The Standard Auxiliary Boundary Stratotype

Head, Martin J.; Aubry, Marie Pierre; Piller, Werner E.; Walker, Mike

Published in:
Episodes

DOI:
10.18814/epiiugs/2022/022012

Publication date:
2023

Citation for published version (APA):
Head, M. J., Aubry, M. P., Piller, W. E., & Walker, M. (2023). The Standard Auxiliary Boundary Stratotype: A proposed replacement for the Auxiliary Stratotype Point in supporting a Global boundary Stratotype Section and Point (GSSP). *Episodes*, *46*(1), 35-45. https://doi.org/10.18814/epiiugs/2022/022012

by Martin J. Head[1]*, Marie-Pierre Aubry[2], Werner E. Piller[3], and Mike Walker[4,5]

The Standard Auxiliary Boundary Stratotype: a proposed replacement for the Auxiliary Stratotype Point in supporting a Global boundary Stratotype Section and Point (GSSP)

[1] Department of Earth Sciences, Brock University, 1812 Sir Isaac Brock Way, St. Catharines, Ontario L2S 3A1, Canada; *Corresponding author, *E-mail: mjhead@brocku.ca*
[2] Department of Earth and Planetary Sciences, Rutgers University, 610 Taylor Road, Piscataway, NJ 08854, USA
[3] Institute of Earth Sciences, University of Graz, NAWI Graz Geocenter, Heinrichstrasse 26, 8010 Graz, Austria
[4] School of Archaeology, History and Anthropology, Trinity Saint David, University of Wales, Lampeter, Wales, SA48 7ED, UK
[5] Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth, Wales, SY23 3DB, UK

(Received: October 12, 2021; Revised accepted: April 4, 2022)

https://doi.org/10.18814/epiiugs/2022/022012

Auxiliary boundary stratotypes have unquestionable value in extending the knowledge of a Global boundary Stratotype Section and Point (GSSP) between continents, biogeographic provinces, climatic zones, depositional facies and preservational states. Two kinds of such stratotypes are in use, the Auxiliary Stratotype Point and the Auxiliary Stratotype Section, although only the Auxiliary Stratotype Point is recognised by the International Commission on Stratigraphy (ICS). The Standard Auxiliary Boundary Stratotype, which is based on the Auxiliary Stratotype Section, is proposed here as a formal replacement for the Auxiliary Stratotype Point. As such, it would provide a detailed complementary expression of the boundary interval without the designation of a specific point – no such points can replicate the precise level defined by a GSSP either conceptually or in practice. We recommend that requirements for future Standard Auxiliary Boundary Stratotypes broadly follow ICS guidelines for GSSPs but be applied with greater flexibility. Past practice reveals inconsistency in the protocols used for approving such auxiliary boundary stratotypes. We propose that in future they require approval by the respective ICS subcommission. More than one Standard Auxiliary Boundary Stratotype may support a single GSSP but restraint should be exercised in approving them, and each will always be subordinate to the GSSP itself.

Introduction

Auxiliary stratotypes can play a valuable role in extending the correlative potential of a Global boundary Stratotype Section and Point (GSSP) between continents (e.g., Molina et al., 2009), biogeographic provinces (e.g., Wang et al., 2021), climatic zones (e.g., Walker et al., 2009, 2019), depositional facies (e.g., Miller et al., 2015a, b) and preservational states (e.g., Hilgen et al., 2005). However, while an increasing number of GSSPs are being supported by such auxiliary stratotypes, the selection and approval of GSSPs themselves remain the primary task of the International Commission on Stratigraphy (ICS) and its various subcommissions. This process is rigorous. One or more candidate GSSPs undergo scrutiny and selection by a boundary task (working) group of the relevant subcommission before being submitted to that subcommission for further examination. Upon recommendation by the subcommission, the selected candidate GSSP is submitted to the ICS voting membership for approval. All decisions require a 60% supermajority vote for approval. Once approved, the GSSP must be ratified by the Executive Committee of the International Union of Geological Sciences (IUGS EC) before it becomes effective.

With respect to GSSPs and other global chronostratigraphic standards, the procedures followed by the ICS and its constituent subcommissions are currently set out in its revised guidelines (Remane et al., 1996). These formally regulate the procedures for chronostratigraphic boundary definition. Operating alongside these guidelines are ICS statutes that are periodically updated, with the most recent version entering into force on 25 April 2017 and published on the ICS website (International Commission on Stratigraphy, 2017). The previous (and first) edition of the ICS guidelines included the ICS statutes (Cowie et al., 1986). The revised guidelines (Remane et al., 1996) are the first document on stratigraphic procedure to be approved by the full voting membership of the ICS and they remain the fundamental authority in regulating procedures to define global chronostratigraphic boundaries.

The International Stratigraphic Guide (ISG), published by the ICS International Subcommission on Stratigraphic Classification, first appeared in 1976 (Hedberg, 1976) and is currently in its second edition (Salvador, 1994). It offers a recommended approach to stratigraphic classification, terminology and procedure. While the ISG avowedly is not binding in any way, it wields significant influence and provides an invaluable resource for areas not specified by the ICS guidelines.

We provide for the first time a comprehensive review of *auxiliary stratotypes* as they relate to GSSPs, and examine their utility and authority.

Table 1. Terms and definitions of stratotypes of layered stratigraphic units (verbatim from Salvador, 1994, p. 28; largely taken from Hedberg, 1976, p. 26)

Holostratotype. The original stratotype designated by the original author at the time of proposing a stratigraphic unit or boundary.

Parastratotype. A supplementary stratotype used in the original definition by the original author to illustrate the diversity of heterogeneity of the defined stratigraphic unit or some critical feature not evident or exposed in the holostratotype.

Lectostratotype. A stratotype for a previously described stratigraphic unit selected later in the absence of an adequately designated original stratotype (holostratotype).

Neostratotype. A new stratotype selected to replace an older one which has been destroyed, covered, or otherwise made inaccessible.

Hypostratotype (also called *reference section*, *auxiliary reference section*). A stratotype proposed after the original designation of the holostratotype (and parastratotype) in order to extend knowledge of the unit or boundary to other geographic areas. It is always subordinate to the holostratotype.

The *auxiliary stratotype point*, the only such geostandard formally recognised by the ICS, is specifically critiqued. Examples of auxiliary stratotypes and auxiliary stratotype points established explicitly to support GSSPs are analysed, particularly with respect to underlying concepts and procedures. A new concept, the *Standard Auxiliary Boundary Stratotype*, is then proposed, and supporting procedures are advanced.

The International Stratigraphic Guide

The initial (Hedberg, 1976) and current versions (Salvador, 1994; Murphy et al., 2021) of the ISG describe the various kinds of stratotype (holostratotype, parastratotype, lectostratotype, neostratotype, hypostratotype) in use (Table 1). In particular, an auxiliary stratotype is referred to as a *hypostratotype* (also as a reference section or *auxiliary reference section*) and is "a stratotype proposed after the original designation of the holostratotype (and parastratotype) in order to extend knowledge of the unit or boundary to other geographic areas. It is always subordinate to the holostratotype (Salvador, 1994, p. 28; see also Hedberg, 1976, p. 26). However, neither the initial nor current versions of the ISG address the use of an auxiliary stratotype specifically for a GSSP.

ICS Guidelines

With respect to the various kinds of stratotypes listed and defined by the ISG (Hedberg, 1976; Salvador, 1994; Table 1), the initial edition of the ICS Guidelines (Cowie, 1986; Cowie et al., 1986) dismissed their sanctioning by ICS as a means to assist the definition of a GSSP. This edition favoured confining the nomenclature for ICS candidates to: 1) the GSSP itself, and 2) the *auxiliary stratotype point* which would be particularly useful for assisting correlation away from the GSSP and in markedly different facies (Cowie, 1986, p. 79; Cowie et al., 1986, p. 5).

The revised ICS guidelines (Remane et al., 1996) reiterated the position of Cowie et al. (1986) that "if reference sections and points seem necessary in order to give a better understanding of the boundary in another facies or paleobiogeographic context, an *auxiliary stratotype point* may be defined. Such auxiliary points are subordinate to a GSSP." (Remane et al., 1996, p. 78; our italics). The procedure for approval and ratification of a GSSP is described in detail by Remane et al. (1996) but no such procedure is specified for an auxiliary stratotype point. There is indeed no further mention of auxiliary stratotypes or auxiliary stratotype points in Remane et al. (1996) and no reference to them in the current ICS statutes.

GSSPs and Auxiliary Stratotype Points Compared

As accepted by Remane et al. (1996), the definition of a GSSP provided by Cowie et al. (1986) remains valid for the Phanerozoic: "This Boundary Stratotype Section and Point is the designated type of a stratigraphic boundary identified in published form and marked in the section as a specific point in a specific sequence of rock strata and constituting the standard for the definition and recognition of the stratigraphic boundary between two named global stratigraphic (chronostratigraphic) units" (Cowie et al., 1986, p. 5). The GSSP is placed at or close to a marker horizon within the stratotype section that allows global correlation to the GSSP. Nonetheless, it is the position of the GSSP in the stratotype section that fixes the definition, not the marker horizon, about which new knowledge may arise even at the stratotype section itself. The GSSP represents a unique instant in geological time at a specific unique geographical locality (Cowie et al., 1986) and is therefore "the only place where we actually know (by definition) that time and rock coincide within our classification" (Holland, 1984, p. 149).

