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Shift in the Paradigm for GSSP Boundary Definition

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Abstract

For over 200 years the use of biotic events as the basis for the establishment of chronostratigraphic boundaries has been the only approach successfully utilized for international and national chronostratigraphy. The traditional biostratigraphic method provides relatively high resolution, averaging 1 Ma or sometimes less. This biochronological evolutionary approach to the Global Boundary Stratotype section and Point (GSSP) utilizes biotic Primary Markers (PM), with a few exceptions, encompasses the integrated PM and other non-PM markers as the general principles for defining GSSP boundaries and is a reasonably reliable mechanism for global correlation and a relatively stable International Geologic Time Scale (IGTS). The biotic PM's, however, possessed several serious restrictions: the nature of biological taxonomy, climatic, sedimentary, environmental - and directly applicable within the tropics-subtropics only. Biotic evolution and radiogenic isotopes are the only systems in geologic time that encompass the direction of time. The latter possessed less restrictions than the former. The recent tendency to define GSSP's utilizing magnetic chrons, climatic events and geochemistry may work in the Cenozoic, but is useless in the Mesozoic and older sediments because their cyclic nature (repeatedness) and the need for a second, directional in time index (biostratigraphic or radioisotopic) to place the PM in the right position within the scale. I propose here to utilize volcanic ash beds as the best Primary Marker in geologic chronostratigraphy. The U-Pb system is one of the most dependable of the geochronologic systems because it relies on a simple and non-interpretive radioisotopic decay constant. The ash-bed GSSP as a lithological horizon is universal for the GSSP definition and can be correlated as an age in any facies (marine, lagoon and continental), regardless of paleoclimatic zones, palaeoceanographic, geochemical, and most other geological factors. Even moderate level metamorphism (> 900 C°) does not affect the U-Pb dating of zircons. The GSSP at the base of a volcanic ash bed (Primary Marker) could be established in a short working time and these ash beds can be integrated with the existing as well as new biostratigraphic, geochemical, magnetostratigraphic and astronomical data (Secondary Markers) to create a robust, accurate and highly useable time scale. Several potential GSSP's that could be established with the volcanic ash beds close to the traditional and/or historical boundaries serve as examples for this approach and include Devonian-Carboniferous, Moscovian-Kasimovian, Kasimovian-Gzhelian, and Sakmarian-Artinskian boundaries.

(Davydov et al., 2020; JIANG et al., 2007; Librovich and Ovechkin, 1963; McLaren, 1978; Rhodes, 1963; Walliser, 1968)

Keywords: chronostratigraphy, biotic events, biostratigraphy, GSSP paradigm, volcanic ash, U-Pb dating

1. Introduction

The use of evolutionary biotic events as the basis for the establishment of chronostratigraphic boundaries for the time scale has been utilized since the very first geologic map and international time scale were published (Murchison, 1841; Renevier, 1873-1874; Smith, 1815; Lyell, 1855) (Fig. 1) and remain the main criteria for the definition of Global Stratotype Section Points (GSSP) and hence the definitions of the lower boundaries of each segment of the international time scale (Lucas, 2018; Gradstein and Ogg, 2012; Walsh et al., 2004). A biotic (or paleobiological) event is an event recognized in a sequence of sedimentary rocks, where there is a significant change in the biota as recorded by assemblages of fossils over a relatively short period of time (Sageman et al., 1997; Walsh, 1998). A biotic event in terms of GSSP chronostratigraphy has been defined as a first appearance of a single species that are isochronous or nearly so throughout their distribution (Lucas, 2018, and references cited therein). For over 200 years it has been the only approach successfully utilized for international and national chronostratigraphy because no other methods could meet the criteria that were formalized in the first International Stratigraphic Guide (Hedberg, 1976):

1. The International chronostratigraphic scale provides a single universal standard of reference for dating rock strata, or events recorded in rock strata, anywhere in the world.
2. Chronostratigraphy offers the greatest promise for formally named units of worldwide application in geology;
3. Chronostratigraphic units reflect the directional geological history of Earth and can be recognized the world over to the extent that the time-diagnostic features distinctive of the unit can be identified in the rocks.

The international stratigraphic classification is developed in a hierarchical order, where the lower boundary of the Erathems, System and Series are defined by the lower boundary of the lowermost unit within the defined unit (Table 1), and the stage boundaries are defined by a GSSP.

Table 1

chronostratigraphic	geochronologic	Rank
Erathem	Era	2nd order
System	Period	3rd order
Series	Epoch	4th order
Stage	Age	5th order
Substage	Subage	6th order

Therefore, GSSP definitions are the core of the entire stratigraphic classification system and the International time scale (IGTS) relies on the quality of the GSSP. The GSSP concept, that has been utilized for over 60 years (Hedberg, 1976) is a biochronological evolutionary approach to define the boundary within the chronocline of a single species that is integrated with additional proxies (biostratigraphic, geochemical, paleomagnetic etc.) and is capable of providing a precise definition of a GSSP. The reliable correlation of the GSSP boundary can be done by integration with multiple taxa as well as by utilizing non-biologic markers (Lucas, 2018). Such a robust correlation provides, in theory, for the overall stability of the IGTS once the GSSP's are selected.

The original GSSP concept presumes that once the boundary is defined, it becomes a permanent definition (Hedberg, 1976). Later, however, this principle of permanency was revised to allow for the revision of a GSSP after a period of 10 years following the original definition (Remane et al., 1996). Over the last 10 years or so, there has been a tendency to propose the revision of more and more GSSPs, many within a few years of when the original definition was accepted. Several GSSP's, especially those that were proposed 30-20 years ago, now are in a process of revision or serious problems with the definitions have been raised that could require their redefinition (Kaiser, 2009; Štorch, 2017; Marshall, 2018; Geyer and Landing, 2017; Lucas, 2013; Davydov, 2013; Klapper, 2007). An excellent review of the recent status of the Phanerozoic Scale has been done recently by (Lucas, 2018) with the brief description of the most of the problems associated with definition and redefinition of the existing GSSP's.

The newly proposed definitions usually utilize different biotic Primary Markers (PM), that propose different GSSP's and therefore a different geochronologic position of the boundary. It is generally expected that once additional studies on the new GSSP's are performed these new definitions will be permanent.

Seventy-one GSSP's, are already defined (including those that are not yet formally completed) among the 102 Stages in the Phanerozoic, according to the latest data from the Stratigraphic Commission of the International Union of Geological Sciences (IUGS) site (http://www.stratigraphy.org/ICSchart/ChronostratChart2018-08.pdf). The majority of these GSSP's are defined with a biotic event as the Primary Marker (Salvador, 2013). Most of these markers are pelagic or benthic marine fossils, that in theory, when integrated with other biotic and non-biotic data, provide for the global correlation of the entire spectrum of sedimentary successions. These correlations can be difficult when attempting to correlate from deep marine strata to those of marginal marine environments, or even more so, to continental facies. Furthermore, most of the biotic PM's come from stratigraphic successions deposited within the tropical-subtropical belts and defining biota do not occur in successions formed in temperate and polar zones (Gradstein et al., 2012). The marine pelagic facies that many biotic PM's are defined from, constitute at best only about 15% of global strata (Ronov, 1993). In addition, many pelagic facies occur in middle and high latitudes where biotic PM's have never been defined, and thus, the PM's from tropical and subtropical pelagic sediments have been defined from far less than 15% of the existing sediments on Earth.

Because of the difficulty of correlating marine and nonmarine faunal and flora and because of the less extensive record, the continental biota has never utilized as a biotic PM. These markers are not established in continental sequences. In addition, even slight metamorphism can make the biostratigraphy for such units useless, because it alters and destroys the original fossil material. Thus, the biotic PM's are of limited distribution and in a practical sense, leave most of global sedimentary successions without the means for direct correlation. The integration of the biotic PM's with other biostratigraphic and non-biotic events recorded by a wide variety of physical methods (geochemistry, geophysics) helps to resolve the correlation issue, but it is an incomplete solution. Importantly, some correlation tools, such as magnetostratigraphy, astronomic calibration, chemostratigraphy, and magnetic susceptibility are constantly being improved and provide additional increasingly important support in global correlation. But, all of these additional biotic and non-biotic correlation tools possess their own uncertainties and often the final correlations are based on combined tools and events are unsatisfactory for the precision required by many important geoscience research issues.

Another complicated and practically unsolvable issue is the problem of subjectivism and stability of the taxonomy of the taxa that are utilized to determine the chronostratigraphy. Any biological object, including the taxa that are used to determine the chronostratigraphic units, is a part of very complex biological systems. The origination of each taxon in space and time depends on a great number of factors that are difficult if not impossible to know, even in modern biology (Wolf et al., 2018; Zinovyev, 2015; Mazzocchi, 2008; Novikoff, 1945) and far less possible in paleobiology (Fig. 2). This complexity is the reason why the taxonomy is not formalized in modern biology and alternative taxonomic systems and classifications are still widely accepted and protected by the International Code of Zoological Nomenclature (http://www.iczn.org/code) and by the International Code of Nomenclature for algae, fungi, and plants (https://www.iapt-taxon.org). Furthermore, in paleobiology the taxonomy largely depends on the personalities, background and prejudices of the individual paleontologist. It is not unusual that when the generations of paleontologist's change, taxonomic paradigms, as a rule, also change. The taxonomic interpretations and changes, in general, cannot be controlled by non-interpretive factors and therefore, once the biochronology is utilized to determine the GSSP, we always will have a definition problem related to the complexity and interpretive character of the biological systems (species, subspecies, genera etc.). All this could be reconciled in biostratigraphy itself, since the taxonomy generally has a relatively small effect on the accuracy limits of biochronology (≈ 1 million years, sometimes better). However, such changes may affect the definition of a species and consequently may affect the biotic PM's that were originally used to fix the boundaries. Reinterpretation of the taxonomy of biotic PM's will directly affect the definition and the precision of the boundary itself. This is precisely what is happening now for different parts of the Phanerozoic time scale, where, the revision of previously established GSSP's is ongoing (Lucas, 2018; Lucas et al., 2019; Marshall, 2018; Geyer and Landing, 2017; Štorch, 2017; Davydov, 2013; Lucas, 2013; Kaiser, 2009; Klapper, 2007).

The constraints on the theoretical first appearance datum (FAD) and last appearance datum (LAD) of a given species presumed by the Signor–Lipps and Sppil–Rongis concepts (Dornburg et al., 2011; Singor and Lipps, 1982), suggest that in most cases we are dealing with the First Occurrence Datum (FOD) instead of FAD's of the Primary Marker, which further underscores the problems with the biotic markers being assumed to provide the theoretical base for GSSP's. This problem was clearly delineated recently in the entire Phanerozoic (Lucas, 2018). Thus, the boundaries established at the level of the FOD of a biotic PM, by definition, have and always will place significant limitations on the accuracy of correlation and therefore, on the stability in the IGTS (Fig. 3).

