by Martin Brasier, John Cowie and Michael Taylor

Decision on the Precambrian–Cambrian boundary stratotype

The Global Stratotype Section and Point for the Proterozoic–Cambrian boundary has been agreed upon. The boundary is defined in a coastal section near the town of Fortune in southeastern Newfoundland, Canada.

Introduction

The problem of the Precambrian–Cambrian boundary is part of one of the greatest enigmas of the fossil record; i.e. the relatively abrupt appearance of skeletal fossils and complex, deep burrows in sedimentary successions around the world. As will be recounted below, its definition has involved the rolling back of a major frontier in geology over the last three decades.

Until the late 1940s, it was assumed that the Precambrian was largely without fossils and that the base of the Cambrian was marked by the lowest appearance of trilobites, e.g. the 'Olenellus Zone' of Walcott (1890) and Wheeler (1947). More traditionally, it was drawn at a regional unconformity below them, e.g. in Rayner (1967). The first steps towards a more precise definition of the base were taken in 1960, at the Norden IGC in Copenhagen, when M F Glaessner proposed the establishment of a Subcommission on Cambrian Stratigraphy, and in 1968 when Chairman C J Stubblefield and Secretary J W Cowie chose the problem of the 'Base of the Cambrian System' as one of its first tasks. By this time, the existence of a latest Precambrian fauna was widely acknowledged, e.g. in Glaessner and Wade (1966), and work by Russian geologists was beginning to demonstrate a pre-trilobitic succession of skeletal faunas, which were referred to the Cambrian System, e.g. in Rozanov (1967). Meetings on the boundary were organized for the IGC in Czechoslovakia in 1968, and at Montreal in 1972. Much discussion ensued at the latter meeting and a 'Working Group on the Precambrian–Cambrian Boundary' (PC-CBWG) was formed, with J W Cowie as its Chairman. Some of the history of the Working Group has been summarized elsewhere (Cowie, 1992).

In effect, this Working Group was setting itself the challenging task of defining the 'bottom line' of the biostratigraphic scale; i.e. to discover, name and interpret fossils where few had been found before. Many of the fossils unearthed over the following decades were not referable to previously known groups and their potential for stratigraphic correlation was, therefore, completely untested.

The Working Group held its first field meeting in Siberia in 1973, sponsored by the Academy of Sciences of the USSR, to consider possible stratotypes for the Precambrian–Cambrian boundary along the middle reaches of the Aldan and Lena rivers in Yakutia, eastern Siberia. Here, 28 foreign geologists were introduced to the 'Tommotian fauna' and the sections of Rozanov and others (1969). Members discussed, not for the last time, the origin of the lowest small shelly fossil (SSF) assemblage in bed 8 at Ulakhan Sulugur, that was referred to the base of the Tommotian Stage (Cowie and Rozanov, 1974). Discussions also focused on the relationship between lithofacies and biofacies, notably the problem of correlating carbonate shelf facies with archaeocyathans (as in Siberia) with clastic shelf to basinal facies that predominate elsewhere. It was for this reason that B Daily (unpublished) emphasised the potential of trace fossil stratigraphy as a subsidiary guide.

This was followed in 1974 by a meeting in Paris, at which the following points were unanimously agreed (Cowie, 1992).

- The primary task of the Working Group was the choice of a stratotype boundary point; a secondary task was the consideration of associated stratigraphic divisions above and below the boundary.
- Any succession selected for the boundary point must be as continuous as possible, marine, and as monofacial as possible; the main method of guidance in selection should be biostratigraphy although all possible methods of correlation should be enlisted.
- The 'Ediacara' type fauna should be considered as Precambrian.
- The 'olenellid/fallotaspid' trilobite faunas should be considered as Cambrian.
- Between the 'Ediacara' and the trilobite faunas, those fossiliferous successions that could not be allocated with certainty to either the Precambrian or the Cambrian, should have the Working Group's close attention.