Some GSSPs are easier to correlate precisely on a global scale than others. The Danian Stage GSSP is based on ejecta from a large extraterrestrial impact (Molina et al., 2006), and arguably has the potential for global correlation with a precision estimated in years or less. GSSPs dated by counting annually layered deposits from the present day, such as the Greenlandian and Northgrippian stage GSSPs of the Holocene Series (Walker et al., 2018) have such precision measured prospectively in decades. Other GSSPs, however, have far lower potential for precise correlation globally. In particular, the lowest occurrences of fossil taxa, commonly used in the Paleozoic, reflect intrinsic delays in migration away from an initial centre of evolution.

In order to reduce these various limitations, auxiliary stratotypes are intended to support GSSPs by assisting in their global correlation. We examine the two current approaches used to define such auxiliary stratotypes: 1) the ICS-recognised *Auxiliary Stratotype Point* (and its unofficial variant term Auxiliary boundary Stratotype Section and Point, ASSP) – which we consider methodologically and conceptually untenable; and 2) the Auxiliary Stratotype Section (also known as an Auxiliary Section, Auxiliary Boundary Stratotype, Global Auxiliary Stratotype etc.) which is not recognised by ICS and is here renamed as the *Standard Auxiliary Boundary Stratotype* (SABS) (Table 2).

Table 2. Terms used for auxiliary stratotypes (and points) proposed or established to support Global boundary Stratotype Sections and Points (GSSPs). Only the Auxiliary Stratotype Point is presently recognised by the ICS

1. Auxiliary Stratotype Point

Auxiliary Stratotype Point (ASP) (Cowie, 1986; Cowie et al., 1986; Remane et al., 1996; e.g., Pavia and Enay, 1997).
Auxiliary Stratotype Section and Point (ASSP) – a preferred term for an Auxiliary Stratotype Point according to Fernández-López et al. (2009).
Auxiliary boundary Stratotype Section and Point (ASSP) (e.g., Ergaliev et al., 2014; Miller et al., 2015b, 2020; Wang et al., 2021; Figs. 1, 4b).
Auxiliary boundary Stratigraphic Section and Point (ASSP) (Miller et al., 2015a, 2015b, 2020).
Auxiliary Global Stratotype Section and Point (ASSP) (Ma et al., 2021).
Auxiliary GSSP section (e.g., Chen et al., 2017).

2. Auxiliary Stratotype Section

Auxiliary Stratotype Section (e.g., Yu, 1988; Paproth et al., 1991; Becker and Paproth, 1993; Chen and Zhang, 2017; Chen et al., 2017).
Global Auxiliary Stratotype Section (e.g., Chen and Wang, 2003; fig. 2-2B in Chen et al., 2017; Fig. 4a).
Auxiliary Boundary Stratotype (e.g., Hilgen et al., 2005).
Principal Auxiliary Section (Brack et al., 2005).
Auxiliary Section (e.g., Molina et al., 2009; Walaszczyk et al., 2021).
Global Auxiliary Stratotype (e.g., Walker et al., 2009, 2019; Chen and Zhang, 2017; Figs. 2, 3).
Standard Auxiliary Boundary Stratotype – proposed here to replace the Auxiliary Stratotype Point.

Examples of Published Auxiliary Stratotypes Used to Support GSSPs

Auxiliary stratotypes have been proposed increasingly to support GSSPs, with at least 40 such auxiliary stratotypes having been approved or proposed from the Cambrian to Quaternary, and with as many as seven for a single GSSP (the Danian Stage GSSP) (Table 3). Four examples, from the Tremadocian, Northgrippian, and Meghalayan stages, are examined here to illustrate the two contrasting approaches used.

The Tremadocian Stage and Ordovician System GSSP is supported by two Auxiliary boundary Stratotype Sections and Points (ASSPs). The first is at the Lawson Cove section in the northern Wah Wah Mountains, Ibex Area, west-central Utah, USA, at 160.6 m in the measured section (Miller et al., 2015b). This ASSP was approved in 2016 through supermajority vote by the Subcommission on Ordovician Stratigraphy (SOS) (Subcommission on Ordovician Stratigraphy, 2017, p. 8). The second ASSP is in the Xiaoyangqiao section, Dayangcha, North China, at a point given as 19.9 m (±0.2 m) in the measured section (Wang et al., 2021). In 2019, it was likewise approved through supermajority vote by the Subcommission on Ordovician Stratigraphy (Wang et al., 2021).

Walker et al. (2019) published two Global Auxiliary Stratotypes, without accompanying points, to support their newly designated GSSPs defining the Northgrippian and Meghalayan stages/ages and equivalent Middle and Upper/Late Holocene subseries/subepochs (Walker et al., 2018). These auxiliary stratotypes extend knowledge of the short-lived climatic events at 8.2 ka and 4.2 ka whose stratigraphic signals serve as the respective marker events of the GSSPs. These global auxiliary stratotypes were approved by the joint SQS/INTIMATE (Integration of ice-core, marine and terrestrial records) working group on the subdivision of the Holocene, all members being co-authors of Walker et al. (2019).

Ordovician GSSP and Auxiliary boundary Stratotype Sections and Points (ASSPs)

The GSSP for the Tremadocian Stage and Ordovician System is at Green Point, western Newfoundland, at a level of 101.8 m within Bed 23 of the Lower Broom Point Member, Green Point Formation (Fig. 1a). It represents a base-of-slope depositional environment. The GSSP was determined to align with the lowest occurrence (LO) of the conodont *Iapetognathus fluctivagus* Nicoll et al., 1999a (Cooper et al., 2001), although Terfelt et al. (2012) reassigned specimens at the GSSP level to *Iapetognathus preaengensis* Landing in Fortey et al., 1982. The GSSP is 4.8 m below the LO of planktonic graptolites, and aligns closely with a positive peak in the δ^{13}C record (Cooper et al., 2001). Terfelt et al. (2012) reported *Iapetognathus fluctivagus* to have its LO above that of planktonic graptolites at the Green Point section. Miller et al. (2014) rejected the taxonomic judgements of Terfelt et al. (2012), but Miller (2020) noted that *Iapetognathus fluctivagus* had been recorded previously in Bed 22 at Green Point (Miller and Taylor, 1995, p. 109; Nicoll et al., 1999b, Table 2, item 19), extending its range below the level of the GSSP. There are also concerns about substantial reworking of Cambrian conodonts near the level of the GSSP at Green Point (Miller, 2020). A detailed study of the GSSP interval shows a significant geochemical anomaly in the middle of Bed 22 (Azmy et al., 2014, 2015), suggesting that this horizon, about 2.5 m below the GSSP, would be a better position for it. Above this level, a rapid shift to positive δ^{13}C values occurs in the middle of Bed 23. If the shift to positive δ^{13}C values in the upper part of Bed 23 is used to identify the present GSSP level, then the GSSP occurs ~70 cm below peak $\delta^{13}C_{carb}$ values (appendix 1 of Azmy et al., 2014). It is not known whether redeposition within Bed 23 has affected its geochemical signature but this must be considered possible. The GSSP as it stands is problematic, even if taxonomic issues are set aside.

Two ASSPs have been approved for the Ordovician and Tremadocian GSSP. The Lawson Cove ASSP in Utah, USA is placed at 160.6 m within an inner carbonate platform succession (Miller et al., 2015b; Fig. 1c). The ASSP is marked by the LO of *Iapetognathus fluctivagus*. The Lawson Cove ASSP provides a useful shallow-water expression of the GSSP. However, to assume the two are exactly time-equivalent faces three difficulties: 1) the LO of *Iapetognathus fluctivagus* (or *I. preaengensis*) at Green Point is below, not at, the GSSP regardless of whether reworking is invoked; 2) Green Point and Lawson Cove represent very different paleoenvironments: it cannot be certain that the *Iapetognathus fluctivagu*s animal invaded both areas at precisely the same time; 3) the Lawson Cove section records the LO of *Iapetog-*

Table 3. Auxiliary stratotypes (and points) proposed or established to support Global boundary Stratotype Sections and Points (GSSPs). Each listed stratigraphic section is followed by the term used by the author(s)

CAMBRIAN SYSTEM
Jiangshanian Stage
Kyrshabakty section, Kazakhstan – Auxiliary boundary Stratotype Section and Point (ASSP) (Ergaliev et al., 2014).

ORDOVICIAN SYSTEM
Tremadocian Stage
Lawson Cove section, Utah, USA – Auxiliary Boundary Stratigraphic Section and Point (ASSP) (Miller et al., 2015a, b).
Xiaoyangqiao section, Dayangcha, North China – Auxiliary Boundary Stratotype Section and Point (ASSP) (Wang et al., 2019, 2021).

Sandbian Stage
Dawangou section, Kalpin, China – Global Auxiliary Stratotype Section / Auxiliary Stratotype Section (Chen and Wang, 2003; Chen and Zhang, 2017; Chen et al., 2017).

CARBONIFEROUS SYSTEM
Tournaisian Stage
Hasselbachtal section, Sauerland, Germany – Auxiliary Stratotype Section (Paproth et al., 1991; Becker and Paproth, 1993; Becker, 1996).
Nanbiancun section, near Guilin, Guangxi Province, South China – Auxiliary Stratotype Section (Yu, 1988; Paproth et al., 1991; Wang, 1993).