It is proposed in this paper to utilize the volcanic ash bed as a lithological horizon that is dated with CA-IDTIMS or similar high-precision radiometric dates as a Primary Marker within suitable stratotype sections. This approach provides a stability of the GSSP definition and attains the resolution of correlation that is an order of magnitude more precise and robust than most previous definitions and that will never require redefinition of the volcanic ash lithological horizon, and therefore will provide for the real stability of the IGTS (Fig. 4).

2. The Nature of the Chronostratigraphic Units and Their Boundaries

From the beginning (Murchison, 1841; Renevier, 1873-1874; Lyell, 1855; Renevier, 1896; d'Orbigny, 1842-1849), and still today, the International Time Scale comprises a hierarchical succession of units in which the lower boundary of the younger unit defines the upper boundary of the subjacent unit. This also means that the lower boundary of the lowest subunit (e.g., substage/subage) within a larger unit (e.g., stage/age) defines the base of the larger unit. (Fig. 1). At the same time the dual nature of the chronostratigraphic classification has been recognized. As with any complex object, the time scale is dialectic (dual). That is, it reflects the objective evolution of the Earth and all associated processes (physical, chemical, sedimentologic, biologic, climatic, cosmic, gravitational etc.) that are preserved in the rock record. At the same time, it is interpretive (subjective) by nature as we are forced to interpret and classify the rock record in a way that best mirrors our understanding of these processes at the local, regional, sub-global and global scales (Hedberg, 1976). Thus, the "…Chronostratigraphic boundaries are conventional boundaries" (Remane et al., 1996, p. 78; Hedberg, 1976). This is obviously evolving from the fact that the GSSP and its position potentially could be revised. The historical priority principle for boundary definition is the major factor that facilitates the stability of the time scale.

The hierarchal classification for stratigraphic units has evolved over time in the International stratigraphic guide and sometimes in the different stratigraphic codes of many countries. The temporal interaction of physical, chemical, sedimentologic, biotic, climatic, cosmic, and gravitational factors in solid Earth, are expressed in the geological record as the diverse stratigraphic units of different rank. The correlation of the myriads of these units requires their classification into a hierarchical system, which is accomplished in both by the International stratigraphic guide and in the stratigraphic codes of different countries. The development of this system in general has proceeded from the definitions of the highest hierarchical chronostratigraphic units (Eonothem by the end of the 18th century) towards smaller subdivisions within the system. By the mid-19th century, all the major geological Erathems, Systems and many Series were already established and quickly utilized in the practice of geology throughout the world (Renevier, 1896; Lyell, 1855; Hedberg, 1976; Murchison et al., 1845; d'Orbigny, 1842-1849). All this suggests that the processes that determine the formation of chronostratigraphic units from the System and hierarchically above, reflect the large scale directional processes inherent in the evolution of Earth. The higher units in the hierarchy formed as an expression of global factors, whereas Series and Stages and units lower in the hierarchy are controlled by a combination of global, sub-global, regional and local factors. Hence, the terminology and general ages of the higher hierarchal units (Erathem, System) has been long recognized, but it has taken more than a hundred years to define the divisions that occupy lower positions in the chronostratigraphic hierarchical system (series, stage and rarely, the substage), and this process continues today.

The biotic events have been widely utilized to identify geologic units since the first geologic map was published (Smith, 1815), and especially after the recognition of the utility and importance of the fossils in the designation the superposition and correlation of the strata (Murchison, 1841; Smith, 1816-1819; d'Orbigny, 1842-1849). Biochronology was considered as the only basis for the International chronostratigraphic classification "La seule base logique de classification stratigraphique internationale me paraît donc être la base paléontologique" (Renevier, 1896, p.554) (Fig. 1) and this approach is still in effect until today (Salvador, 2013). It should be noted that there is not a single subdivision of the chronostratigraphic scale of any rank, of which its boundaries have not undergone significant changes since its original definition. This is because the processes that create sedimentary and biologic systems are continuous but variable temporally and spatially at all scales. Interregional, regional and local processes (tectonics, climate, volcanism, etc.), which are superimposed on the global processes and events, are the primary controls on the geological records at regional and (or) local levels. Consequently, in different basins, regions and continents, numerous and alternative subdivisions have appeared, whose boundaries are diachronous with respect to each other (Figs. 3,5). It is therefore a complex problem to pick one biotic event (boundary) in such sedimentary systems that is truly globally synchronous (Lucas, 2018). This is the fundamental problem of selecting the base of a chronostratigraphic unit (Fig. 5).

After relatively short period of the definitions of the bases of a chronostratigraphic units at the "natural" events (unconformities, sharp facies change etc.) the stratigraphic classification generally developed towards the GSSP chronostratigraphy (Lucas, 2018). The core of this approach required the establishment of the chronostratigraphic boundaries within the continuous sedimentary record (Hedberg, 1976). There are two solutions to the problem of the continuous processes and separation and definition of the units within the chronostratigraphic scale. It has long been assumed that the unit boundary encompasses a certain transitional zone, which includes all possible options for the diachronicity of a unit at the global scale. That was the approach in the prototypes of the stratigraphic code of Russia (Librovich and Ovechkin, 1963), where the stratotype just fixes the name and generally identified the superposition of the chronostratigraphic unit within the time scale, but not its boundaries and therefore the boundaries in this case are loosely defined. It was clearly formulated in the following statement: "In general, the temporal length of the chronostratigraphic unit has a greater value itself than the sharpness and clarity of its boundaries" (Meyen, 1974), p. 22). A similar philosophy was shared by many other paleontologists (Kleinpell, 1979; Schindewolf, 1970). The development of the IGTS, however, went in the direction of lucidity and precision of sharp unit boundary definitions (Hedberg, 1976).

The present IGTS classification reflects the regions in which portions of the classification were developed (Lyell, 1855; Renevier, 1896; Leonov, 1973; Murchison et al., 1845; d'Orbigny, 1842-1849). Most of the systems, series and stages were traditionally recognized in Europe and thus the existing IGTS is Eurocentric. The set of names in the current time scale determined by historical priority greatly influences the choices and Timescale of a certain System or Series, which are usually derived from a regional scale, in which the subdivisions are geohistorical in nature. At the same time, some of the systems, i.e. Ordovician, are divided now into a set of the "Stages" that are bounded by the biohorizons useful for precise global correlation. It is difficult to call these "Stages" geohistorical, and some of the researchers believe that "…the recognition of standard global stages is pointless, simply because no stage can be correlated globally" (Lucas, 2018, p. 13). It is true that some of the International Stages are difficult to correlate with their defined boundaries because in different basins, regions and continents, numerous and alternative subdivisions have appeared, whose boundaries are diachronous with respect to each other. Besides, the tools that we have for the global correlation possess some limitations (see text below). But the regional Scale chosen as the International the geohistorical nature of the chronostratigraphic scale. This scale than when compared with other regional scales shows the fundamental values of the regional scale over the international one (Lucas, 2018; Leonov, 1973). The geologic scale that is mechanistically divided by the biohorizons useful for precise global correlation is losing its geohistorical essence and may not be considered as prioritized in the direction of the development of chronostratigraphy.

As always, the political and economic reasons determined the geological timescale. For example, the Carboniferous System would not exist at all if the 19th century understanding of the geology, stratigraphy and biostratigraphy in US or in China would have been more advanced. We would use then, for example, the Pennsylvanian or Hutianian system and Kinderhookian or Tangbagoan instead of the Tournaisian stage as part of the IGTS (Fig. 5). At the same time the set of regional (or at certain point the national) stages always will be an important chronostratigraphic tool in each region or country because they better represent the regional geology in region and have historical priorities associated with these regional studies. The challenge then is to correlate these regional time units to the IGTS, which is frequently not an easy task.

Until the late 1970's, most of the system, series, and stage boundaries, with very few exceptions, were originally established at sharp changes in the geologic record, in particular at unconformities, i.e., the chronostratigraphic units were unconformity-bounded units (Lyell, 1855; Renevier, 1896; Leonov, 1973; Murchison et al., 1845; d'Orbigny, 1842-1849). Therefore, gaps and overlaps were inevitably created between successive chronostratigraphic units, because the original type sections or rock bodies as a whole were necessarily located in different geographic areas (Walsh et al., 2004). To eliminate these gaps and overlaps, chronostratigraphic units became viewed as contiguous spans of time separate from any section, and conceptually defined by paleobiological events or zones (Schindewolf, 1970; Schenk and Muller, 1941; Ager, 1973). The differences between geologic-time units and time-rock units were clearly understood for the first time (Hedberg, 1976). Therefore, the chronostratigraphic scale has been considered a biochronologic scale and inherently interpretive in nature (Ruzhenzev, 1977; Ager, 1973; Schindewolf, 1970; Renevier, 1896), even recently (Chernykh, 2015). To provide better precision and improve the process of global correlation, the International Stratigraphic Guide now suggests that chronostratigraphic boundaries be defined within the rock record and the position of the boundary within the succession be arbitrarily designated by the biotic PM's, typically the first appearance of a selected species (Salvador, 2013; Hedberg, 1976; Remane et al., 1996).

3. Principles of the GSSP Definition

The International Geologic Time Scale (IGTS) provides the common language in geology and is a universal tool for evaluation of geological (and paleobiological) rates and processes. The GSSP concept was developed in the early 1960's, i.e. more than 60 years ago. The core of the GSSP concept (McLaren, 1977; Hedberg, 1976) was the biochronological evolutionary approach that with regards to the GSSP principles provided at that time the most precise method to define GSSP boundaries and a reasonably reliable mechanism for global correlation and a relatively stable IGTS. Chronostratigraphic boundaries must be defined within a stratigraphic succession and the position of the boundary within this succession is arbitrarily designated by the biotic PM's, typically the first appearance of a selected species (Lucas, 2018; Salvador, 2013; Remane et al., 1996; Hedberg, 1976).

Since William Smith (1815), biostratigraphy has become a major correlation tool in geology because of the universal directional nature of biota evolution, that is known as the law of irreversibility (Dollo, 1893). Biostratigraphy was quickly developed and reached the peak of influence in geology around the mid-late 20th century. This period of time is often referred to as the "golden era of paleontology", because of the intensive and worldwide biostratigraphic and paleontological studies that were undertaken (Salvador, 2013; Kauffman and Hazel, 1977; Hedberg, 1976). At that time biostratigraphy was the most powerful and most reliable tool for the correlation not only on a regional, but on a global scale, particularly with shallow marine and pelagic fossil groups (graptolites, ammonoids, conodonts, foraminifera etc.). The average duration of most of the biostratigraphic zones is around 1-2 Myrs and no other method at the time could compete as a comparably reliable and precise correlation tool (Nikitin and Zhamoida, 1984; Kauffman and Hazel, 1977). Some of the zones in Mesozoic and particularly in the Cenozoic are estimated to be even shorter, ~ 0.2-0.3 Myrs (Neumann and Lippolt, 1981). The advantage of using biochronology for GSSP definitions was encompassed in the fundamental approach to the IGTS (McLaren, 1977) for the following reasons:

1. The directional character of evolution makes the biostratigraphic method universal since the first appearance of recognizable fossils.
2. The traditional biostratigraphic method provides relatively high resolution around 1 Ma, sometimes better.
3. Fossils are widely distributed and frequently occur in a variety of sedimentary strata reflecting various paleoenvironments of deposition.
4. Biostratigraphic analysis is relatively quick and economical.