Increased support for work on the boundary was made possible in 1974, when 'The Precambrian–Cambrian Boundary' was accepted as Project 29 by the IGCP Board. A meeting in Cambridge, UK, in 1978, reviewed discoveries of sub-trilobitic small skeletal fossils and trace fossils from around the world, as well as the potential of magnetostratigraphy. The Cambridge meeting recommended to the Working Group that "The Precambrian–Cambrian boundary should be placed as close as is practicable to the base of the oldest stratigraphic unit to yield Tommotian (sensu lato) fossil assemblages" (Cowie, 1978). Although there was little support at this time for a boundary defined by trace fossils, their potential for the correlation of strata below the first trilobites was now being explored (see Alpert, 1977; Brasier, 1979, figure 1).

Candidates for the Precambrian–Cambrian GSSP were discussed in some detail at a meeting in Bristol, England in 1983, and three were selected for further consideration, as follows.

- Ulakhan-Sulugur on the Aldan River in eastern Siberia, of the former USSR (now in Russia); here the boundary level (at the base of bed 8) lay in carbonate facies, within a succession of small skeletal fossils and algae that lay below the earliest archaeocyathans, brachiopods and other markers of 'Tommotian type'; this section was well known and well studied.
- The section at Meishucun near Kunming, in Yunnan Province of southern China. Here, the boundary level (Marker B) lay within a phosphorite facies and was marked by the abrupt appearances of phosphatised micromolluscs and problematica. This section was well-studied but little known outside of China.
- Several sections on the Burin Peninsula of southeastern Newfoundland, Canada; here both small skeletal fossils and trace fossils were known to occur in a mixed carbonate-siliciclastic succession. Only outline studies were available from this region and no precise section was pinpointed.

At this meeting, it was again decided that the boundary stratotype should be placed "as close as practicable to the lowest known appearance of diverse shelly fossils with a good potential for correlation" (Cowie, 1985). Such an emphasis upon SSFs provided a great stimulus to their study, but there was growing concern about their utility for correlation. A preliminary mandate for the Meishucun section was deferred at the Moscow IGC in 1984, when it was recognised that greater international agreement on SSF taxonomy was necessary. This led to an 'SSF Workshop' in Uppsala in 1986, organized by S Bengtson. It can now be seen that this meeting resulted in several new thrusts. First, it became apparent that the boundary successions in China had a distinct character, which could be traced into India, Pakistan and Iran (Brasier, 1989a) but correlation beyond these former terranes of Gondwana was more problematical. Second, it encouraged the view that small skeletal fossils were long-ranging, highly variable, over-split taxonomically, taphonomically poorly understood, often restricted by facies and provincial in distribution (Landing and others, 1989; Qian and Bengtson, 1989). Attempts were made to draw the data on pandemic forms together, comparing the first appearances of successive taxa on a global scale (e.g. Brasier, 1989b) but the results were not entirely encouraging for high-resolution stratigraphy. The problems of SSFs were beginning to come into focus.

Knowledge about the Chinese sections improved after visits by Group members in the late 1970s and early 1980s, and most especially after publications in English (Luo and others, 1984; Xing and others, 1991) and the international meeting on the Terminal Precambrian and Cambrian Systems at Yichang in 1987. The problems of correlating the three sub-trilobitic markers at Meishucun (termed A, B and C) were reviewed in English by Brasier (1989a). Scientists outside China showed considerable concern about five factors relating to the GSSP candidate at Meishucun.

- The comparative age of the Zone II assemblage above Marker B, chosen by the Chinese as the candidate boundary point; this question arose because it was thought to contain fossils found above the Tommotian in Siberia (Bengtson and others, 1984).
- The presence of a possible gap just below Marker B, shown by an abrupt change in lithofacies (e.g. Brasier, 1989a; Landing, 1994).
- The lack of faunal continuity between the three markers, also suggestive of breaks in the sequence (Qian and Bengtson, 1989).
- The interpretation of carbon isotopic profiles reported by Brasier and others (1990). For example, Kirschvink and others (1991) suggested that Zone II might correlate with the basal Atdabanian excursions in Siberia.
- The interpretation of Rb/Sr clay mineral isochrons (e.g. 596.9± 4.6 Ma, Xing and others, 1991); recent data from U-Pb isochrons from ash bands near Marker B indicate a much younger age of 525± 7 Ma (Compston and others, 1992).