PERMIAN SYSTEM
Asselian Stage
Usolka (Krasnousolsk) section, southern Ural Mountains, Russia – proposed Auxiliary stratotype section (Ramezani et al., 2007).

Sakmarian Stage
Kondurovsky section, Russia – potential Auxiliary stratotype (Chernykh et al., 2020).

Wuchiapingian Stage
Tieqiao section, Laibin, South China – Supplementary reference section (Jin et al., 2006); Auxiliary Global Stratotype Section and Point (ASSP) (Ma et al., 2021).

TRIASSIC SYSTEM
Ladinian Stage
Seceda section, northern Italy – Principal auxiliary section (Brack et al., 2005).

JURASSIC SYSTEM
Bajocian Stage
Bearreraig Bay section, Isle of Skye, Scotland, UK – Auxiliary stratotype point (Pavia and Enay, 1997).

Bathonian Stage
Cabo (Cape) Mondego section, Portugal – Auxiliary Stratotype Section and Point (ASSP) (Fernández-López et al., 2009a, b).

CRETACEOUS SYSTEM
Coniacian Stage
Słupia Nadbrzeżna section, central Poland – Auxiliary section (Walaszczyk et al., 2021).
Střeleč section, Czech Republic – Auxiliary section (Walaszczyk et al., 2021).
El Rosario section, northeastern Mexico – Auxiliary section (Walaszczyk et al., 2021).

PALEOGENE SYSTEM
Paleocene Series
Danian Stage
Aïn Settara section, central Tunisia – Auxiliary section (Molina et al., 2009).
Ellès section, central Tunisia – Auxiliary section (Molina et al., 2009).
Caravaca section, southern Spain – Auxiliary section (Molina et al., 2009).
Zumaya section, northern Spain – Auxiliary section (Molina et al., 2009).
Bidart section, southwestern France – Auxiliary section (Molina et al., 2009).
El Mulato section, northeastern Mexico – Auxiliary section (Molina et al., 2009).
Bochil section, southeastern Mexico – Auxiliary section (Molina et al., 2009).

Selandian Stage
Loubieng section, France – Auxiliary section (Steurbaut and Sztrákos, 2008; Schmitz et al., 2011).

Eocene Series
Ypresian Stage
Zumaia–Getaria section, northern Spain – prospective Auxiliary stratotype section and point (Payros et al., 2016).
Forada section, northeastern Italy – suggested Auxiliary Boundary Stratigraphic Section and Point (ASSP) (Boscolo-Galazzo et al., 2019).

Lutetian Stage
Agost section, southern Spain – prospective Auxiliary stratotype section and point (Molina et al., 2012; Payros et al., 2016).
Otsakar section, western Pyrenees, Spain – prospective Auxiliary stratotype section and point (Molina et al., 2012; Payros et al., 2016).
Sejnen section, Tunisia – prospective Auxiliary section (hypostratotype) (Karoui-Yaakoub et al., 2015).

Oligocene Series
Rupelian Stage
Jhaff section, Cap Bon peninsula, northeastern Tunisia – potential Auxiliary section (hypostratotype) (Karoui-Yaakoub et al., 2017).
Tanzania Drilling Project, site 12, southern Tanzania – potential Auxiliary section (hypostratotype) (Karoui-Yaakoub et al., 2017).
Fuente Caldera section, Spain – potential Auxiliary section (hypostratotype) (Karoui-Yaakoub et al., 2017).

NEOGENE SYSTEM
Miocene Series
Tortonian Stage
Monte Gibliscemi section, Sicily, Italy – Auxiliary boundary stratotype (Hilgen et al., 2005).

Pliocene Series
Zanclean Stage
Loulja-A section, Bou Regreg area, Morocco – Auxiliary boundary stratotype (suggested by van der Laan et al., 2006).

QUATERNARY SYSTEM
Holocene Series
Greenlandian Stage
Eifelmaar Lakes succession, Germany – Global auxiliary stratotype (Walker et al., 2009).
Splan Pond succession, eastern Canada – Global auxiliary stratotype (Walker et al., 2009).
Lake Suigestu succession, Japan – Global auxiliary stratotype (Walker et al., 2009).
Lake Maratoto succession, New Zealand – Global auxiliary stratotype (Walker et al., 2009).
Cariaco Basin succession, Venezuela – Global auxiliary stratotype (Walker et al., 2009).

Northgrippian Stage
Gruta do Padre speleothem, Brazil – Global auxiliary stratotype (Walker et al., 2019).

Meghalayan Stage
Mount Logan plateau ice field, Yukon, Canada – Global auxiliary stratotype (Walker et al., 2019).

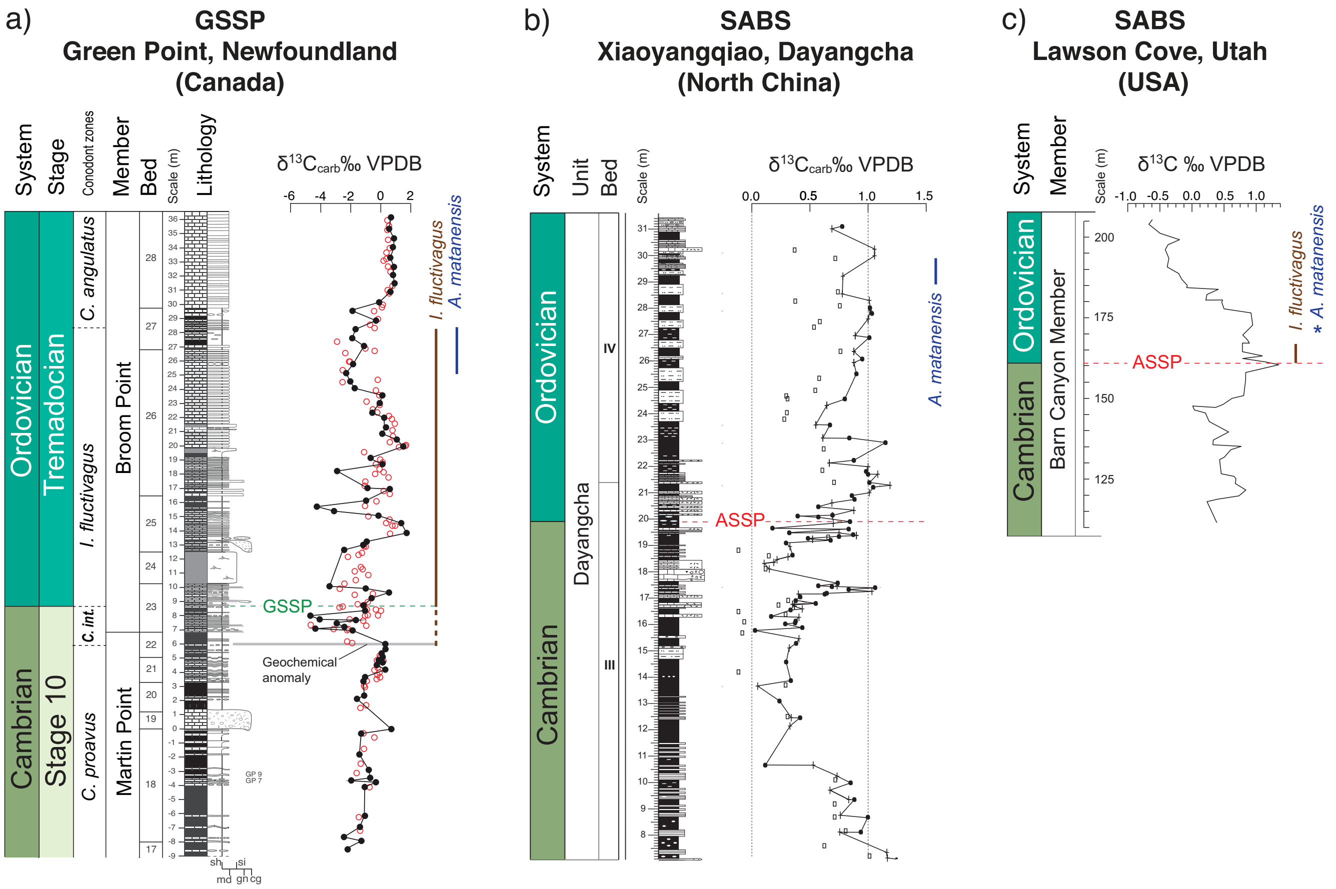

Figure 1. The GSSP for the Tremadocian Stage and Ordovician System, and its two Standard Auxiliary Boundary Stratotypes (SABS), each designated as an Auxiliary boundary Stratotype (or Stratigraphic) Section and Point (ASSP) in the original publication. a) $\delta^{13}C_{carb}$ profile across the GSSP at Green Point, western Newfoundland (from figs. 2 and 6 of Azmy et al., 2014). Note the geochemical anomaly just below the GSSP (Azmy et al., 2014) and the disputed lowest occurrence (LO) of the conodont **Iapetognathus fluctivagus** *as the primary guide to the GSSP. b) SABS (ASSP) at Xiaoyangqiao, Dayangcha, North China, showing lithostratigraphic details and the $\delta^{13}C_{carb}$ profile (from fig. 6 of Wang et al., 2021).* **Iapetognathus fluctivagus** *has not been recorded from this section; correlation to the GSSP being assisted by the $\delta^{13}C_{carb}$ record. c) SABS (ASSP) at Lawson Cove section, Utah, USA, showing lithostratigraphic units and $\delta^{13}C$ profile. The LO of* **Iapetognathus fluctivagus** *at a level of 160.6 m marks the base of the ASSP horizon, and lies ~15 cm above the highest positive values in the $\delta^{13}C$ record (from fig. 14 of Miller, 2015b). The occurrence of the planktonic graptolite* **Anisograptus matanensis** *is shown for Green Point (a) and Xiaoyangqiao (b); it is not recorded from Lawson Cove (c) but occurs at a horizon 2.4 m above the base of* **I. fluctivagus** *at Lava Dam North located 25 km to the northeast. In detail, precise correlations of these two auxiliary stratotype points to the GSSP are not possible even disregarding problems with the GSSP itself.*