However, several issues suggest that the biostratigraphic approach is no longer the best choice. First, and perhaps most important, biostratigraphic zones no longer provide the highest chronostratigraphic resolution. Recent geochemical (stable and radioactive isotopes), paleo-magnetostratigraphy, cyclostratigraphic/astronomic tuning, and magnetic susceptibility methods often provide a higher resolution (Fig 6). Also, global correlation is hampered because index fossils are often restricted to certain sedimentary facies, certain provinces and to marine environments within the tropics-subtropics. The scientific paleontological community is decreasing in size, and this will affect both the time it takes to conduct biostratigraphic analyses and its economic value. It commonly has taken at least 20 years to establish a GSSP, sometimes nearly 30 years when the FOD of certain fossil is utilized as the PM (Wang, 2018; Paproth, 1990). Current practice shows that the taxonomy of index species and/or phylogenetic lineages involving biotic PM's are frequently modified (Lucas, 2018; Ueno, K. and Task group, 2016; Klapper, 2007; Nemyrovska, 1999) and together with political reasons and changes in the stratigraphic ranges of the PM's of the GSSP's (Lucas, 2018), directly affect the stability of the definitions. The approach to designate a GSSP within the faunal chronoclines often causes a significant change of the traditional boundaries that had served chronostratigraphy for decades, and this causes confusion and controversy for the general geologic community (Corradini et al., 2016; Ueno, K. and Task group, 2016; Melchin et al., 2012; Webby, 1998) and requires to develop conversion tools similar or better than GeoWhen (http://www.stratigraphy.org/bak/geowhen/geolist.html). Such a tools, however, gives just general conversion between the certain stages, but not the precise position of the GGSP's among legacy units.

The main problem with utilizing biotic events (i.e., first appearance of a species, i.e. FAD) as a PM is a potential diachronism of any taxon (Singor and Lipps, 1982), that often turns out to be a local first occurrence of the species at a GSSP (FOD) that is causing the GSSP replacement (Corradini and Kaiser, 2009; Lucas, 2018; Klapper, 2007; Brosse et al., 2016; Baresel et al., 2016). The interpretive character of the taxonomy makes the situation even worse. Modern biology retains alternative taxonomic classifications because of the complex nature of biological processes. Considering that paleobiology cannot utilize the methods that help with biological taxonomy (molecular analyses, ethology, social behavior), paleontological taxonomy will always be interpretive and subject to modification and hence in principle will not provide the needed stability of the time scale that is required by the recent scientific issues being addressed in the geosciences.

In light of the existing problems with the definition and correlation of biotic PM's, we have to ask the question: what would be the ideal Primary Marker for GSSP definitions that could meet to all of the requirements and challenges of the modern geology?

1. This PM should not be tied to any one facies, i.e. it could provide correlation of marine, continental, lagoonal sediments and in all transitions among those facies without the need to switch to the other markers and events and to retain the initial precision documented by the PM.
2. Its distribution is not controlled by the Earth's paleoclimate, in other words, could equally be correlated in stratigraphic successions originally deposited in the tropics, subtropics, mid-latitudes and in the polar areas.
3. This event that marks the PM must encompass a very short period of time, to provide the precise position of the boundary associated with this PM.
4. The PM could be correlated in metamorphic and other igneous rocks.
5. The PM should be based on a clear and reliable parameter, which are not subject to multiple interpretations.
6. The PM must provide the precision for correlation that equals or exceeds the precision of the existing PM's (biotic events).
7. The PM will be permanent. This means we might return to the principle of historical priority in chronostratigraphy once again.

4. Volcanic Ash Beds as a Primary Markers of the Chronostratigraphic Boundaries

It is here argued that volcanic ash beds would be the best Primary Marker in geologic chronostratigraphy. Radioisotopic dating, together with biotic evolution, tracks the direction of time (McLaren, 1978). The biotic PM's have many limitations as discussed above. Nevertheless, it has been preferred over the radioisotopic method in part because it reflects the tradition that dates back to the 19th century. Also, until recently, perhaps the last ten or fifteen years, the radioisotopic method was not competitive with biostratigraphy in terms of practicability, stability of the results and the temporal precision. Following the discovery of radioactive decay and the development of mass-spectrometry in the early 20th century, the precision and reliability of the radioisotopic method of calibration of the rocks had been far from reliable (Harland et al., 1982). When the secondary ionization (SIMS or SHRIMP) mass-spectrometry was first developed, radioisotopic dating could somewhat compete with biostratigraphic data, i.e. with precision around 1-2% (Schmitz and Kuiper, 2013). However, the results were not consistent, with different laboratories often producing different dates (Gradstein, 2012). The radioisotopic dating was revolutionized by the development of new zircon treatment methods (Mattinson, 2005) and the EARTHTIME initiative to facilitate inter-lab intercalibration together with the development of common standards (Bowring et al., 2004). Now, the resolution of zircon U-Pb ages (< 0.1-0.01%) (Schmitz and Kuiper, 2013) exceeds the resolution of biostratigraphy by an order of magnitude or more. Additional advantages to using the U-Pb ages of volcanic ash beds to designate the chronostratigraphic boundaries include the following (Schmitz and Kuiper, 2013; Schmitz, 2012):

1. The U-Pb system is one of the most dependable of the geochronologic systems in geochronology.
2. The result of radioisotopic analyses rely on a simple and non-interpretive radioisotopic decay constant.
3. A single volcanic ash bed usually formed within few days or at most a few weeks and it is thus, geologically, an instantaneous layer and event. None of the existing biochronologically defined GSSP's can provide the precision of the boundary position established at the base of a volcanic ash bed.
4. Once the boundary at the base of a volcanic bed and its U-Pb age are established, there would be no scientific reason to initiate the revision of such a boundary. Thus, this satisfies the principle for the stability of GSSP's and the chronostratigraphic scale that biotic markers frequently do not provide (Hedberg, 1976).
5. The use of ash-beds to define GSSP's provides a universal and uncomplicated approach to global correlation. Utilizing other ash beds and/or a wide variety of other calibrated markers (e.g., biostratigraphic, chemostratigraphic, cyclostratigraphic, etc.), ash-bed GSSP's can be correlated in any sedimentary facies (marine, lagoon and continental), regardless of global climatic zones, oceanographic,

geochemical, and most other geological complications. Even metamorphosed strata can be correlated as this heating does not affect U-Pb dating up to about 900° C (Watson et al., 2006; Bindeman and Melnik, 2016).

6. Volcanic ash PM's may be selected that are close to traditional, historically prioritized boundaries to make the new GSSP consistent with legacy data.
7. The recent chronostratigraphic scale is developed with the inconsistent criteria and different types of Primary Markers, i.e. FAD's, LAD's, magnetic reversals, geochemical spikes and climatic events were proposed and accepted as the GSSP (Lucas, 2018; Miller and Wright, 2017; Smith et al., 2015). All of these PM's are of processes that are repetitive in nature, so that they are inherently not able to be uniquely identified without directional events (biotic and/or radioisotopic) (Lucas, 2018). Volcanic ash PM approach could make the GSSP consistent in terms of their definition criteria.
8. It is much easier, simpler and quicker to designate and ratify a GSSP with a volcanic ash bed as interpretive parameters, such as biological taxonomy, are not involved. This does require a search for sections with ash beds close to the traditional boundaries that also contain other geologic events useful for global correlation (e.g., biological, geochemical, paleomagnetic, cyclostratigraphic, etc.).
9. Although radioisotopic ages also are interpretive in the sense that they rely on standards and methods (e.g., Schmitz and Kuper, 2013; Schoene et al., 2013), the accuracy and precision of the ages will only improve as technology is further developed. Thus, the correlation power of chronostratigraphic definitions based on volcanic ash PM's will only become better and more precise. More importantly, the PM definition (the ash bed) will never change. Thus, the time scale will be stable and the "headache" of non-paleontological/stratigraphic communities having to keep track of every new and seemingly unstoppable revision in the International Geologic Time Scale will disappear.
10. There are some complexities with the zircon mineral itself (older cores within the crystals, unrecognized micro-cracks and micro-inclusions, significant residence time in the magma chamber), but there are several approaches to eliminate or reduce these problems (Rivera et al., 2016; Rivera et al., 2014; Schoene, 2014) and they are not as complex as the problems associated with the biological nature of fossils. Pb loss and Pb inheritance that is sometimes associated with the U-Pb radioisotopic analyses is not an issue anymore, as the new methods of chemical abrasion effectively remove Pb-loss domains from zircon crystals (Mattinson, 2005; Schmitz and Kuiper, 2013).
11. The ratification by the International Commission on Stratigraphy of a GSSP at the base of a volcanic bed could be accomplished in a short time compared to the 20-30 years that it has taken for some boundary definitions (e.g., Ueno, K. and Task group, 2016; Villa, 1991). For example, several potential GSSP's for the Devonian-Carboniferous boundary, and the bases of the Moscovian, Kasimovian, Gzhelian and Artinskian Stages that can be documented and accepted within a short time as are proposed in this paper (see later discussion).

I'm not proposing to redefine the existing GSSP's, but I am confident that the ash-bed Primary Marker approach could be utilized for most of the GSSP's currently under discussion as well as those that may require redefinition in the future due to problems with the occurrences of the biotic PM's (First appearance and first occurrence issue) or for other reasons. Nothing needs to be changed in the procedure for GSSP establishment, except, the utilization of a volcanic ash bed as the Primary Marker.

The natural boundaries (Walliser, 1984) must be a prioritized boundary in this respect. The term "natural boundary" originally proposed "… for a stratigraphical boundary which is characterized by a globally recognizable, extraordinary change in the composition of the biota within one or several ecological realms" (Walliser, 1984, p.241). With our recent knowledge and deterministic approach it would be better to define a natural boundary as the narrow stratigraphic interval in the stratigraphic record determined and associated with sudden and global events expressed in the atmosphere, hydrosphere, biosphere and solid sphere of the Earth as a sharp change of parameters of the state of these spheres. The "natural boundary" is not a boundary in a strict sense, but rather a short time transition during which sharp changes occur. Therefore, the selection of the GSSP close to the natural boundary is conditional, as is any other GSSP, and would be, by the occurrence of a convenient volcanic ash bed within the transition of the "natural boundary".