Further documentation also became available on the Siberian sections (Sokolov and Zhuravleva, 1983; Rozanov and Sokolov, 1984) and some members of the Working Group were able to examine the GSSP at Ulakhan-Sulugur during the Second International Symposium on the Cambrian System in 1990 (Astashkin and others, 1990). Its potential for carbon isotope- and magnetostratigraphy appeared good (e.g. Kirschvink and others, 1991). Discussion, however, centred on the origin of bed 8: was it a stratified layer, or was it piped down along karstic fissures from about a metre above? Support for the latter view was given by field data (Khomentovsky and others, 1990) but isotopic data has proved more equivocal (Brasier and others, 1993). A view is emerging of a widespread unconformity near the base of the Tommotian across much of the Siberian Platform, representing a hiatus of uncertain duration (e.g. Landing, 1994).

Until 1983, the potential of southeastern Newfoundland for a mixed, carbonate/SSF-siliciclastic/trace-fossil stratigraphy was little tested. Hutchinson (1962) and Greene and Williams (1974) had reported SSF assemblages below the earliest trilobites. T P Fletcher (1978) had presented an outline stratigraphy of the Burin Peninsula at Cambridge. This work was followed up by further litho- and biostratigraphy (T P Fletcher, unpublished), accompanied by magnetostratigraphy (J Kirschvink, unpublished). The latter discovered, however, that the whole section was remagnetised in Ordovician times. A Working Group visit to the Burin Peninsula in 1979 was followed up by important ground work on SSFs, trace fossils and lithostratigraphy (Bengtson and Fletcher, 1981, 1983). Further researches culminated in a series of papers which detailed the stratigraphic distribution of trace fossils, SSFs and lithostratigraphy (Crimes and Anderson, 1985; Narbonne and others, 1987; Narbonne and Myrow, 1988; Landing, 1988; Landing and others, 1989).

An understanding emerged that SSFs, which had hitherto provided the focus of Working Group discussions, were very greatly affected by provincialism and a virtual restriction to shallow carbonate facies. This suggested, to some, that definition of the boundary might be better guided by trace fossils as well as body fossils. The advantages of trace fossils were stressed to be as follows (e.g. Crimes, 1987; Narbonne and others, 1987; Narbonne and Myrow 1988).

- They are especially common in siliciclastic facies, in which SSFs are typically rare and poorly preserved. This is important since these deposits comprise nearly 70 per cent of exposed rocks in the boundary interval.
- Cambrian trace fossils appear to have been less restricted in terms of habitat range than in later intervals.
- Several successive trace fossil zones from around the world may be recognized in strata below the lowest trilobites.
- These zones include ichnogenera with a limited stratigraphic range and a broad stratigraphic distribution. Of these, the *Phycodes pedum* Zone assemblage contains typical Cambrian ichnotaxa in a high-diversity assemblage with branched morphologies, complex feeding burrows, escape traces and dwelling burrows. The underlying *Harlaniella podolica* Zone assemblage is of lower diversity and comprises simple, horizontal, sediment-feeder traces, e.g. *Nenoxites, Palaeopascichnus*.
- The ranges of *Harlaniella podolica* and *Phycodes pedum* are believed not to overlap; one succeeds the other, providing a rare example of faunal replacement within a boundary succession.
- At Fortune Head, Burin Peninsula, these two traces are seen within a stratigraphic succession that shows little evidence of environmental change. Correlations of the boundary level are also possible between Fortune Head and other localities on the Burin Peninsula. Similar faunal changes were purported to take place at other localities around the world.

These ideas were discussed at a meeting at St John's, Newfoundland in August 1987, and followed by field excursions through the 'Terminal Proterozoic' and lower Cambrian (Narbonne, 1987). By this time, the Working Group was under some pressure to reach a decision, because it had examined the problem since 1972. It was also clear that whilst it might be possible to reach a decision on the boundary point, its global correlation was going to be open to wide dispute. Non-biostratigraphic methods of correlation, such as carbon-, strontium-, event-stratigraphy and geochronology would be needed to improve stratigraphic resolution at this level. A proposal was put forward, therefore, by M D Brasier and K J Hsu to the IGCP Board in 1989, to encourage such researches through a project on 'Precambrian–Cambrian Event Stratigraphy'. Project 303 was accepted and its first meeting took place in Siberia in July–August 1990. The findings of this project have an important bearing on correlation of the Precambrian–Cambrian boundary, which will be discussed elsewhere.