nathus fluctivagus about 15 cm above the highest positive values in the $\delta^{13}C$ record (Miller et al., 2015b) as compared with the GSSP at Green Point which occurs ~70 cm below peak $\delta^{13}C_{carb}$ values. Furthermore, the planktonic graptolite *Anisograptus matanensis* Ruedemann, 1937 occurs ~2.4 m above the LO of *Iapetognathus fluctivagus* at the Lava Dam North section near Lawson Cove (Miller et al., 2015b) but its LO is ~17 m above the GSSP at Green Point (Cooper et al., 2001). The ASSP can therefore be considered no more than to approximate closely the level of the GSSP.

The Xiaoyangqiao ASSP, Dayangcha, North China (Fig. 1b), was deposited in an outer shelf to shelf margin setting, and therefore complements both the GSSP and Lawson Cove ASSP (Wang et al., 2019, 2021). It also extends the expression of the GSSP horizon to a different paleogeographic province. It generally supports correlation of the boundary based on biostratigraphy and correspondence of sea-level lowstands, and accords with the $\delta^{13}C$ record. In detail, however, correlation to the GSSP is approximate, as neither *Iapetognathus fluctivagus* nor *Iapetognathus preaengensis* (if one adopts the taxonomy of Terfelt et al., 2012) occur in the Xiaoyangqiao section. This and the relatively low stratigraphic resolution of the $\delta^{13}C$ record make it difficult to match geochemical excursions with certainty, and especially to identify at Xiaoyangqiao the peak of $\delta^{13}C$ values close to the GSSP. Wang et al. (2021) specify a 40-cm interval (19.9 m ± 0.2 m) rather than an actual point to represent the most likely correlation with the GSSP horizon.

Northgrippian GSSP and Global Auxiliary Stratotype

The Northgrippian GSSP is defined in the NorthGRIP1 Greenland ice core at a depth of 1228.67 m corresponding to a significant shift in the oxygen isotope record to more negative $\delta^{18}O$ and δD values, reflecting abrupt cooling (Fig. 2c, d). The duration of this cooling epi-

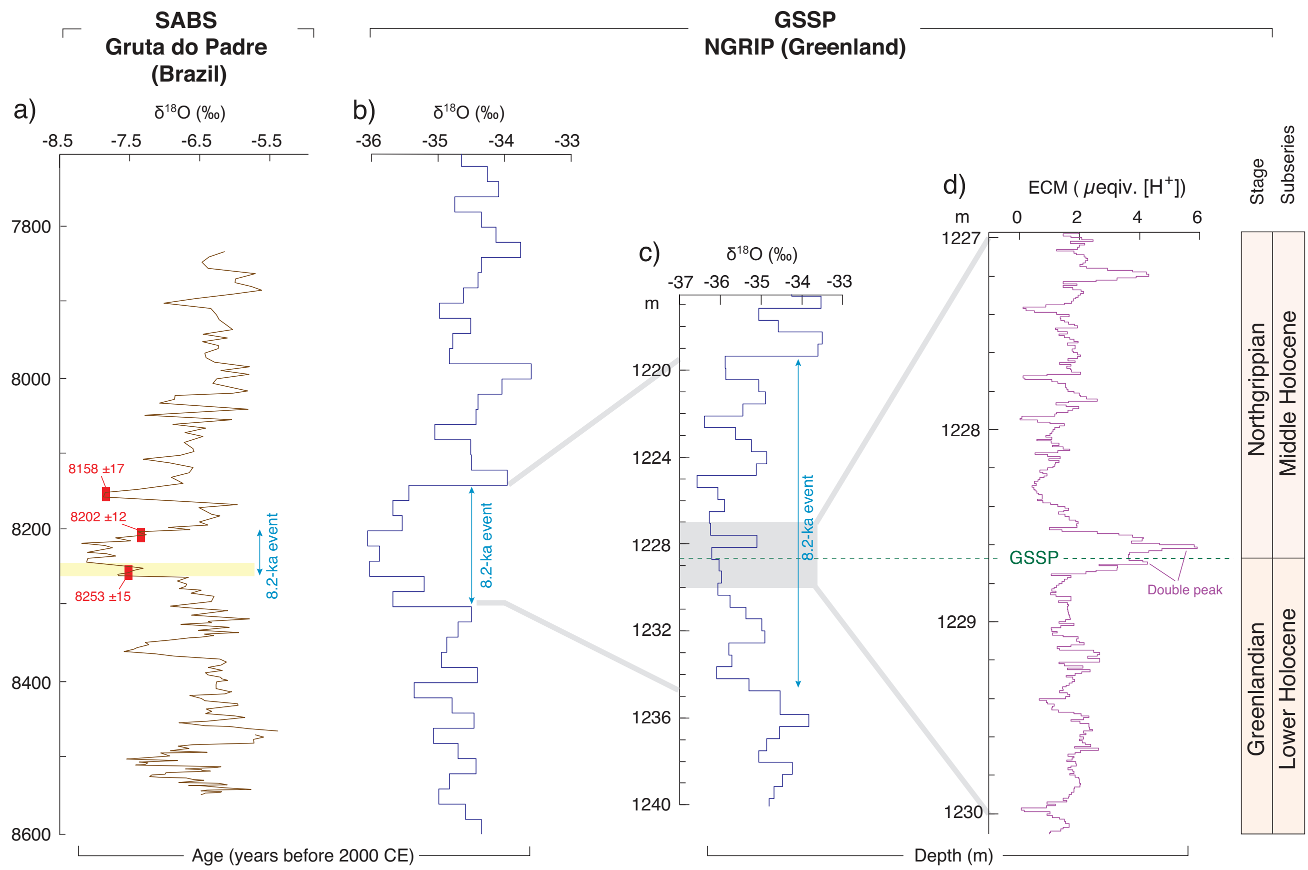

Figure 2. The GSSP for the Northgrippian Stage and Middle Holocene Subseries, and its Standard Auxiliary Boundary Stratotype (SABS). a) speleothem PAD07 represents the SABS at the Gruto do Padre site, Brazil (originally designated as a Global Auxiliary Stratotype by Walker et al., 2019). The age model is based on U–Th dating, and the horizontal yellow bar shows the abrupt decrease in $\delta^{18}O$ values from 293 to 287 mm depth around 8200 ± 25 yr BP. b–d) GSSP in the NGRIP1 ice core, Greenland. The age model is based on layer counting. The 8.2 ka climatic event serves as the primary guide to the GSSP and is approximately synchronous at the SABS. In detail, however, the GSSP is placed at 1228.67 m within a double acidity peak in electrical conductivity measurements (ECM) in the NGRIP1 ice core (d). This level most likely represents atmospheric fallout from a volcanic eruption (Walker et al., 2018, 2019) and cannot be precisely determined in a record from Brazil. The SABS (a) nonetheless provides an exemplary expression of the 8.2 ka climatic event at a low-latitude site.

sode is about 160 yr. More specifically, the GSSP is placed in the middle of a double acidity peak which is from a volcanic eruption. This double peak is found in all deep Greenland ice cores, allowing the GSSP to be traced precisely across this territory. The most precise dating of the GSSP comes from the Greenland DYE-3 core, where the annual layer situated in the middle of the double peak was deposited 8236 yr before the year 2000 CE (b2k) with a maximum counting error of 47 yr (i.e., true age is within ±47 yr of 8236 yr b2k with more than 95% probability; Walker et al., 2019). This of course is a high northern latitude cooling signal.

The auxiliary stratotype for the Northgrippian Stage is speleothem PAD07 from the Gruto do Padre in northeastern Brazil, designated by Walker et al. (2019) to extend knowledge of the 8.2 ka climatic event into the low latitudes (Fig. 2a, b). The $\delta^{18}O$ profile in this speleothem contains a record of the 8.2 ka event, which in this case is an expression of the South American monsoon and increase in rainfall. The interval in the PAD07 speleothem is constrained by U–Th dates with a precision of about 20 years or better. This yields a best age estimate for the onset of the 8.2 ka event of 8200 ± 25 yr BP (2σ uncertainty; where BP here and elsewhere means before 1950 CE) and agrees closely with the age of 8186 yr BP (8236 b2k) in the NGRIP1 ice core (see above). However, the absence of a correlatable double-peak volcanic signature in the Gruto do Padre record conceals the precise position of the GSSP level.