5. Volcanic Ash CA-IDTIMS and Biotic PM Uncertainty and Abundance in Rock Record

Most of the paleontologists with whom the proposal to shift GSSP's definition from biotic PM into volcanic ash PM was discussed, arguee that volcanic ash beds are very rare and that the practicability of biostratigraphy incomparably exceeds that of radioisotopic dating. The value of biostratigraphy has been proven by the over 200 years of geological practice and it is not refuted here. The problems discussed here appears as the needs of modern geology requires a level of temporal resolution at the global scale that is impossible to resolve with biostratigraphy. We need directly and precisely correlated marine, evaporitic and continental sequences, deep-water and shallow water sediments, carbonates, siliciclastics and volcaniclastic, low- mid- and high-latitudinal sediments and biotic events. Biostratigraphy in this complex correlation does not work as well as we wish. The radioisotopic dates resolve many of these problems right away. In fact, just one or a couple of radioisotopic ages is resolving the problem of precise correlation of the Permian-Triassic transition and the boundary of the marine succession in S. China and the continental successions in the Karoo Basin and the East-European Platform (Rubidge et al., 2013; Gastaldo et al., 2018; Gastaldo et al., 2020; Davydov et al., 2020 in press). This problem remained unresolved for many decades.

The volcanic ashes are rare, but not as rare as many people believe. They are much more frequent and widely distributed than is thought in the geologic community and occur in any facies, marine, transitional or continental and regardless of climatic belt. With radioisotopic ages we are obtaining precise and countable rates in sedimentary and paleobiologic processes that are lacking in biostratigraphy. In fact, the general magnitude of diachroneity of many biotic, sedimentary and climatic events was clearly recognized because of radioisotopic ages.

When the new CA-IDTIMS method was developed (Mattinson, 2005), only a few labs could do the analyses. Now, many new labs are doing this work, and their numbers are going to increase, no doubt. The radioisotopic dating for the last couple decades increased the accuracy and precision an order of two magnitudes (fig. 7) (Schmitz and Kuiper, 2013) and it will be improved further. The dating already exceeds the biostratigraphic method on the order of at least one magnitude or more. In terms of correlation precision of the chosen PM's, the biotic one on average has a precision of 0.5-1.0 Ma, whereas the radioisotopic PM may be correlated with the precision of 0.1-0.01%, i.e., from ± 0.14 Ma in the Cryogenian (Macdonald et al., 2010) ±0.047 Ma in the Cretaceous (Eberth and Kamo, 2019) that would never be reached by paleobiology.

As was discussed above, when the biotic PM is found below the GSSP, it necessitates boundary redefinition (Remane et al., 1996; Corradini et al., 2016) and the position of the boundary may be chosen higher or lower than the original GSSP, but definitely at a different position within the chronostratigraphic scale (Corradini et al., 2016). The advantage of the volcanic ash bed PM is that even if and when the radioisotopic age in the PM will be improved and therefore changed, it would not effect the GSSP definition at the volcanic ash bed, but rather improve the correlation precision, which already exceeds all other conceivable limits. Therefore, the GSSP with volcanic ash PM's will be stable.

6. Proposed Criteria for the GSSP Designation with an Ash-Bed as the Primary Marker:

1. The boundary must be chosen as close as possible to historically traditional (original and/or natural) boundaries.
2. The boundary should occur within a fossiliferous succession to facilitate the correlation of the defined boundary to biostratigraphy.
3. There must be an integration of the PM and GSSP with as many proxies as possible (biostratigraphy, chemostratigraphy, magnetostratigraphy, magnetic susceptibility, cyclostratigraphy).
4. It is here argued that multiple auxiliary sections should be established that contain ash beds of the similar age (within the uncertainty), that have integrated additional proxy data from various paleoecologic or paleogeographic settings (e.g., marine vs continental, deep marine vs shallow marine, etc.).
5. Develop regional time scales that are calibrated to the International time scale via proxy data. These could be termed Regional Section Stratotype and Point (RSSP). These RSSP's and their associated time scales will facilitate the understanding of regional events within a global context.

7. Geohistrical *vs Numerical Scales

There is a principal difference between the Phanerozoic International chronostratigraphic scale and Precambrian chronometric scale. The Phanerozoic chronostratigraphic scale is geohistorical in nature. The chronostratigraphic subdivisions of any rank and any scale (regional to global) are uneven in duration and objective in the sense that they represent the expression of the complex combination of the irregular cosmic, planetary and Earth's tectonic, climatic and volcanic processes that create atmospheric, hydrospheric, sedimentary and biologic systems in our planet. The workflow in Phanerozoic scale origin is going from the real rock record into the relative time interpretation (rock-time model of Harland, 1978; Hedberg, 1976), utilizing the integrated set of methods and tools that provide a calibration and correlation of the scale's subdivision with biotic events and zonations, radioisotopic ages, sedimentation rates, cyclostratigraphy, magnetostratigraphy and geochemical proxies. Although the boundaries (and GSSP's) may be established arbitrarily, their chosen position placed within the transition from one chronostratigraphic unit to another is at a geologic event (biologic, magnetic, climatic PM's). Most of the systems, series and stages were traditionally recognized in Europe, and their boundaries in most cases are associated with the European regional geological history, the boundaries of which are adjusted with regard to their global correlatability (McCann, 2008; Smith et al., 2015).

A completely different approach has been undertaken with the official Precambrian Scale that at first had been divided into chronometric subdivisions that delimit principal and broad time intervals in the sense of the duration of cycles of sedimentation, orogeny, and magmatism. The boundaries of the subdivision are defined chronometrically in years without specific reference to any bodies of rock (Plumb, 1991).

The rock units are assigned to the specific time scale only with regards to the interpretation of the unit's superposition, stratigraphic correlation, and isotopic age determination. The principal difference of the Precambrian scale from the Phanerozoic chronostratigraphic scale is that the chronometric boundaries of the former are not tied to the actualistic rock record and thus do not represent chronostratigraphic divisions in the sense of the Phanerozoic scale (van Kranendonk et al., 2012). Basically, the Precambrian and Phanerozoic scales are based on two opposite models: the Precambrian Scale was developed as the time-rock model (Plumb, 1991), whereas the Phanerozoic Scale – as the rock-time model (Harland, 1978; Hedberg, 1976). It is clear that the way the Precambrian Scale was established was determined by the lack of reliable correlation of the events within these rocks and still insufficient understanding of the framework of the rock record at a global scale.

It was recognized, however, in the last couple of decades that the principles of the Phanerozoic Scale must be applied in upper Precambrian Scale development, i.e. the scale could be based on the rock record to define a "natural" time scale (rock-time model of Harland, 1978), in which major divisions are defined in the observable stratigraphic record that were correlated globally (Bleeker, 2004). With the advanced modern isotopic geochronology and sufficient global-wide correlation, the two systems in the Precambrian, i.e., Cryogenian (the onset of the first global glaciation) and Ediacaran (megascopic, largely prokaryotic marine animals) were defined as a rock-time model unit. The biostratigraphic and lithologic (carbonate cap) events also play an important role in the systems' recognition. Now, there is also an attempt to defined as a natural geohistorical units the rest of the Precambrian subdivisions, besides Cryogenian and Ediacaran, (van Kranendonk et al., 2012). The newly obtained precise U-Pb zircon age dates revealed that "...many of the current divisions are either misplaced in terms of global geodynamic events, impractical in terms of global correlation, or meaningless in terms of significant lithostratigraphic, biogeological, and biogeochemical changes that have since been recognized and critically assessed to a significant degree across the globe" (van Kranendonk et al., 2012, p. 310). Once a precise correlation of the main geological global-wide events accomplished, they will also be defined with the rock-time model, i.e. with geohistorical, rather than chronometric boundaries.

The approach to define the GSSP at a volcanic ash bed proposed here is also tied to a rock-time model, because it is proposed to be placed in the specific section and close to the historically prioritized traditional boundary of the existing chronostratigraphic unit. Thus, it is geohistorical (chronostratigraphic) and not chronometric (numeric) in nature. The volcanic ash bed in that case plays the same function as the other PMs, i.e., provides the worldwide correlation. The position of the ash lithologic horizon that serves as the PM of a supposed GSSP must be placed as close as possible to the existing traditional and/or natural boundary in the existing International chronostratigraphic scale. Thus, nothing is changed in the principles of time scale development.

In summary, the volcanic ash bed approach is not arguing to abandon the chronostratigraphic scale based on biotic events and not simply to use numbers to define the new GSSP's in the IGTS. It is suggested to exploit a lithologic volcanic ash bed as a GSSP within the geohistorical content to correlate this GSSP as precisely and as widely as possible. The biotic as well as other events utilized in chronostratigraphy are still an important integrative part of the chronostratigraphic scale. Rather, the approach is resolving the tasks that cannot be reached with the traditional biotic PM's and even with other newly proposed type of PM's (magnetic chrons, isotopic spikes, climatic events). The latter express a worldwide signal and may provide a very high resolution, but they are repetitive in nature and thus require additional directional in time events (biotic or radioisotopic) to tie these events within the chronostratigraphic succession.

As was explained above, the biotic PM's possessed many limitations (climatic, facial, bathymetric etc.) and particularly cannot assure that we are dealing with an isochronous event globally. Besides, the resolution of biotic PM's is on average 1 Ma or less (see text above and Fig. 7), whereas with a volcanic ash bed PM we can trace an isochronous boundary worldwide and establish the superposition of rocks with the resolution > 0.01% (Fig. 7)

We do have numerical calibration of the existing International Geologic Time Scale that is defined with the biotic PM's, that help to correlate the established GSSP's. However, the problem is that the existing PMs, especially the biotic ones, in some cases are not synchronous at the level of resolution required in modern geology (Smith et al., 2015). They sometimes occurs below the horizon in the rock record which was chosen as the boundary GSSP (Lucas, 2018), as predicted by the Signor–Lipps and Sppil–Rongis concepts (Dornburg et al., 2011; Singor and Lipps, 1982). Therefore, most of the GSSP's established with the biotic PMs are already in a process of undergoing re-definition (Lucas, 2018; Aretz and Corradini, 2015; Klapper, 2007) and potentially under the threat of further redefinition. This will never be the case with the volcanic ash bed PM as the obtained high precision age, integrated with the other proxies, may be correlated truly worldwide. It is true, that radioisotopic ages are not permanent—they change with new methods and techniques. However, these methods and techniques are already exceeding the precision of biotic PM's order of magnitude (Fig. 7) and they are going to be improved, not become worse (Schmitz and Kuiper, 2013). Most important, the age improvement of the volcanic ash PM would not require the redefinition of the GSSP as the volcanic ash bed would be the same and therefore the chronostratigraphic boundaries and scales will remain permanent.

