M. 1999. Organic-walled microfossils from the Chert-Phosphorite Member, Tal Formation, Precambrian–Cambrian Boundary, India. *Precambrian Research*, **97**, 99–113.
- TEWARI, M. & KNOLL, A. 1994. Large acanthomorphic acritarchs from the Infrakrol Formation of the Lesser Himalaya and their stratigraphic significance. *Journal of Himalayan Geology*, **5**, 193–201.
- TROMPETTE, R. 1996. Temporal relationship between cratonization and glaciation: The Vendian-early Cambrian glaciation in Western Gondwana. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **123**, 373–383.
- TROMPETTE, R. 1997. Neoproterozoic (~600 Ma) aggregation of Western Gondwana: a tentative scenario. *Precambrian Research*, **82**, 101–112.
- VIDAL, G. 1981. Micropaleontology and biostratigraphy of the Upper Proterozoic and Lower Cambrian sequences in East Finnmark, northern Norway. *Norges Geologiske Undersøkelse Bulletin*, **53**, 362.
- VIDAL, G. & MOCZYDLOWSKA, M. 1995. The Neoproterozoic of Baltica—stratigraphy, paleobiology and general geological evolution. *Precambrian Research*, **73**, 197–216.
- WALTER, M. R., VEEVERS, J. J., CALVER, C. R. & GREY, K. 1995. Neoproterozoic stratigraphy of the

- Centralian Superbasin, Australia. *Precambrian Research*, **73**, 173–195.
- WALTER, M. R., VEEVERS, J. J., CALVER, C. R., GORJAN, P. & HILL, A. C. 2000. Dating the 840–544 Ma Neoproterozoic interval by isotopes of strontium, carbon, and sulfur in seawater, and some interpretative models. *Precambrian Research*, **100**, 371–433.
- WANG, X., ERDTMANN, B., XIAOHONG, C. & XIAODONG, M. 1998. Integrated sequence-, bio- and chemo- stratigraphy of the terminal Proterozoic to Lowermost Cambrian “black rock series” from central South China. *Episodes*, **21**, 3, 178–189.
- YEO, G. M. 1981. The Late Proterozoic Rapitan Glaciation in the Northern Cordillera. *Geological Survey of Canada, Paper* **81–10**, 25–46.
- YIN, L. M. & GUAN, B. D. 1999. Organic-walled microfossils of Neoproterozoic Dongjia, Lushan Country, Henan Province, North China. *Precambrian Research*, **94**, 121–137.
- YOUNG, G. M. 1995. Are Neoproterozoic glacial deposits preserved on the margins of Laurentia related to the fragmentation of two supercontinents? *Geology*, **23**, 153–156.
- YOUNG, G. M. 2002. Stratigraphic and tectonic settings of Proterozoic glaciogenic rocks and banded iron-formations: relevance to the snowball Earth debate. *Journal of African Earth Sciences*, **35**, 451–466.
- ZHANG, Y., YIN, L., XIAO, S. & KNOLL, A. H. 1998. Permineralised fossils from the terminal Proterozoic Doushantian Formation South China. *Paleontological Society Memoirs*, **72**, 52.
- ZHARKOV, M. A. 1981. *History of Paleozoic Salt accumulation*. Springer-Verlag, Berlin.
- ZHOU, CH., TUCKER, R., XIAO, SH., PENG, ZH., YUAN, X. & CHEN, ZH. 2004. New constraints on the age of Neoproterozoic glaciations in South China. *Geology*, **32**, 437–440.