Meghalayan GSSP and Global Auxiliary Stratotype

The Meghalayan GSSP is defined in the KM-A speleothem from the Mawmluh Cave, Meghalaya, northeast India (Walker et al., 2018; Fig. 3a), at a depth of 7.45 mm from the top of the unweathered interval of the KM-A speleothem (Head, 2019). The 4.2 ka climatic event is clearly seen in the $\delta^{18}O$ profile of this speleothem in which less negative $\delta^{18}O$ values reflect reduced rainfall signalling a weakened monsoon. The GSSP is placed midway between the onset and intensification of this climate event (Head, 2019; Walker et al., 2019). Constrained by U–Th dates, the GSSP has a modeled age of 4200 ± 30 yr BP (where BP = 1950 CE) and 4250 ± 30 yr b2k, based on the Berkelhammer et al. (2012) time scale (Walker et al., 2019).

This climate event, lasting two to three centuries, is strongly expressed in proxy records of many mid- and low-latitude regions where it often

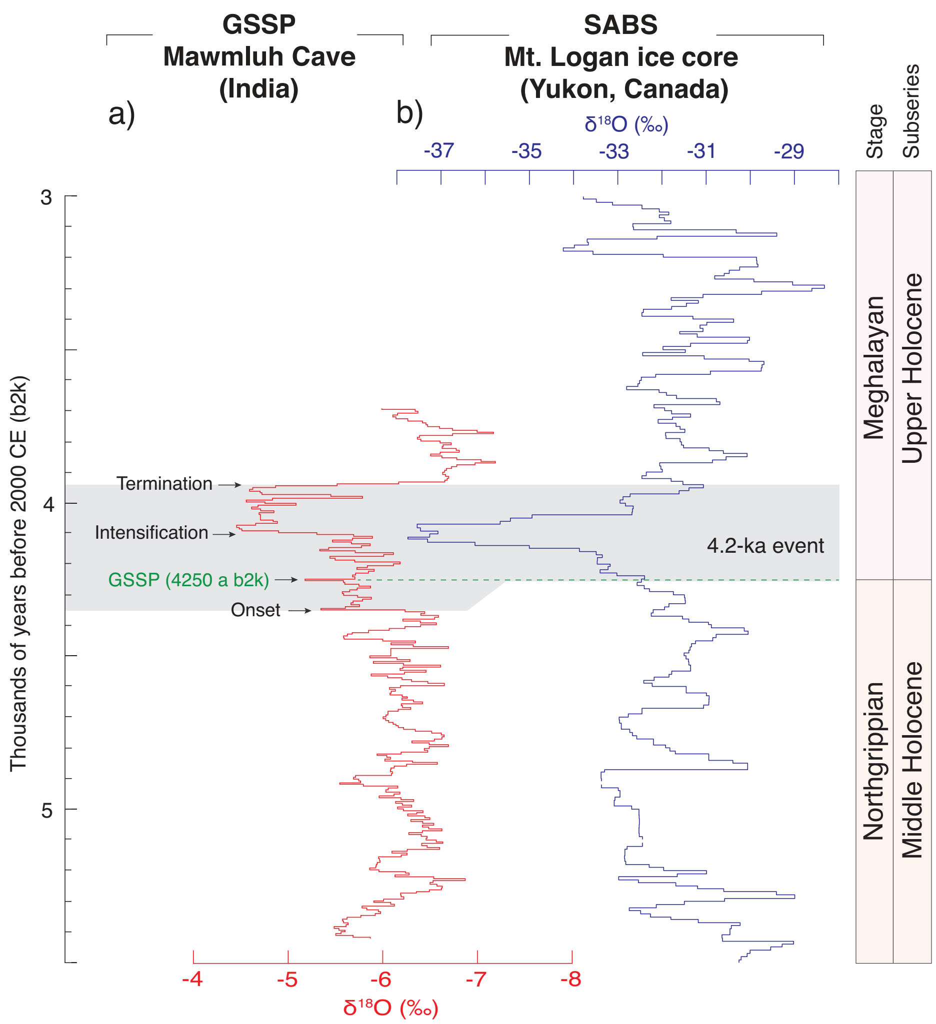

Figure 3. The GSSP for the Meghalayan Stage and Middle Holocene Subseries, and its Standard Auxiliary Boundary Stratotype (SABS). a) GSSP in the KM-A speleothem from Mawmluh Cave, northern India. b) SABS represented by the Prospector Russell Col ice core record from the Mount Logan plateau ice field, Yukon, Canada (originally designated as a Global Auxiliary Stratotype by Walker et al., 2019). The primary guide to the GSSP is the 4.2 ka climatic event (indicated by the grey bar) which is expressed in the KM-A speleothem by an onset, an intensification, and a termination in the $\delta^{18}O$ record. The GSSP is constrained by U–Th dating and placed at the approximate midpoint between onset and intensification (a). The Mount Logan ice core is constrained by tephrochronology. This ice core provides an outstanding high-latitude record of the 4.2 ka climatic event, complementing that of the low-latitude GSSP (Walker et al., 2019), but differences in the $\delta^{18}O$ signature of this event along with small errors in the age models prevent a precise identification of the GSSP horizon. Adapted from fig. 10 of Walker et al. (2019).

represents aridification (Walker et al., 2018). A low-latitude GSSP is therefore appropriate. However, the event is expressed differently at higher latitudes, explaining the choice of an auxiliary stratotype in the plateau ice field on Mount Logan in the Yukon (Walker et al., 2019; Fig. 3b). The signature of the 4.2 ka event here includes lowered $\delta^{18}O$ values and higher deuterium excess and calcium values between 4250 and 3950 yr b2k. This signal appears to represent enhanced moisture transport from the tropical Pacific during pronounced El Niño events (Walker et al., 2019). The 4.2 ka isotopic event in the Mount Logan ice field is tied by a tephra layer to the Greenland ice core record, the chronology of which allows dating between 4250 and 3950 yr b2k with an error of ±70 years. This is remarkably close to the age of the 4.2 ka event at the GSSP (Walker et al., 2019). However, there was no intention to locate the precise GSSP level in the Mount Logan isotope record because its 4.2 ka event signature is not identical with that of the GSSP, and the age estimates at both records have errors measured in decades.

Discussion

It is clear from the examples discussed above that the concept of an auxiliary stratotype supporting and extending the knowledge of a GSSP is a valuable one. Auxiliary stratotypes are now firmly established tools in the development and application of formal chronostratigraphy. However, the current ICS guidelines recognise explicitly the *Auxiliary Stratotype Point* (ASP; Remane et al., 1996), or according to Fernández-López et al. (2009a) more appropriately an *Auxiliary Stratotype*

Section and Point, or an *Auxiliary boundary Stratotype Section and Point* (Ergaliev et al., 2014).

An auxiliary stratotype point nonetheless faces a conceptual challenge. As Odin et al. (2004, p. 6) observed, “The unique character of a GSSP is its guarantee that the boundary it defines is conclusive”, and as noted by Harland (1992, p. 1234). “A synchronous boundary cannot be defined in rock at more than one point”. We contend that it is impossible to identify a point elsewhere that represents the same instant in time as a GSSP. Even in the Xiaoyangqiao section, where an ASSP is ostensibly defined, the auxiliary *point* is a 40-cm interval (19.9 ± 0.2 m) that most likely correlates to the GSSP. The approach used for the Holocene and its stages is more pragmatic. Sections are designated and described, and the 8.2 ka and 4.2 ka climatic events used as primary guides for the Northgrippian and Meghalayan GSSPs are identified without the designation of a point. To define an auxiliary point would be meaningless anyway as both GSSPs have dating errors measured in decades and the climatic signals contain lags and leads that make precise correlation impossible. In the case of the Northgrippian, the volcanic layer at the GSSP has not been traced beyond the Greenland ice cap. Many pre-Quaternary GSSPs rely on a biostratigraphic datum – typically the lowest occurrence of a specified taxon – as the primary guide. But such datums have temporal value only if demonstrated by rigorous analysis and independent age calibration. They will always be influenced by imperfectly known local ecological controls, adding uncertainty when correlating to an auxiliary stratotype.

In those cases where an ASSP is defined, the point within the ASSP section may need to be moved as new information is revealed either about the ASSP section or the GSSP itself. In the case of the Lawson Cove ASSP, this seems inevitable so long as the Green Point (Ordovician) GSSP remains at its current position. Given all the uncertainties discussed, an ASSP can never serve as a stable reference point.

In view of these considerations, we propose replacing the auxiliary stratotype point with an auxiliary boundary stratotype, exemplifying the boundary interval without designating an actual point. We recommend it be known as a *Standard Auxiliary Boundary Stratotype* (SABS) rather than one of the existing terms using ‘global’ (Table 2) because while these sections are nodes in a global network of correlation, their practical relevance is of geographically limited scope. Only the GSSP has truly global applicability. The term ‘standard’ nonetheless identifies these stratotypes as geostandards officially selected to support the GSSP.

Procedures for defining, approving, and ratifying a GSSP are detailed in Remane et al. (1996). The ICS voting membership should not be diverted from its more urgent tasks of scrutinising GSSP proposals. Final approval of proposed GSSP-supporting auxiliary stratotypes has in the past been granted either by the relevant boundary working group (e.g., Paproth et al., 1991; Walker et al., 2009, 2019) or by the relevant ICS subcommission. We consider the latter as providing a more appropriate level of oversight and authority. The Cambrian (Ergaliev et al., 2014) and Ordovician subcommissions (Subcommission on Ordovician Stratigraphy, 2017, p. 8; Miller, 2015b, 2020; Wang et al., 2021) have already approved such auxiliary stratotypes. Indeed, they are regarded within the Cambrian subcommission as serving not only as important regional standards but as functional global standards in the event that a GSSP is later deemed unusable (Ergaliev et al., 2014).