8. Permian-Triassic Boundary Definition Problems and Potential Solution with the Volcanic Ash Primary Marker

The Permian-Triassic boundary, which is associated with the one of the most severe extinction events in Earth history, has been established at the base of the bed 27c in Meishan Section D, Changxing County, Zhejiang Province, China (Yin et al., 2001). The boundary was selected at the horizon where the conodont *Hindeodus parvus* was first documented. *Hindeodus parvus* proposed to occur within the chronocline *Hindeodus latidentatus-H. parvus - Isarcicella turgida-I. isarcica* (Yin et al., 2001). *Hindeodus parvus* is widely distributed within the tropics, subtropics and in even in the mid-latitudes which seems to make it a good choice for the P-T PM (Algeo et al., 2012; Twitchett et al., 2001; Yin et al., 2001). However, there are several different interpretations of the conodont evolution within this chronocline (Jiang et al., 2011; Orchard and Krystyn, 1998; Kozur, 1996; Wang Chengyuan, 1996; Ding Meihua et al., 1996) that might affect on the taxonomic definition of *Hindeodus parvus* itself and thus on the FAD/FOD of the species in different section. Also, even within South China the First Occurrence (FO) of *Hindeodus parvus* sometimes occurs before or after the GSSP in Meishan (Brosse et al., 2016; Yuan et al., 2015; Jiang et al., 2007) and the boundary in these sections is identified at different chronostratigraphic level with the other biotic, chemostratigraphic, and magnetostratigraphic markers or radioisotopic age of a volcanic tuff bed (Yuan et al., 2019). Recently, the problems with the chemostratigraphic and radioisotopic calibration in regards of the FAD of *H. parvus* has been documented in different regions (Brosse et al., 2016; Yuan et al., 2015; Jiang et al., 2007.) The intercalibration of the biostratigraphic and chemostratigraphic markers within the Permian-Triassic transition reveals that the negative spike of carbonate and organic carbon stable isotopes and at the PTB occurs at different stratigraphic positions in different sections in the late Permian (Chen et al., 2015; Yuan et al., 2015; Payne et al., 2010; Mu et al., 2009) or in the early Triassic (Zhang et al., 2019; Shen et al., 2013). The review of the best biostratigraphically calibrated sections (Korte and Kozur, 2010), produced a curve with several minimum and maximum spikes within the P-T transition zone. What Korte and Kozur (2010) showed is where the FOD of the conodont species *Hindeodus parvus* occurs and is used to mark the P-T boundary, the negative spike in carbon stable isotopic data appears later or earlier than the P-T boundary. Therefore, either the FAD of *Hindeodus* parvus or the negative C-isotope spike at the PTB transition are not globally synchronous. The former is most likely as the newly proposed unitary association zone at the PTB in S. China in Meishan section extends from bed 27a through the bed 27d and thus, the GSSP occurs within this zone (Brosse et al., 2016). It means that the FAD of *Hindeodus parvus* may occur earlier in sections other than that of the defined GSSP. This is predicted by the Singor-Lipps model and has recently been confirmed by high-precision U-Pb dating (Baresel et al., 2017). The numeric age of the PTB has also changed recently, mostly because of the uncertainty associated with estimates of sedimentation rates (Burgess et al., 2017; Baresel et al., 2017), which may never be estimated correctly.

The establishment of a revised Permian-Triassic boundary at the base of the volcanic ash bed 25 at Meishan section (Yin et al., 2001) would resolve all the above-mentioned problems. First, this boundary is associated with the P-T extinction event in South China as documented at Meishan section (Shen et al., 2019). Second, it is corresponding to the base (i.e. bed 26) of the Unitary Association Zone that has recently been proposed to define the PTB (Brosse et al., 2016), and it also agrees with the data provided in Yuan et al., (2019). If the PTB was defined at ash bed 25 in the Meishan section (that is an instantaneous event), then the interpretation of the synchroneity of other biotic, chemostratigraphic, or geophysical markers would no longer be needed to establish the boundary. Rather, those features could be correlated locally as well as globally to the radioisotopic age of this boundary (251.954± 0.037; Burgess et al., 2017), regardless of the climate, bathymetry, paleogeographic setting or degree of methamorphism or alteration of the sediments. Because this boundary as defined in South China incorporates a rich data set, its correlation potential and precision are excellent, and does not require any additional study, just a decision of the Triassic Subcommission of the International Commission on Stratigraphy.

9. Additional Cases Where the Potential GSSP's Can Be Established with a Volcanic Ash Bed as a Primary Marker

In addition to the PT GSSP at Meshian, several potential GSSP's that could be established with the volcanic ash beds that are close to the traditional and/or historical boundaries are described below.

9.1 Devonian-Carboniferous Boundary

The Working group to designate the Devonian-Carboniferous boundary (DCB) was established in 1976 by the International Commission on Stratigraphy (ICS) and worked for over 15 years before the boundary definition was ratified (Paproth et al., 1991). The detailed research that was carried out on sediments and fossils within the D-C transition zone in Europe, Asia, Africa, Australia, and America resulted in the proposal of the DCB near the "classic" base of the Carboniferous associated with the base of *Gattendorfia* ammonoid Zone in Germany. The boundary is placed at the base of bed 89 in La Serre section, France (Fig. 8), which is coincident, as it was thought, with the FAD of the conodont species *Siphonodefla sulcata* within the evolutionary lineage from *Siphonodella praesuirata* to *Siphonodelia sulcaia* (Paproth et al., 1991). The boundary has been successfully recognized in many sections globally. However, when the GSSP in France was carefully re-studied, the earlier occurrence of *Siphonodefla sulcata*, was discovered 0.5 m below the GSSP (Fig. 8) (Kaiser, 2009). This is another case that supports the validity of Signor-Lipps and Sppil-Rognis effects (Heads, 2012; Dornburg et al., 2011; Singor and Lipps, 1982) and again underscores the problems and limitations associated with biotic PM's.

This issue with the existing DCB was extensively discussed in both subcommissions on Devonian and Carboniferous stratigraphy for over 18 years, which lead to the dissolution of the old Working Group and the establishment of a new DCB Task Group (TG) (Richards and Task Group, 2009). After an additional 10 years of extensive studies of the conodonts and sections, the TG still has not reached a decision even on what criteria will be used to establish the new DCB. Several proposals are still outstanding for the boundary definition. Two proposed biotic PM's are associated with evolutionary events within the conodont lineages and "FAD's" of *Protognathodus kockeli* or *Siphonodella bransoni*. (Corradini et al., 2016) The third proposal suggests placing the DCB close to Hangenberg Black Shale (Aretz, 2014), i.e. at the traditional and ''natural D/C boundary'' (Walliser, 1986), but is unclear how the latter boundary could be correlated globally, especially in shallow-water, high-latitude, and continental facies.

From these proposed biotic PM's, *Protognathodus kockeli* is the most abundant and widely documented species of *Protognathodus* that has wide geographic distribution, but in many regions, it occurs only in Carboniferous strata. *Protognathodus kockeli* originates from *P. collinsoni*, however the older part of the range of *Pr. kockeli* is often not found in several sections around the world because of a sedimentation break (Corradini et al., 2016; Corradini et al., 2011).

Siphonodella bransoni, according recent studies (Corradini et al., 2016), is a well-known, abundant and widely distributed species that could be a good biotic PM for the DCB boundary definition. But, the "FAD" of the species occurs well above the traditional DCB associated with the FAD of the ammonoid *Gattendorfia* and therefore this and other historically lowermost Carboniferous taxa would then become Devonian (Corradini et al., 2016).

The Hangenberg Black Shale is recognized in many deep-water marine sections around the world, but as a sedimentary facies, it would never be recognized in marine shallow-water successions and of course, not in lagoonal and terrestrial successions. Furthermore, the Hangenberg Black Shale cannot be a Primary Marker as black shales are cyclic (repeated) in nature and therefore the event could only be recognized with the directional markers (biostratigraphic or radioisotopic).

It is here proposed to establish the DCB GSSP at the volcanic ash bed that is very close to the Hangenberg Black Shale. This is the ASKQ 1 ash bed in the Kowala section, Poland (Myrow et al., 2014) (Fig. 8). The section has excellent biostratigraphic, chemostratigraphic and cyclostratigraphic data (Broda et al., 2018; Malec, 2014; Vleeschouwer et al., 2013; Dzik, 1997; Wrzołek, 1992; Racki, 1992). The volcanic ash beds ASKQ 1 occurs 26 cm below the Hangenberg Black Shale (Fig. 8) and can be selected as the Primary Marker for the Devonian-Carboniferous Boundary GSSP. Its age is already documented as 358.97 ± 0.11 (Myrow et al., 2014). The volcanic ash PM occurs close to the lower-middle *Siphonodella praesulcata* zone (Malec, 2014) and is associated with the profound turnover in conodont and ammonoid faunas (Fig. 8). This boundary is the ideal "natural" boundary of Walliser (1984) that is associated with one of the major global climatic, oceanic water perturbations (anoxia) and extinction events (Raup and Sepkoski, 1982). Utilizing the sedimentation rates provided in Myrow *et al.* (2014) the age of the FOD of *Siphonodella sulcata* in Kowala section is approximately 358.78 ± 0.2 Ma. This is consistent, within the uncertainty, with the ages 358.88 Ma (FAD of *Siphonodella sulcata*) proposed in the 2012 Geologic Time Scale for the DCB (Davydov et al., 2012; Schmitz, 2012). This confirms the advantage of the integration of biostratigraphic and radioisotopic data utilizing quantitative tools (Davydov et al., 2012; Schmitz & Davydov, 2012).

9.2 Moscovian-Kasimovian Boundary GSSP

The Working Group (WG) to establish the Moscovian-Kasimovian boundary (MKB) was proposed at the Subcommission on Carboniferous Stratigraphy meeting in Provo (September, 1989), to establish: "A boundary at the base of the *Protriticites* Zone, (basal Kasimovian; basal Missourian; mid-Cantabrian)", led by Elisa Villa, Spain (Villa, 1991). The WG considered several taxa among two groups (fusulinids and conodonts) and many marine sections around the world. Although the base of the fusulinid *Protriticites* zone is associated with the traditional Moscovian-Kasimovian boundary in the Moscow Basin and correlated globally within the tropics-subtropics (Davydov, 2007), the conodonts *Idiognathodus sagittalis*, *Swadelina nodocarinata* and *Idiognathodus turbatus* were considered as Primary Markers for the MKB (Villa, E. and a Task Group, 2008). One more species, *Idiognathodus heckeli* also has been proposed recently (Ueno, K. and Task group, 2014). All these conodonts occur higher than the traditional MKB boundary, and a GSSP defined by them would be approximately 1.0-1.3 Myrs younger than the traditional boundary (Fig. 9). Considering that the Kasimovian duration is only 3.3 Myrs (Davydov et al., 2010; Schmitz and Davydov, 2012), the proposed potential biotic PM's for the MKB will exclude from the Kasimovian the traditional lower Kasimovian and the Kreviakian regional Stage of the Moscow Basin (Goreva and Alekseev, 2010). The Kreviakian includes the characteristic Kasimovian fauna that was utilized to designate the Kasimovian stage when it was first established (Ivanov, 1926; Alekseev et al., 2004).