The chosen GSSP candidate at Fortune Head, Burin Peninsula, Newfoundland was first put forward by Canadian and US members of the Working Group in 1987. The results of a straw poll held in St John's at that time seemed favourable (Cowie and Brasier, 1989). Written proposals were then requested by Chairman J W Cowie from each of the three GSSP candidates, to outline their utility for correlation by biostratigraphic and non-biostratigraphic (e.g. geochronologic, palaeomagnetic and stable isotopic) techniques, for accessibility, and potential for conservation. These were submitted in October 1990 as follows: A Yu Rozanov (Ulakhan-Sulugur); Xing Y, Luo, H, Jiang, Z and Zhang, S (Meishucun); and E Landing and G N Narbonne (Fortune Head, Newfoundland). A postal ballot of the 23 Voting Members was arranged by J W Cowie in the Spring of 1991. This ballot received a 100 per cent response, giving an overall majority of 52 per cent to the Burin candidate, 35 per cent to China and 13 per cent to Siberia. Following the guidelines of ICS, a second postal ballot was held on the Burin section alone, in the summer of 1991, which led to a 61 per cent majority for the section at Fortune Head. This majority was large enough to allow ratification by the ICS and the IUGS (at the IGC in Kyoto, August 1992), when Chairmanship of the Cambrian Subcommission passed to M D Brasier. Responsibility for the basal boundary of the Cambrian also passed from the Working Group to the Cambrian Subcommission at this time.

The Fortune Head GSSP

The Fortune Head GSSP section is situated near the tip of the Burin Peninsula, southeastern Newfoundland (figure 1), in low cliffs that extended beyond 'Fortune Dump'. Easy access is possible from the town of Fortune; there are no political or geographical problems of access. The stratotype was pictured in *Episodes* of December 1987 (Narbonne, 1987, figure 1).

Coastal cliff exposures at Fortune Head display some 440 m of the Chapel Island Formation, with beds dipping at 15 to 46 degrees to the west (steeper dips are toward the top of the section). Several small faults are present well above the stratotype level, but marker horizons allow easy correlation across them (Landing and others, 1988, p.35). Breaks in deposition are minor and restricted to the bases of thin, wave-deposited sand units.

In this region, Cambrian deposition (Figure 2) was accommodated by local, long-term extension of the basement, comprising Late Precambrian volcanics and clastics affected by the 'Avalonian Orogen'. The Fortune Bay Basin began with the deposition of 2750 m of upwardly fining red beds that grade into peritidal sandstones at the top (Bengtson and Fletcher, 1983; Landing and others, 1988). These were succeeded by ca. 1000 m of siliciclastic shelf facies, placed in the Chapel Island Formation, and deposited during a major 'sea level' cycle as follows: peritidal sandstone and shales (Member 1); storm-influenced muddy deltaic and shelf sandstones and mudstones (Member 2A); thinly laminated siltstones of the distal shelf, deposited below wave base (Member 2B and Member 3); mudstones with thin limestones, deposited under low energy, inner shelf to peritidal conditions (Member 4); and sandstones and siltstones of an offshore to shoreface storm-dominated shelf (Myrow and Hiscott, 1994). These were then capped by the macrotidal sandstones and siltstones of the Random Formation, which can be traced across the Avalonian region (Hutchinson, 1962; Landing, 1992).

Member 1 of the Chapel Island Formation (ca. 180 m) includes uppermost Precambrian sediments. It yields biostratigraphically important trace fossils of the *Harlaniella podolica* ichnofossil Biozone (Bengtson and Fletcher, 1983; Crimes and Anderson, 1985). *Harlaniella podolica* and *Palaeopascichnus delicatus* range into Member 2, where they are last seen 0.2 m below the GSSP. Organic-walled tubes of *Sabellidites cambriensis* first appear near the top of Member 1 and range at least as high as Member 4. The *Sabellidites cambriensis* skeletal fossil Biozone is defined between the first occurrence of this taxon, and the higher first appearance of calcareous tube *'Ladatheca' cylindrica* in Member 2B.