After a Standard Auxiliary Boundary Stratotype has been approved by the appropriate subcommission, an announcement with details of the stratotype has, in some instances, been published in the IUGS journal *Episodes* (e.g., Ergaliev et al., 2014; Wang et al., 2021). *Episodes* with its wide circulation seems appropriate for the publication of such geostandards. We know of two instances where either a permanent plaque has been cemented into the outcrop (Dawangou section, China; fig. 2-2b in Chen et al., 2017; Fig. 4a) or an impressive monument (Xiaoy-

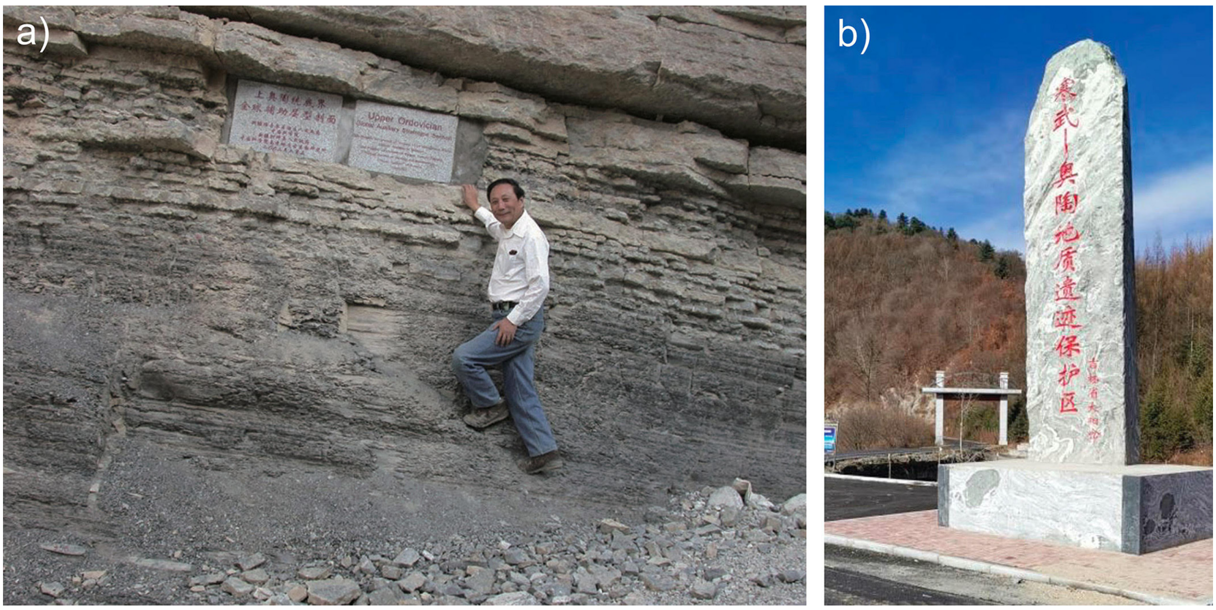

Figure 4. Examples of permanent markers for Standard Auxiliary Boundary Stratotypes (SABS). (a) Plaque inscribed “Upper Ordovician Global Auxiliary Stratotype Section” at the Darriwilian–Sandbian stage interval, Dawangou, showing the boundary approximately at the feet of Chen Xu who is figured (fig. 2-2B in Chen et al., 2017). (b) Monument at the Xiaoyangqiao section in the Cambrian–Ordovician protection zone, marking what is described as the “global Auxiliary Boundary Stratotype Section and Point (ASSP)” for the base of the Ordovician System (fig. 14A in Wang et al., 2021).

angqiao section, China; fig. 14 in Wang et al., 2021; Fig. 4b) has been erected at the auxiliary stratotype site. While such features can sometimes attract unwanted attention, they provide valuable information for those Earth scientists wishing to access the site, and they promote the science of stratigraphy more broadly.

The current ICS-sanctioned *Auxiliary Stratotype Point* is impractical, and this has led to the introduction of at least nine competing terms (Table 2). The introduction of a *Standard Auxiliary Boundary Stratotype* with procedures in place for its selection and formalization will end confusion and allow such stratotypes to be used more effectively in supporting GSSPs.

Recommendations

In recognising the value of those auxiliary stratotypes approved to support GSSPs, we recommend that:

1. *Standard Auxiliary Boundary Stratotype* be the term used to identify its sanctioned role in specifically supporting a GSSP in contrast to auxiliary reference sections used in a more general sense (Salvador, 1994; Table 1).
2. Standard Auxiliary Boundary Stratotypes broadly follow requirements established for GSSPs although greater flexibility may be warranted depending on circumstances and with respect to the desirability for a range of continents, (bio)geographic provinces, climatic zones, depositional facies, and preservational states to be represented.
3. The boundary interval be indicated clearly, but without a specific point designated.
4. Future Standard Auxiliary Boundary Stratotypes require the supermajority approval of the voting membership of the appropriate ICS subcommission.
5. While multiple Standard Auxiliary Boundary Stratotypes may be approved to support a single GSSP, restraint be exercised to avoid a confusing proliferation. These stratotypes will always be subordinate to the GSSP itself.
6. Following approval by the respective subcommission, each Standard Auxiliary Boundary Stratotype be listed on the ICS website as well as that of the respective subcommission, and an announcement published in the IUGS journal *Episodes*.
7. An informative monument or plaque be erected at the stratotype if possible and desired.

Acknowledgments

MJH acknowledges support from a Natural Sciences and Engineering Research Council of Canada Discovery Grant. We appreciate the comments of the two journal reviewers, and guidance from associate editor Brian Pratt.

References

Azmy, K., Stouge, S., Brand, U., Bagnoli, G., and Ripperdan, R., 2014, High-resolution chemostratigraphy of the Cambrian–Ordovician GSSP: Enchanced global correlation tool. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 409, pp. 135–144.

Azmy, K., Kendall, B., Brand, U., Stouge, S., and Gordon, G.W., 2015, Redox conditions across the Cambrian–Ordovician boundary: Elemental and isotopic signatures retained in the GSSP carbonates. Palaeogeography, Palaeoclimatology, Palaeoecology v. 440, pp. 440–454.

Becker, R.T., 1996, New faunal records and holostratigraphic correlation of the Hasselbachtal D/C-Boundary Auxiliary Stratotype. Annales de la Société géologique de Belgique, v. 117, pp. 19–45.

Becker, R.T., and Paproth, E., 1993, Auxiliary stratotype section for the Global Stratotype Section and Point (GSSP) for the Devonian-Carboniferous boundary: Hasselbachtal. Annales de la Société géologique de Belgique, v. 115, pp. 703–706.

Berkelhammer, M.B., Sinha, A., Stott, L., Cheng, H., Pausata, F.S.R., and Yoshimura, K., 2012, An abrupt shift in the Indian Monsoon 4000 years ago. Geophysical Monograph Series, v. 198, pp. 75–88.

Boscolo-Galazzo, F., Capraro, L., Fornaciari, E., Giusberti, L., and Luciani, V., 2019, The Forada section (northeastern Italy): a candidate Auxiliary Boundary Stratigraphic Section and Point (ASSP) for the base of the Ypresian. STRATI 2019, Third International Congress on Stratigraphy, 2–5 July, 2019, Milano, Italy, Abstract Book, p. 307.

Brack, P., Rieber, H., Nicora, A., and Mundil, R., 2005, The Global boundary Stratotype Section and Point (GSSP) of the Ladinian Stage (Middle Triassic) at Bagolino (Southern Alps, Northern Italy) and its implications for the Triassic time scale. Episodes, v. 28, pp. 233–244.

Chen, X., and Wang, Z.H., 2003, Global Auxiliary Stratotype Section of the Upper Ordovician in China. Journal of Stratigraphy, v. 27, pp. 264–265.

Chen, X., and Zhang, Y., 2017, Introduction. In: Chen, X., Zhang, Y., Goldman, D., Bergström, S.M., Fan, J., Wang, Z., Finney, S.C., Chen, Q., and Ma, X. (Eds.), Darriwilian to Katian (Ordovician) Graptolites from Northwest China. Elsevier Inc., Amsterdam, pp. 1–5.

Chen, X., Zhang, Y., Wang, Z., Goldman, D., Bergström, S.M., Fan, J., Finney, S.C., and Chen, Q., 2017, 2. Biostratigraphy. In: Chen, X., Zhang, Y., Goldman, D., Bergström, S.M., Fan, J., Wang, Z., Finney, S.C., Chen, Q., and Ma, X. (Eds.), Darriwilian to Katian (Ordovician) Graptolites from Northwest China. Elsevier Inc., Amsterdam, pp. 7–38.

Chernykh, V.V., Chuvashov, B.I., Shen, S.-Z., Henderson, C.M., Yuan, D.-X., and Stephenson, M.H., 2020, The Global Stratotype Section and Point (GSSP) for the base-Sakmarian Stage (Cisuralian, Lower Permian). Episodes, v. 43, pp. 961–979.