After over 30 years of study, no formal proposal for a marker species to define the MKB has been accepted. Even though different phylogenetic lineages have been proposed as potential biotic PM's, none have been formally accepted (Ueno, K. and Task group, 2016) because of the extreme provincialism of marine faunas during the Moscovian-Kasimovian transition. This again demonstrates that the biotic PM's are hard to define, and they do not provide chronostratigraphic stability at the global scale because of the complexity associated with the interpretive character of taxonomy and because of the significant provincialism at that time.

Here it is proposed to establish the MKB at the base of the 3 cm thick volcanic ash, bed 7 (Sungatullina et al., 2015) in the Usolka section (sample 08USO-7.09 from Schmitz and Davydov, 2012). Bed 7 occurs 0.3 m below the base of the index species *Streptognathodus subexelsus* (Fig. 9). In the Moscow Basin this boundary coincides with the traditional MKB at the base of Kreviakian regional Stage (Goreva and Alekseev, 2010) and the *Protriticites pseudomontiparus* fusulinid zone that traditionally defined the boundary for over 50 years (Davydov, 1997). The Usolka section possesses the integrated data, including sedimentology, biostratigraphy, paleomagnetic properties, carbon and oxygen stable isotopes that make it a good GSSP candidate (Sungatullina et al., 2015). The volcanic ash has been dated as 305.953 ± 0.087 Ma (Schmitz and Davydov, 2012). We are going to re-collect and re-date this and a couple more ash beds below and above the occurrence of *Streptognathodus subexelsus* in Usolka section, to reinforce the earlier study.

9.3 Kasimovian-Gzhelian Boundary GSSP

Since 2000, the WG to establish the Moscovian-Kasimovian boundary has been also dealing with the Kasimovian-Gzhelian boundary (KGB) (Villa, 2000). Several potential Primary Markers have been proposed, with two conodont indexes being the most promising: *Streptognathodus zethus* and *Streptognathodus simulator* (Villa, 2000). The first species is recognized at the base of lowest Gzhelian strata in the Moscow Basin and in the Little Pawnee Shale Member of the Cass Formation, U.S. midcontinent, at the level which some North American stratigraphers have proposed to place the Missourian - Virgilian boundary (Villa, 2001). However, in the Southern Urals *Streptognathodus zethus* is recognized in the middle-upper Kasimovian (Chernykh and Ritter, 1996; Davydov and Popov, 1993), i.e. significantly below the traditional Kasimovian-Gzhelian boundary.

In 2008, the conodont species *Streptognathodus simulator* was accepted as the official biotic PM of the Kasimovian-Gzhelian Boundary (Heckel et al., 2008). Although the PM has been chosen over 10 years ago, it is still unclear how to designate the FAD of the *Streptognathodus simulator* in the global stratigraphic sections. In Southern Urals, the FAD of the species is proposed to occur within the chronocline *Streptognathodus praenuntius* - *Streptognathodus simulator* (Chernykh et al., 2006), whereas in North America a different chronocline *Streptognathodus eudorensis* - *Streptognathodus simulator* is proposed, (Barrick et al., 2008). Therefore, we cannot be sure that the first appearance of *Streptognathodus simulator* in the North American midcontinent and in Urals is synchronous.

In the Usolka section of the Southern Urals, the first *Streptognathodus simulator* was documented immediately above a distinct turbiditic limestone that contains fusulinids. We choose this to represent the Kasimovian-Gzhelian boundary, which is close to volcanic ash bed (97USO-2.7) dated as 303.54 ± 0.18 Ma (Chernykh et al., 2006; Davydov et al., 2008; Schmitz and Davydov, 2012). Volcanic ash 97USO-2.7 occurs 11.4 meters above the base of the section (Schmitz and Davydov, 2012). This is 0.11 m below the first occurrence of *Streptognathodus simulator* in the Usolka section as documented by the most recent study in the section (Sungatulina et al., 2015). Resampling and re-dating of this volcanic ash bed is required to confirm the age of the volcanic ashes below and above the boundary.

9.4 Sakmarian-Artinskian Boundary GSSP

The Cisuralian Working group, chaired by Dr. B. I. Chuvashov was established during the International Congress on the Permian System, Perm, U.S.S.R. (Utting, 1991). The WG was supposed to work with all stages within the Cisuralian, i.e. Asselian, Sakmarian, Artinskian and Kungurian, but initially focused mostly on the GSSP for the Carboniferous-Permian boundary, which was successfully established soon after (Davydov et al., 1998; Davydov et al., 1995).

The GSSP for the Sakmarian-Artinskian boundary has been proposed at 2.7 m above the base of bed 4 in Dal'ny Tulkas Road Cut section, Bashkortostan, Russia coinciding with the FOD of *Sweetognathus whitei* within the chronocline *Sw. binodosus-Sw. anceps-Sw. whitei* (Chuvashov et al., 2015; Davydov et al., 2005; Chuvashov et al., 2002). This boundary is very close to the traditional Sakmarian-Artinskian boundary in Southern Urals (Karpinsky, 1890). Dal'ny Tulkas Road Cut section contains several important fossil groups (conodonts, fusulinids and ammonoids), as well as chemostratigraphic (carbon and oxygen stable isotopes, Sr isotopes), paleomagnetic and radioisotopic data (Chuvashov et al., 2015; Schmitz and Davydov, 2012; Zeng et al., 2012). Nonetheless, there are problems with the taxonomy of the biotic Primary Marker of the Sakmarian-Artinskian boundary - the conodont species *Sweetognathus whitei* (Rhodes). The species was originally described from the Tensleep Sandstone of Wyoming (Rhodes, 1963). The other abundant conodont documented in the Tensleep topotype is *Streptognathodus elongatus* (Rhodes, 1963). The specimens of the latter species have been recently reinterpreted as *Streptognathodus fusus* and *S. postfusus* and are believed to be middle Asselian in age (Henderson, 2018). Henderson also believes that *Sweetognathus whitei* from the topotype in Wyoming differs from the forms identified in the Urals as *Sweetognathus "whitei".* This suggests that the *S. whitei* and *S. "whitei"* are polyphyletic and represent two morphologically similar species of different age (Henderson, 2018). No further studies proving this opinion have been reported. However, another interpretation suggests the Artinskian age and monophyletic origin of *Sweetognathus whitei* (Chernykh, 2015). Again, as is the case with many other biotic PM's, the situation cannot be easily resolved because of the interpretive character of the complex biological entities.

Here it is proposed to place Sakmarian-Artinskian boundary at the base of the 3 cm thick ash bed (sample 07DTR-Bed2), that is dated as 290.81 ± 0.09 Ma, in the upper part of bed 2 at Dal'ny Tulkas Road Cut section (Schmitz and Davydov, 2012; Fig. 10). It is 4.0 m below the occurrence of conodont species *Sweetognathus whitei* in the section. The sedimentation rate in Dal'ny Tulkas Road Cut section is very high (Schmitz and Davydov, 2012, Fig. 10) and therefore the proposed boundary is still very close to the traditional Sakmarian-Artinskian boundary in the Urals. The uncertainty of the proposed boundary with the biostratigraphic conodont and ammonoid zonations would be less than 0.66 Myrs (Schmitz and Davydov, 2012, Fig. 10), i.e. less than the resolution of the conodont zones (Henderson et al., 2012). The GSSP at the base of volcanic ash bed 07DTR-Bed2 is much more precise than any zonal biostratigraphic boundary in upper Cisuralian, i.e. 5-6 Myrs (Davydov et al., 2012). The proposed boundary could be correlated globally regardless of marine-continental facies, climatic belts, and metamorphism.

10. Conclusions

1. The use of ash beds to define the GSSP in the International Geologic Time Scale (IGTS) provides potential resolution that is an order of magnitude more precise, and will never require redefinition, and therefore will provide for the real stability of the IGTS.
2. This new approach may disappoint some paleontologists, because it breaks the monopoly of biotic PM's in GSSP definition. Being a micropaleontologist myself, I apologize for this to my colleagues and am saddened no less than they are, but at the same time, as has been reviewed here, the weakness, relative unreliability, and instability of the biotic PM's suggest biotic PM's be abandoned in the selection of future PM's. The process of replacement the biotic PM's in the International Geologic Time Scale with non-biotic markers has already started and should proceed vigorously in the future.
3. The GSSP definitions at volcanic ash beds applies the same principles as biotic PM's and therefore is not a replacement of the chronostratigraphic scale by the numeric scale, but rather it is an attractive choice of the GSSP definition that provides precise, world-wide boundaries, and therefore meets the main goals of the International geology and stratigraphy (Hedberg, 1976).
4. The proposed approach described here could be developed further with the help from the larger geological community to establish this approach as an accepted, reliable and common method in the GSSP definition.
5. The application of volcanic ash beds as PM's in the GSSP definition does not mean immediate replacement of the existing and already accepted ISC boundaries. I consider this approach as a new method that can resolve the issues with the undecided GSSPs and the GSSPs under revision and do so rather quickly (at least quicker than 25+ years as with some Pennsylvanian boundaries). It will also stabilize boundary definitions (in contrast to the case with Devonian-Carboniferous and other Upper Paleozoic boundaries), will make a useable chronostratigraphy accessible to a wider community, will restore historical priority as a main principle in chronostratigraphy, and will make legacy data consistent with the newly established GSSP and thus available for the larger geological community in many different applications.

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Figure Captions

Figure 1. First International Chronostratigraphic scale and the prototype of the International Stratigraphic Guide by E. Renevier (1873-1874, 1894), that was subsequently developed into the International Stratigraphic Guide by Hedberg (1976). Three main types of stratigraphic units: chronostratigraphic, biostratigraphic and lithostratigraphic - were introduced by Renevier (1873-1874). The biochronology (paleontology) was considered as the only basis for the International chronostratigraphic classification.

Figure 2. Simplified model of the hierarchical complexity of nature (modified from Novikoff, 1945). Physical and chemical processes of nature (in yellow) are fully described, generally understood and can be modeled and partially predicted. Biological and sociological processes (in grey) are generally described, partly and/or poorly understood and can be modeled only at the initial stages (molecular analyses, macrosociology).

Figure 3. General distribution of biotic Primary Markers with respect to paleoclimate and latitude. The theoretical origination and extinction of species according Signor–Lipps and Sppil–Rongis effects (Dornburg et al., 2011; Signor and Lipps, 1982), extended species appearance downwards and species disappearance upwards from the observed ones (red dashed lines). The observed origination is younger and supposed extinction is older than the accepted First and Last Occurrence Datums (FOD and LOD) of the biotic PM. Global climatic fluctuations and other factors result in the diachronous Primary Marker's FOD and LOD along latitudinal gradients.