The Precambrian–Cambrian boundary point (Figure 3) lies 2.4 m above the base of Member 2 in the Chapel Island Formation,

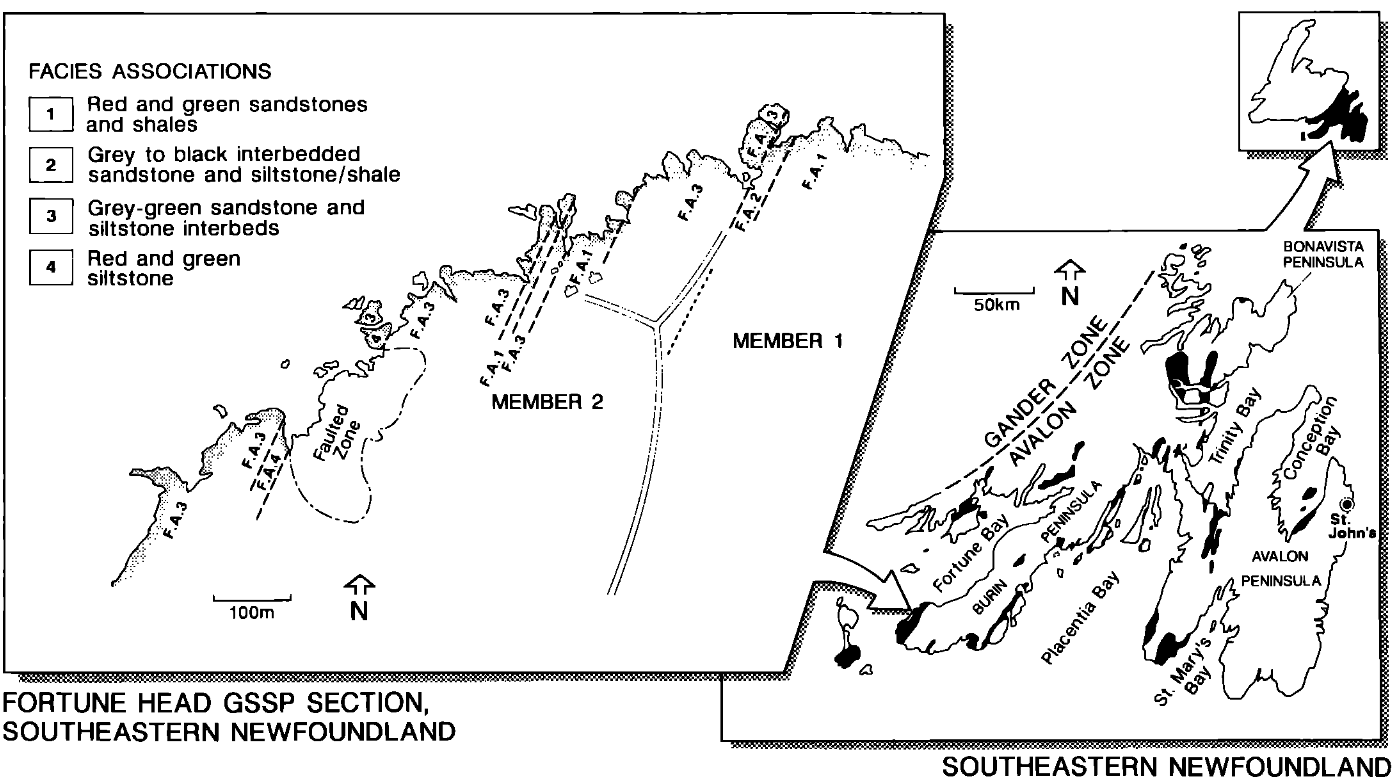

Figure 1 Generalized locality map of Newfoundland (inset) showing location of the Fortune Head stratotype and detail map of the 440 m-thick section at Fortune Head. Diagonal ruling indicates strike direction. FA = facies associations. Based on Landing and others (1988, figures 4 and 19).