Cooper, R.A., Nowlan, G.S., and Williams, S.H., 2001, Global Stratotype Section and Point for base of the Ordovician System. Episodes, v. 24, pp. 19–28.

Cowie, J.W., 1986, Guidelines for Boundary Stratotypes. Episodes, v. 9, pp. 78–82.

Cowie, J.W., Ziegler, W., Boucot, A.J., Bassett, M.G., and Remane, J., 1986, Guidelines and Statutes of the International Commission on Stratigraphy (ICS). Courier Forschungsinstitut Senckenberg, v. 83, p. 1–14.

Ergaliev, G.Kh., Zhemchuzhnikov, V.G., Popov, L.E., Bassett, M.G., and Ergaliev, F.G., 2014, The Auxiliary boundary Stratotype Section and Point (ASSP) of the Jiangshanian Stage (Cambrian: Furongian Series) in the Kyrshabakty section. Episodes, v. 37, pp. 41–47.

Fernández-López, S., Pavia, G., Erba, E., Guiomar, M., Henriques, M.H., Lanza, R., Mangold, C., Morton, N., Olivero, D., and Tiraboschi, D., 2009a, The Global Boundary Stratotype Section and Point (GSSP) for base of the Bathonian Stage (Middle Jurassic), Ravin du Bès Section, SE France. Episodes, v. 32, pp. 222–248.

Fernández-López, S.R., Pavia, G., Erba, E., Guiomar, M., Henriques, M.H., Lanza, R., Mangold, C., Olivero, D., and Tiraboschi, D., 2009, Formal proposal for the Bathonian GSSP (Middle Jurassic) in the Ravin du Bès Section (Bas-Auran, SE France). Swiss Journal of Geosciences, v. 102, pp. 271–295.

Fortey, R.F., Landing, E., and Skevington, D., 1982, Cambrian–Ordovician boundary sections in the Cow Head Group, western Newfoundland. In: Bassett, M.G., and Dean, W.T. (Eds.), The Cambrian–Ordovician

Boundary Sections, Fossil Distributions, and Correlations. National Museum of Wales, Geological Series 3, pp. 95–129.

Harland, W.B., 1992, Stratigraphic guidance and regulation: a critique of current tendencies in stratigraphic codes and guides. Bulletin of the Geological Society of America, v. 104, pp. 1231–1235.

Head, M.J., 2019, Formal subdivision of the Quaternary System/Period: present status and future directions. Quaternary International, v. 500, pp. 32–51.

Hedberg, H.D. (Ed.), 1976, International Stratigraphic Guide. John Wiley, NewYork, London, 200 pp.

Hilgen, F.J., Aziz, H.A., Bice, D., Iaccarino, S., Krijgsman, W., Kuiper, A., Montanari, A., Raffi, I., Turco, E., and Zachariasse, W.J., 2005, The Global boundary Stratotype Section and Point (GSSP) of the Tortonian Stage (Upper Miocene) at Monte dei Corvi. Episodes, v. 28, pp. 6–17.

Holland, C.H., 1984, Steps to a standard Silurian. Proceedings of the 27th International Geological Congress, Moscow 4–14 August, 1984, v. 1 Stratigraphy. VNU Science Press, Utrecht, Netherlands, pp. 127–156.

International Commission on Stratigraphy, 2017, Statutes, 2017. https://stratigraphy.org/statutes [accessed 25th September 2021].

Jin,Y., Shen, S., Henderson, C.M., Wang, X., Wang, W., Wang, Y., Cao, C., and Shang, Q., 2006, The Global Stratotype Section and Point (GSSP) for the boundary between the Capitanian and Wuchiapingian Stage (Permian). Episodes, v. 29, pp. 253–262.

Karoui-Yaakoub, N., Ben M'Barek-Jemaï, M., Mtimet, M.S., and Molina, E., 2015, Integrated stratigraphy of the Ypresian–Lutetian transition in northern Tunisia: Correlation and paleoenvironmental reconstruction. Journal of African Earth Sciences, v. 110, pp. 176–187.

Karoui-Yaakoub, N., Grira, C., Mtimet, M.S., Negra, M.H., and Molina, E., 2017, Planktic foraminiferal biostratigraphy, paleoecology and chronostratigraphy across the Eocene/Oligocene boundary in northern Tunisia. Journal of African Earth Sciences, v. 125, pp. 126–136.

Ma, Q., Ye, F., Wang, W., Sheng, Y., Shu, L., and Chen, X., 2021, Grid mapping revealed hidden geochemical lens and its chemostratigraphic bias in the middle-upper Permian marine carbonate sequence in Laibin, South China. Geological Journal, v. 56, pp. 6088–6101. doi:10.1002/gj.4156

Miller, J.F., 2020, Study and use of Upper Cambrian to Lower Ordovician conodonts in central, southern, and western Laurentia, 1933–2018. Palaeobiodiversity and Palaeoenvironments, v. 100, pp. 95–133.

Miller, J.F., and Taylor, M.E., 1995, Biostratigraphic significance of *Iapetognathus* (Conodonta) and *Jujuyaspis* (Trilobita) in the House Limestone, Ibex Area, Utah. In: Cooper, J.D., Droser, M.L., and Finney, S.C. (Eds.), Ordovician Odyssey: Short Papers for the Seventh International Symposium on the Ordovician System. Pacific Section, Society for Sedimentary Geology (SEPM), Fullerton, California, Book 77, pp. 109–112.

Miller, J.F., Repetski, J.E., Nicoll, R.S., Nowlan, G., and Ethington, R.L., 2014, The conodont *Iapetognathus* and its value for defining the base of the Ordovician System. GFF, v. 136, pp. 185–188.

Miller, J.F., Ethington, R.L., Repetski, J.E., Ripperdan, R.L., and Taylor, J.F., 2015a, Proposed Auxiliary Stratigraphic Section and Point (ASSP) for the base of the Ordovician System at Lawson Cove, Utah, USA. Short Papers and Abstracts for 12th International Symposium on the Ordovician System, at James Madison University, pp. 121–122.

Miller, J.F., Evans, K.R., Ethington, R.L., Freeman, R.L., Loch, J.D., Repetski, J.E., Ripperdan, R.L., and Taylor, J.F., 2015b, Proposed Auxiliary Boundary Stratigraphic Section and Point (ASSP) for the base of the Ordovician System at Lawson Cove, Utah, USA. Stratigraphy, v. 12, pp. 219–236.

Molina, E., Alegret, L., Arenillas, I., Arz, J. A., Gallala, N., Hardenbol, J., von Salis, K., Steurbaut, E., Vandenberghe, N., and Zaghbib-Turki, D., 2006, The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, "Tertiary", Cenozoic) at El Kef, Tunisia: Original definition and revision. Episodes, v. 29, pp. 263–273.

Molina, E., Alegret, L., Arenillas, I., Arz, J.A., Gallala, N., Grajales-Nishimura, J.M., Murillo-Muñetón, G., and Zaghbib-Turki, D., 2009, The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, "Tertiary", Cenozoic): auxiliary sections and correlation. Episodes, v. 32, pp. 84–95.

Molina, E., Alegret, L., Apellaniz, E., Bernaola, G., Caballero, F., Monechi, S., Ortiz, S., Orue-Etxebarria, X., Payros, A., and Tosquella, J., 2012, The Global Stratotype Section and Point for the Base of the Lutetian Stage: Auxiliary Sections and Correlation in Spain. Abstracts of the 34th International Geological Congress, Brisbane, Australia, p. 1508.

Murphy, M.A., Salvador, A., Piller, W.E., and Aubry, M.-P., 2021, International Stratigraphic Guide – An abridged version. International Subcommission on Stratigraphic Classification of IUGS, International Commission on Stratigraphy. Online: https://stratigraphy.org/guide/guide

Nicoll, R.S., Miller, J.F., Nowlan, G.S., Repetski, J.E., and Ethington, R.L., 1999a, Designation of holotypes for new species of *Iapetonudus* Nicoll, Miller, Nowlan, Repetski, and Ethington and *Iapetognathus* Landing. Journal of Micropalaeontology, v. 18, p. 124.

Nicoll, R.S., Miller, J.F., Nowlan, G.S., Repetski, J.E., and Ethington, R.L., 1999b, *Iapetonudus* (new genus) and *Iapetognathus* Landing, unusual earliest Ordovician multielement conodont taxa and their utility for biostratigraphy. Brigham Young University Geology Studies, v. 44, pp. 27–101.

Odin, G.S., Gardin, S., Robaszynski, F., and Thierry, J., 2004, Stage boundaries, global stratigraphy, and the time scale: towards a simplification. Carnets de Géologie/Notebooks on Geology - Article 2004/02 (CG2004_A02).

Paproth, E., Feist, R., and Flajs, G., 1991, Decision on the Devonian–Carboniferous boundary stratotype. Episodes, v. 14, pp. 331–336.

Pavia, G., and Enay, R., 1997, Definition of the Aalenian–Bajocian Stage boundary. Episodes, v. 20, pp. 16–20.