Figure 4. Local lithofacies and occurrences of graptolite Primary Marker (biotic PM) in relation to facies and preservation. Red line - ideal isochronous stage boundary; black solid line - the First Occurrence Datum of biotic PM; black dashed line – known First Occurrence Datum. Graptolites are best preserved in pelagic shales (green and white symbols). The stage boundary traced with graptolites is diachronous, because the mode of life (graptolites never lived in lagoonal or terrestrial sediments); environmental changes, and preservation issues (poor fossilization in sandstone and destruction of the fossils during metamorphism). Orange star indicates potential occurrence of volcanic ash at the defined GSSP. Yellow stars – other dated ashes that precisely constrained boundary globally. Green shadow around red dashed line represents U-Pb analyses maximum uncertainty, that is in order of magnitude is better that the uncertainty of PM marker. PM – graptolite primary marker; the uncertainty of the biotic PM (shadow pink on left side of diagram) is about ± 1 Ma. Note, that the established Stage boundary associated with the FOD of the graptolite species and the discovery of an occurrence of this species below the boundary, according the current rules of the International Commission on Stratigraphy, would require redefinition of this boundary. If the GSSP was established at the volcanic ash bed it would be a globally traceable event regardless of environmental, sedimentary, climatic, metamorphism and other factors.

Figure 5. Regional Scales of Carboniferous System (from Davydov et al., 2012). The natural boundaries, associated with global and relatively sudden geological events, such as extinction (in red), can be traced globally (Devonian-Carboniferous and Mid-Carboniferous boundaries). The other boundaries are diachronous with respect to each other because of regional biotic evolution, tectonism, paleoclimate and other regional and interregional factors.

Figure 6. Directional and cyclic methods of subdividing the geological succession and its relation to the chronostratigraphic scale. Biostratigraphy (evolution) and radioisotopic dating (decay of radioactive elements) both are directional methods because the evolution of biota and decay of radioactive elements are irreversible, and they thus can provide an independent temporal framework for testing correlation, and for establishing the rates of geologic processes. The cyclic (repeated proxies) method, although providing high-resolution, only becomes useful after the cycles (repeated values) are tied to the chronostratigraphic scale by either of the directional methods: biological evolutionary or radioisotopic dating (figure modified from Li et al., 2016).

Figure 7. Precision and accuracy of biostratigraphic and radioisotopic methods.

A, the average precision of biostratigraphic zones in different geologic Periods. These zonation's with maximum precision 0.5-1.0 Myrs applicable only in marine sediments in tropics-subtropics. In high latitudes the precision is significantly smaller. **B**, (left side box) representative analytical precision and accuracy for individual analysis and group weighted mean U–Pb zircon ages using in situ (SIMS or LA–ICP–MS) and isotope dilution (CA-IDTIMS) methods (modified from Schmitz & Kuiper, 2013). Since the development of the new techniques (CA-IDTIMS of Mattinson, 2005) the precision increased over 100 times, whereas the biostratigraphic precision (right side box) remains the same (the average duration 0.5-1.0 Myrs) for the last 50-80 years. Radioisotopic dating applicable anywhere regardless of climatic zone and geologic setting (continental or marine) and medium grade metamorphism

Figure 8. The existing and proposed GSSP of the Devonian-Carboniferous boundary. The current position of the boundary is at the base of the bed 89 in La Serre trench E section, south of Cabrieres, Montagne Noire, France (Paproth et al., 1991). The boundary coincides with the "First Appearance Datum (FAD)" of the conodont species *Siphonodella sulcat*a. The red dots on the section show the occurrences of this species that were recovered below the GSSP from the bed 84b (Kaiser, 2009). The current GSSP (red thick line) occurs 2.35 m above the base of Hangenberg black shales in La Serre section and the major global extinction event (red arrow) in marine biota. The latter boundary is the natural Devonian-Carboniferous boundary suggested by Walliser (1984). The proposed GSSP (red dashed line) is located 26 cm below the Hangenberg Black Shale at the base of 2-3 cm thick bentonitic volcanic ash A2KQ1 that is dated as 358.97 ± 0.11 Ma (Myrow et al., 2014). This age is consistent, within the uncertainty, with the calculated age 359.05 ± 0.07 Ma of the base of the Hangenberg black shales in Hasselbachtal section in the 2012 Geologic Time Scale (Schmitz and Davydov unpublished data and Davydov et al., 2012). The pick on the photo is 65 cm long. Conodonts: *Pr. - Protogtathus*; *Si. – Siphonodella*; HBS – Hangenberg Black Shales. The biostratigraphic data from La Serre trench У section are from Paproth et al. (1991) and Kaiser (2009); from Kowala Quarry section are from (Dzik, 1997) and (Malec, 2014).

Figure 9. Usolka section, southern Urals, Russia. Two potential GSSP's at volcanic ash beds are proposed. Volcanic ash 08USO-7.09 occurs 6.5 meters above the base of the section (Schmitz and Davydov, 2012). *Streptognathodus subexcelsus*, the index of the traditional base of the Kasimovaian of Moscow Basin, in Usolka section occurs 0.3 m above this ash bed. Volcanic ash 97USO-2.7 occurs 11.4 meters above the base of the section (Schmitz and Davydov, 2012). This is 0.11 m below the first occurrence of *Streptognathodus simulator* in Usolka section as documented by the most recent study (Sungatulina et al., 2015). This species is considered as an index for the International Gzhelian Stage (Heckel et al., 2008). Beds numbers and distribution of conodonts according to Sungatulina *et al*., (2015) and Schmitz and Davydov (2012). Red lines indicate the GSSP's of the proposed the base of the Kasimovian (ash bed 08USO-7.09) and the base of the Gzhelian (ash bed 01DES63) in this section. Conodont's genera abbreviations: *Id. Idiognathodus*; *Sw. - Swadellina*; *St. – Streptognathodus*. Photos at the bottom: A – enlarged part of the section with volcanic ash bed 08USO-7.09; B - the same with volcanic ash beds 97USO-2.7 and 01DES63 (photo G.M. Sungatulina).

Figure 10. The potential GSSP of the Sakmarian-Artinskian boundary at Dal'ny Tulkas Roadcut Section, Bashkortostan, Russia. The biotic Primary Marker *Sweethognathus "whitei"* has been proposed at 0 meters in the section (Chernyk et al., 2006). The GSSP proposed here (red line) occurs at a volcanic ash within the bed 2 (- 4.0 m in this section) and was dated as 290.81 ± 0.09 Ma (sample 07DTR-Bed2) (Schmitz and Davydov, 2012). The red line indicates the proposed position of the GSSP for the Sakmarian-Artinskian boundary coincides with the base of this volcanic ash bed. The ages of two other samples (DTR905 and 01DES403) are 288.36 ± 0.10 Ma and 288.21 ± 0.06 Ma respectively (Schmitz and Davydov, 2012). Photos at the bottom: A - general view of Dal'ny Tulkas Roadcut section (photo G.M. Sungatulina); B - volcanic ash 07DTR-Bed 2. Biostratigraphic data from Schmitz and Davydov, (2012) and Chernykh et al., (2015).

References

Ager, D.V., 1973. The nature of the stratigraphical record. Macmillan, London.

Alekseev, A.S., Goreva, N.V., Isakova, T.N., Makhlina, M.K., 2004. Biostratigraphy of the Carboniferous in the Moscow Syneclise, Russia. Newsletter on Carboniferous stratigraphy 22, 28–35.

Algeo, T., Henderson, C.M., Ellwood, B., Rowe, H., Elswick, E., Bates, S., Lyons, T., Hower, J.C., Smith, C., Maynard, B., Hays, L.E., Summons, R.E., Fulton, J., Freeman, K.H., 2012. Evidence for a diachronous Late Permian marine crisis from the Canadian Arctic region. Bulletin of the Geological Society of America 124, 1424–1448. 10.1130/B30505.1.

Aretz, M. 2014. Redefining the Devonian-Carboniferous Boundary: an overview of problems and possible solutions. In: Rocha, R., Pais, J., Kullberg, J.S., Finney, S. (Eds.), Strati 2013: Springer, Switzerland, 227–231.

Aretz, M. and Corradini, C., 2015. The redefinition of the Devonian-Carboniferous Boundary: recent developments and introduction to the workshop. In: STRATI 2015. Berichte des Institutes für Erdwissenschaften 21, 14.

Baresel, B., d'Abzac, F.-X., Bucher, H., Schaltegger, U., 2016. High-precision time-space correlation through coupled apatite and zircon tephrochronology: An example from the Permian-Triassic boundary in South China. Geology 45, 83–86. 10.1130/G38181.1.

Baresel, B., Bucher, H., Bagherpour, B., Brosse, M., Guodun, K., Schaltegger, U., 2017. Timing of global regression and microbial bloom linked with the Permian-Triassic boundary mass extinction: implications for driving mechanisms. Scientific reports 7, 43630.

Barrick, J.E., Heckel, P.H., Boardman, D.R., 2008. Revision of the conodont Idiognathodus simulator (Ellison 1941), the marker species for the base of the Late Pennsylvanian global Gzhelian Stage. Micropaleontology 54, 125–137.

Bindeman, I.N. and Melnik, O.E., 2016. Zircon Survival, Rebirth and Recycling during Crustal Melting, Magma Crystallization, and Mixing Based on Numerical Modelling. Journal of Petrology 57, 437–460. 10.1093/petrology/egw013.

Bleeker, W., 2004. Towards a 'natural' time scale for the Precambrian - A proposal. Lethaia 37, 219–222. 10.1080/00241160410006456.

Bowring, S.A., Erwin, D.H., Renne, P., 2004. EARTHTIME; a community-based effort towards high-precision calibration of Earth history. Abstracts with Programs e Geological Society of America. Geological Society of America (GSA), p. 211.

Broda, K., Collette, J., Budil, P., 2018. Phyllocarid crustaceans from the Late Devonian of the Kowala quarry (Holy Cross Mountains, central Poland). Papers in Palaeontology 4, 67–84. 10.1002/spp2.1099.

Brosse, M., Bucher, H., Goudemand, N., 2016. Quantitative biochronology of the Permian–Triassic boundary in South China based on conodont unitary associations. Earth-Science Reviews 155, 153–171. 10.1016/j.earscirev.2016.02.003.

Burgess, S.D., Muirhead, J.D., Bowring, S.A., 2017. Initial pulse of Siberian Traps sills as the trigger of the end-Permian mass extinction. Nature communications 8, 164. 10.1038/s41467-017-00083-9.