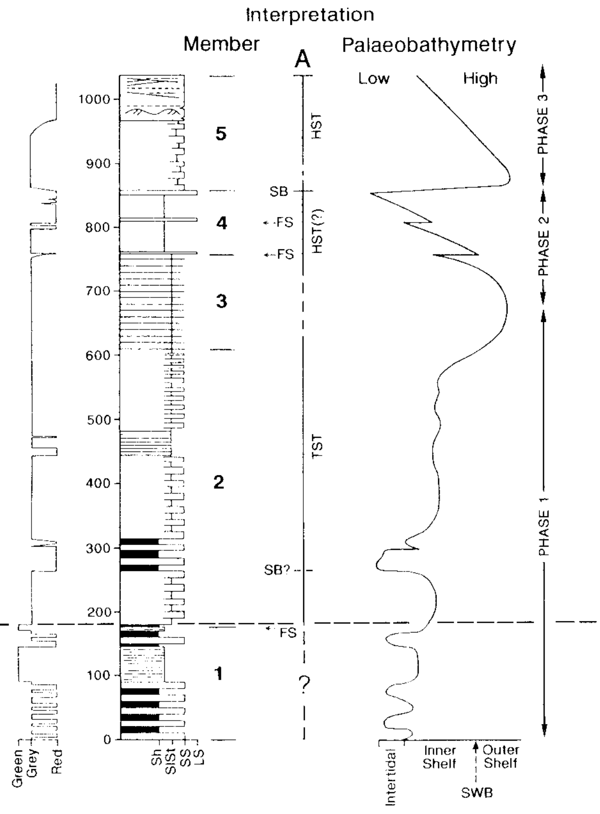

Figure 2 Generalized stratigraphic section for the Chapel Island Formation, showing inferred paleobathymetry, three-phase depositional history, and sequence-stratigraphic interpretation. The Precambrian–Cambrian boundary stratotype point is shown. FS = flooding surface; MFS = maximum flooding surface. SB = sequence boundary. TST = transgressive systems tract. HST = highstand systems tract. SWB = storm wave base. Sh = shale; Sltst = siltstone; SS = sandstone; LS = limestone. The scale is in metres from the beginning of the exposure. Based on Myrow and Hiscott (1993, figure 3)

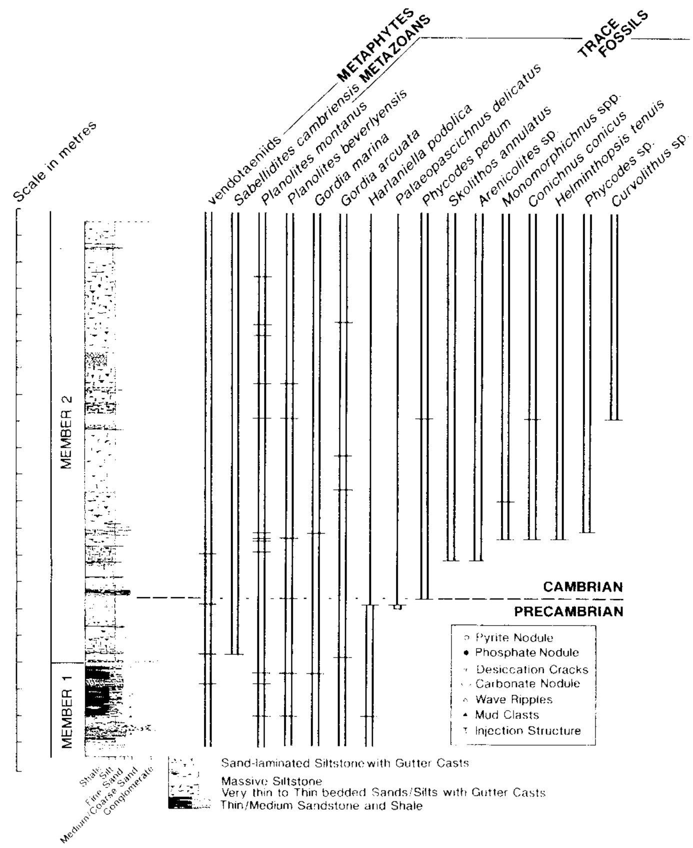

Figure 3 Faunal succession and lithology through the Precambrian–Cambrian boundary stratotype section at Fortune Head. Based on Narbonne and others (1987, figure 5) and Landing and others (1988, figure 20). For fossil distribution and lithological data from the overlying 420 m of continuously exposed strata at Fortune Head, see Narbonne and others (1987, figure 4), Landing and others (1988, figures 21–23); Myrow and Hiscott (1993, figure 8).