Payros, A., Pujalte, V., Orue-Etxebarria, X., Apellaniz, E., Bernaola, G., Baceta, J.I., Caballero, F., Dinarès-Turell, J., Monechi, S., Ortiz, S., Schmitz, B., and Tosquella, J., 2016, The relevance of Iberian sedimentary successions for Paleogene stratigraphy and timescales. In: Montenari, M. (Ed.), Stratigraphy and Timescales, Volume 1, pp. 393–489. Elsevier Inc. doi:10.1016/bs.sats.2016.08.001

Ramezani, J., Schmitz, M.D., Davydov, V.I., Bowring, S.A., Snyder, W.S., and Northrup, C.J., 2007, High-precision U–Pb zircon age constraints on the Carboniferous–Permian boundary in the southern Urals stratotype. Earth and Planetary Science Letters, v. 256, pp. 244–257.

Remane, J., Bassett, M.G., Cowie, J.W., Gohrbandt, K.H., Lane, H.R., Michelson, O., and Naiwen, W., 1996, Revised guidelines for the establishment of global chronostratigraphic standards by the International Commission on Stratigraphy (ICS). Episodes, v. 19, pp. 77–81.

Ruedemann, R., 1937, A new North American graptolite faunule. American Journal of Science, ser. 5, pp. xxxiii + 57.

Salvador, A. (Ed.), 1994, International stratigraphic guide: A guide to stratigraphic classification, terminology, and procedure (Second edition): International Subcommission on Stratigraphic Classification of IUGS International Commission on Stratigraphy and The Geological Society of America, Boulder, Colorado, pp. i–xix, 1–214.

Schmitz, B., Pujalte, V., Molina, E., Monechi, S., Orue-Etxebarria, X., Speijer, R.P., Alegret, L., Apellaniz, E., Arenillas, I., Aubry, M.-P., Baceta, J.-I., Berggren, W.A., Bernaola, G., Caballero, F., Clemmensen, A., Dinarès-Turell, J., Dupuis, C., Heilmann-Clausen, C., Orús, A.H., Knox, R., Martín-Rubio, M., Ortiz, S., Payros, A., Petrizzo, M.R., von Salis, K., Sprong, J., Steurbaut, E., and Thomsen, E., 2011, The Global Stratotype Sections and Points for the bases of the Selandian (Middle Paleocene) and Thanetian (Upper Paleocene) stages at Zumaia, Spain. Episodes, v. 34, pp. 220–243.

Steurbaut, E., and Sztrákos, K., 2008, Danian/Selandian boundary criteria and North Sea Basin–Tethys correlations based on calcareous nannofossil and foraminiferal trends in SW France. Marine Micropaleontology, v. 67, pp. 1–29.

Subcommission on Ordovician Stratigraphy, 2017, Ordovician News, no.

34 (for 2016), 101 pp.

Terfelt, F., Bagnoli, G., and Stouge, S., 2012, Re-evaluation of the conodont *Iapetognathus* and implications for the base of the Ordovician System GSSP. Lethaia, v. 45, pp. 227–237.

Yu, C.M. (Ed.), 1988, Devonian-Carboniferous Boundary in Nanbiancun, Guilin, China. Aspects and Records. Science Press, Beijing, 379 pp.

van der Laan, E., Snel, E., de Kaenel, E., Hilgen, F.J., and Krijgsman, W., 2006, No major deglaciation across the Miocene-Pliocene boundary: Integrated stratigraphy and astronomical tuning of the Loulja sections (Bou Regreg area, NW Morocco). Paleoceanography, 21, PA3011, doi:10.1029/2005PA001193

Walaszczyk, I., Čech, S., Crampton, J.S., Dubicka, Z., Ifrim, C., Jarvis, I., Kennedy, W.J., Lees, J.A., Lodowski, D., Pearce, M., Peryt, D., Sageman, B.B., Schiøler, P., Todes, J., Uličný, D., Voigt, S., Wiese, F., with contributions by Linnert, C., Püttmann, T., and Toshimitsu, S., 2021, The Global Boundary Stratotype Section and Point (GSSP) for the base of the Coniacian Stage (Salzgitter-Salder, Germany) and its auxiliary sections (Słupia Nadbrzeżna, central Poland; Střeleč, Czech Republic; and El Rosario, NE Mexico). Episodes, online: doi:10.18814/epiiugs/2021/021022

Walker, M., Johnsen, S., Rasmussen, S.O., Steffensen, J.P., Popp, T., Gibbard, P., Hoek, W., Lowe, J., Andrews, J., Björck, S., Cwynar, L.C., Hughen, K., Kershaw, P., Kromer, B., Litt, T., Lowe, D.J., Nakagawa, T., Newnham, R., and Schwander, J., 2009, Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records. Journal of Quaternary Science, v. 24, pp. 3–17.

Walker, M., Head, M.J., Berkelhammer, M., Björck, S., Cheng, H., Cwynar, L., Fisher, D., Gkinis, V., Long, A., Lowe, J., Newnham, R., Rasmussen, S.O., Weiss, H., 2018, Formal ratification of the subdivision of the Holocene Series/Epoch (Quaternary System/Period): two new Global Boundary Stratotype Sections and Points (GSSPs) and three new stages/subseries. Episodes, v. 41, pp. 213–223.

Walker, M., Head, M.J., Berkelhammer, M., Björck, S., Cheng, H., Cwynar, L., Fisher, D., Gkinis, V., Long, A., Lowe, J., Newnham, R., Rasmussen, S.O., and Weiss, H., 2019, Subdividing the Holocene Series/Epoch: formalization of stages/ages and subseries/subepochs, and designation of GSSPs and auxiliary stratotypes. Journal of Quaternary Science, v. 34, pp. 173–186.

Wang, C.Y., 1993, Auxiliary Stratotype Sections for the Global Stratotype Section and Point (GSSP) for the Devonian-Carboniferous boundary: Nanbiancun. Annales de la Société géologique de Belgique, v. 115, pp. 707–708.

Wang, X.F., Stouge, S., Maletz, J., Bagnoli, G., Qi, Y.P., Raevskaya, E., Wang, C.S., and Yan, C.B., 2019, Correlating the global Cambrian–Ordovician boundary: Precise comparison of the Xiaoyangqiao section, Dayangcha, North China with the Green Point GSSP sections, Newfoundland, Canada. Palaeoworld, v. 28, pp. 243–275.

Wang, X., Stouge, S., Maletz, J., Bagnoli, G., Qi, Y., Raevskaya, E.G., Wang, C., and Yan, C., 2021, The Xiaoyangqiao section, Dayangcha, North China: the new global Auxiliary Boundary Stratotype Section and Point (ASSP) for the base of the Ordovician System. Episodes, doi:10.18814/epiiugs/2020/020091

Martin J. Head is a stratigrapher and Full Professor of Earth Sciences at Brock University, Canada, and is a status-only full professor at the University of Toronto, Canada. He is currently Vice-Chair of the International Subcommission on Quaternary Stratigraphy (SQS), having served as its Chair (2012–2020), and is Co-Convener of its Working Group on the Middle–Upper Pleistocene Subseries Boundary. Martin is concurrently a voting member of the SQS Working Group on the Anthropocene and of the International Subcommission on Stratigraphic Classification, and an advisory board member of the INQUA Stratigraphy and Chronology Commission (SACCOM). He specializes in marine dinoflagellate cysts and acritarchs of the late Cenozoic including their biostratigraphy, paleoecology and taxonomy.

Werner E. Piller is Full Professor Emeritus of Paleontology and Historical Geology at the University of Graz, Austria. He is presently Chair of the International Subcommission on Stratigraphic Classification (ISSC) and a voting member of the Subcommission on Neogene Stratigraphy (SNS). From 2004 to 2009 he was Vice-President and from 2009 to 2017 President of the Regional Committee for Mediterranean Neogene Stratigraphy (R.C.M.N.S.) of the IUGS. From 2004 to 2013 he chaired the Austrian National Committee for the International Geoscience Program (IGCP) of UNESCO, and since 2013 he has served as Chair of the National Committee for Geo/Hydro-Sciences of the Austrian Federal Ministry of Education, Science and Research (including related UNESCO Programs).

Marie-Pierre Aubry is a Distinguished Professor of Earth Sciences at Rutgers University, USA. She is the Secretary of the International Subcommission on Neogene Stratigraphy (SNS), a voting member of the International Subcommission on Stratigraphic Classification (ISSC) and a Commissioner on the North American Commission on Stratigraphic Nomenclature (NACSN). She was Chair of UNESCO/IUGS IGCP Project 308 (Paleocene/Eocene Boundary Events in Space and Time, 1990–1995) and the ICS Working Group on the Paleocene/Eocene Boundary (1989–2004). Her scientific interests include Earth Cenozoic history as well as the evolutionary dynamics of the marine plankton. She has edited and contributed to several books in Earth Sciences and she is the author of a multi-volume series on Cenozoic coccolithophores. She is a Fellow of the AAAS.

Mike Walker is Emeritus Professor of Quaternary Science, University of Wales, Lampeter, UK, and Honorary Professor, Aberystwyth University, UK. He is former President of the Quaternary Research Association of Great Britain, and past Chair of the Natural Environment Research Council Radiocarbon and Cosmogenic Isotopes committees. He chaired the SQS Working Group that defined the Pleistocene–Holocene boundary, and the SQS Working Group on the subdivision of the Holocene. His principal research interests are in late Quaternary climate change and its manifestations in proxy records. He has worked extensively on problems of stratigraphy and chronology during the Last Termination.