i.e. just above the transition to storm-influenced facies and 18.2 m above the base of the succession at Fortune Head. This GSSP is a point in rock that defines a moment in time and was selected with guidance from the level marked by the lowest occurrence of *Phycodes pedum* (a trace fossil), at the base of the Cambrian *Phycodes pedum* Biozone (Figure 2; see Narbonne and others, 1987, figure 8B). The marker fossil is preserved as a series of branched, hypichnial ridges on the lower surface of a sandstone. Its appearance at this level is not directly traceable to a change in facies, which takes place lower in the sequence (Member 1 to Member 2A boundary). In addition, both peritidal and subtidal facies in Member 1 contain *Harlaniella podolica*, and facies identical to those in Member 1 are interbedded within Member 2A, but do not show upper Precambrian trace fossils. These features suggest that environmental factors, while significant, were only of second-order influence upon the distribution of trace fossils though this section. The boundary point also defines the base of the Lower Cambrian 'Placentian Series' of Landing and others (1989).

The first occurrence of calcareous shelled skeletal fossils (*'Ladatheca' cylindrica*) here lies some 400 m above the Precambrian–Cambrian boundary. As mentioned above, their appearance is related to facies and taphonomic conditions and is unlikely to mark the true origin of biomineralization. Trilobites appear some 1400 m above the boundary point, and mark the start of the Lower Cambrian 'Branchian Series' of Landing (1992).

Non-biostratigraphic means of correlation

The boundary level lacks carbonates suitable for carbon or strontium isotope analysis. Studies on nodules and bedded limestones higher in the Burin succession show the effects of widespread thermal alteration during deep burial and granitic intrusion (Brasier and others, 1992). Similar problems have affected suitability of the stratotype for palaeomagnetic correlation (see above). Regrettably, this means that the Asiatic sections of Siberia and China cannot be correlated with the new GSSP by means of carbon isotope- and magnetostratigraphy, although they provide a valuable tool for correlation elsewhere (Kirschvink and others, 1991; Brasier and others, 1994).

Geochronology of the boundary

Recent U-Pb radiometric determinations on volcanic zircons are available from New Brunswick, in strata possibly correlated with the upper part of Member 5 (Bowring and others, 1993). These yield a date of 530.7±0.7 Ma (Isachsen and others, 1994); previously reported as 531±1 Ma by Bowring and others (1993) and Landing

(1994) and provides a maximum age for the base of the overlying quartzite formation. The boundary point lies some 800 m below its possible correlative, the Random Formation, in the Burin Peninsula.

A further guide to the radiometric age of the Precambrian–Cambrian boundary comes from recent U-Pb dates from Siberia (Bowring and others, 1993). In the Olenek region, volcanic breccias occur within the Nemakit–Daldynian Stage, above the first small shelly fossil (*Cambrotubulus* sp.) but below the first skeletal assemblage with *Anabarites trisulcatus*. These breccias have recently been dated at 543.6±0.24 Ma (Bowring and others, 1993), which gives an estimated age for the base of the Nemakit–Daldynian of about 544 Ma. This level has been correlated with the base of the Cambrian in Newfoundland (Narbonne and others, 1987), on the following grounds: occurrence of *Phycodes* sp. at an unspecified level within the Nemakit Daldynian (Fedonkin, 1987; actually this taxon may not appear until the middle of the stage: M A Fedonkin, pers. comm., 1993); occurrence of *Sabellidites cambriensis*, which ranges from the base of the stage (Sokolov and Fedonkin, 1985). A provisional estimate for the age of the Precambrian–Cambrian boundary is, therefore, ca. 544 Ma.

Acknowledgements

The following are thanked for comments and contributions to this report: T P Crimes, T P Fletcher, E Landing, and A R Palmer.

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