Chen, Z.-Q., Yang, H., Luo, M., Benton, M.J., Kaiho, K., Zhao, L., Huang, Y., Zhang, K., Fang, Y., Jiang, H., Qiu, H., Li, Y., Tu, C., Shi, L., Zhang, L., Feng, X., Chen, L., 2015. Complete biotic and sedimentary records of the Permian–Triassic transition from Meishan section, South China: Ecologically assessing mass extinction and its aftermath. Earth-Science Reviews 149, 67–107. 10.1016/j.earscirev.2014.10.005.

Chernykh, V.V., 2015. Principles of zonal biochronology. Institute of Geology and Geochemistry of RAS, Ekaterinburg (In Russian).

Chernykh, V.V., Chuvashov, B.I., Davydov, V.I., Schmitz, M.D., Snyder, W.S., 2006. Usolka section (southern Urals, Russia): a potential candidate for GSSP to define the base of the Gzhelian Stage in the global chronostratigraphic scale. Geologija 49, 205–217.

Chernykh, V.V. and Ritter, S.M., 1996. Conodont biostratigraphy of the Nikolsky section (southern Urals): a progress report. Permophiles, 39–40.

Chuvashov, B.I., Chernykh, V.V., Davydov, V.I., Shen, S.Z., Henderson, C.M., 2015. Dal'ny Tulkas Section. In: Southern Urals. Deep water successions of the Carboniferous and Permian. XVIII International Congress on the Carboniferous and Permian. Pre-Congress A3 Trip, 6-10 August 2015., 20–29.

Chuvashov, B.I., Chernykh, V.V., Leven, E.Y., Davydov, V.I., Bowring, S.A., Ramezani, J., Glenister, B.F., Henderson, C.M., Schiappa, T.A., Northrup, C.J., Snyder, W.S., Spinosa, C., Wardlaw, B.R., 2002. Progress report on the base of the Artinskian and base of the Kungurian by the Cisuralian Working Group. Permophiles, 13–16.

Corradini, C. and Kaiser, S.I., 2009. Morphitypes in the early *Siphonodella* lineage: implications for the defintion of the Devonian/Carboniferous boundary. Permophiles (supplement) 53, 13.

Corradini, C., Kaiser, S.I., Perri, M.C., Spalletta, C., 2011. Protognathodus (Conodonta) and its potential as a tool for defining the Devonian/Carboniferous Boundary. Rivista Italiana di Paleontologia e Stratigrafia 117, 15–28.

Corradini, C., Spalletta, C., Mossoni, A., Matuja, H., Over, J.D., 2016. Conodonts across the Devonian/Carboniferous boundary: a review and implication for the redefinition of the boundary and a proposal for an updated conodont zonation. Geological Magazine 154, 888–902. 10.1017/S001675681600039X.

Davydov, V.I., 1997. Middle/Upper Carboniferous boundary: Problems of definition and correlation. Proceedings of the XIII International Congress on Carboniferous and Permian 1, 113–121.

Davydov, V.I., 2007. *Protriticites* foraminiferal fauna and its utilization in the Moscovian–Kasomovian boundary definition. Proceedings of the XV International Congress on Carboniferous and Permian, 456–466.

Davydov, V.I., 2013. The GSSP at the Aidaralash section is solid and has no alternative. Permophiles, 13–15.

Davydov, V.I., Arefiev, M.P., Golubev, V.K., Karasev, E.V., Naumcheva, M.A., Schmitz, M.D., Silantiev, V.V., Zharinova, V.V., (in press). Radioisotopic and biostratigraphic constraints on the classical middle-upper Permian succession and tetrapod fauna of the Moscow Syneclise, Russia. Geology (Boulder).

Davydov, V.I., Chernykh, V.V., Chuvashov, B.I., Schmitz, M.D., Snyder, W.S., 2008. Faunal assemblage and correlation of Kasimovian-Gzhelian Transition at Usolka Section, Southern Urals, Russia (a potential candidate for GSSP to define base of Gzhelian Stage). Stratigraphy 5, 113–135.

Davydov, V.I., Crowley, J.L., Schmitz, M.D., Poletaev, V.I., 2010. High-precision U-Pb zircon age calibration of the global Carboniferous time scale and Milankovitch band cyclicity in the Donets Basin, eastern Ukraine. Geochemistry, Geophysics, Geosystems 11, n/a-n/a. 10.1029/2009GC002736.

Davydov, V.I., Glenister, B.F., Spinosa, C., Ritter, S.M., Chemykh, V.V., Wardlaw, B.R., Snyder, W.S., 1995. Proposal of Aidaralash as GSSP for the Base of the Permian System. Permophiles, 1–9.

Davydov, V.I., Glenister, B.F., Spinosa, C., Ritter, S.M., Chernykh, V.V., Wardlaw, B.R., Snyder, W.S., 1998. Proposal of Aidaralash as Global Stratotype Section and Point (GSSP) for base of the Permian System. Episodes 21, 11–18.

Davydov, V.I., Korn, D., Schmitz, M.D., Gradstein, F.M., Hammer, O., 2012. Chapter 23 - The Carboniferous Period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., (Eds.), The Geologic Time Scale. Elsevier, Boston, 603–651.

Davydov, V.I. and Popov, A.V., 1993. Nikolsky section. Permian System: Guide to Geological Excursions in the Uralian Type Localities. Occasional Publication ESRI, New Series, 12–130.

Davydov, V.I., Schmitz, M.D., Snyder, W.S., Wardlaw, B.R., 2005. Progress Toward Development Cisuralian (Lower Permian) Time Scale (biostratigraphy, chronostratigraphy, radiometric calibration). In Lucas, S.G. and Zeigler, K.E., eds., The Nonmarine Permian, New Mexico Museum of Natural History and Science Bulletin 30, 48–55.

Ding Meihua, Zhang Kexin, Lai Xulong, 1996. Evolution of *Clarkina* lineage and *Hindeodus- Isarcicella* lineage at Meishan section, South China. In: Yin Hongfu (Ed.), The Palaeozoic - Mesozoic boundary, candidates of the Global Stratotype Section and Point of the Permian-Triassic Boundary. China University of Geosciences Press, 65–71.

d'Orbigny, A., 1842-1849. Paleontologie francaise; terrains jurassiques., Paris.

Dollo, L., 1893. Les Lois De L'évolution. Arno, New York.

Dornburg, A., Beaulieu, J.M., Oliver, J.C., Near, T.J., 2011. Integrating fossil preservation biases in the selection of calibrations for molecular divergence time estimation. Systematic biology 60, 519–527. 10.1093/sysbio/syr019.

Dzik, J., 1997. Emergence and succession of Carboniferous conodont and ammonoid communities in the Polish part of the Variscan sea. Acta Palaeontologica Polonica 42, 57–170

Eberth, D.A. and Kamo, S.L., 2019. First high-precision U–Pb CA–ID–TIMS age for the Battle Formation (Upper Cretaceous), Red Deer River valley, Alberta, Canada: implications for ages, correlations, and dinosaur biostratigraphy of the Scollard, Frenchman, and Hell Creek formations. Canadian Journal of Earth Sciences 56, 1041–1051. 10.1139/cjes-2018-0098.

Finney, S., 2005. Global Series and Stages for the Ordovician System: A Progress Report: 10.1344/104.000001381. Geologica Acta 3, 309–316. 10.1344/104.000001381.

Gastaldo, R.A., Kamo, S.L., Neveling, J., Geissman, J.W., Looy, C. v., Martini, A.M., 2020. The base of the Lystrosaurus Assemblage Zone, Karoo Basin, predates the end-Permian marine extinction. Nature communications 11, 1428. 10.1038/s41467-020-15243-7.

Gastaldo, R.A., Neveling, J., Geissman, J.W., Kamo, S., 2018. A lithostratigraphic and magnetostratigraphic framework in a geochronologic context for a purported Permian–Triassic boundary section at Old (West) Lootsberg Pass, Karoo Basin, South Africa: GSA Bulletin; September/October 2018; v. 130; no. 9/10; p. 1411–1438; https:// doi .org /10 .1130 /B31881 .1; 19 figures; 1 table; Data Repository item 2018119; published online 3 April 2018. GSA Bulletin 130, 1411–1438.

Geyer, G. and Landing, E., 2017. The Precambrian–Phanerozoic and Ediacaran–Cambrian boundaries: a historical approach to a dilemma. Geological Society, London, Special Publications 448, 311. 10.1144/SP448.10.

Goreva, N.V. and Alekseev, A.S., 2010. Upper carboniferous conodont zones of Russia and their global correlation. Stratigraphy and Geological Correlation 18, 593–606. 10.1134/S086959381006002X.

Gradstein, F.M., 2012. Introduction. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., (Eds.), The Geologic Time Scale. Elsevier, Boston, 1–29.

Gradstein, F.M. and Ogg, J.G., 2012. Chapter 2 - The Chronostratigraphic Scale. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), The Geologic Time Scale. Elsevier, Boston, 31–42.

Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), 2012. The Geologic Time Scale. Elsevier, Boston.

Harland, W.B., 1978. Geochronologic Scales;. In: Cohee, G.V., Glaessner, M.F., Hedberg, H.D. (Eds.), Contributions to the geologic time scale: Papers given at the Geological Time Scale Symposium 106.6, 25th International Geological Congress, Sydney, Australia, August 1976 / edited by George V. Cohee, Martin F. Glaessner and Hollis D. Hedberg. American Association of Petroleum Geologists, Tulsa, Okla, 9–32.

Harland, W.B., Cox, A.V., Llewellyn, E.G., Pickton, C.A.G., Smith, A.G., Walters, R., 1982. A geologic time Scale. Cambridge University Press, Cambridge.

Heads, M., 2012. Bayesian transmogrification of clade divergence dates: a critique. Journal of Biogeography 39, 1749–1756. 10.1111/j.1365-2699.2012.02784.x.

Heckel, P.H., Alekseev, A.S., Barrick, J.E., Boardman, D.R., Goreva, N.V., Isakova, T.N., Nemyrovska, T.I., Ueno, K., Villa, E., Work, D.M., 2008. Choice of conodont I*diognathodus simulator* (sensu stricto) as the event marker for the base of the global Gzhelian Stage (Upper Pennsylvanian Series, Carboniferous System). Episodes 31, 319–325.

Hedberg, H.D., 1976. International Stratigraphic Guide. John Wiley and Sons, New York.

Henderson, C.M., 2018. Permian conodont biostratigraphy. In: Lucas, S.G. and Shen, S. (Eds.), The Permian Times. Special Publications, 119–142.

Henderson, C.M., Davydov and, V.I., Wardlaw, B.R., Gradstein, F.M., Hammer, O., 2012. Chapter 24 - The Permian Period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), The Geologic Time Scale. Elsevier, Boston, 653–679.

Ivanov, A.P., 1926. Middle and Upper Carboniferous deposits of the Moscow area. Bulletin of Moscow Society of Natural Studies, Geol. Section 4, 138-178 (in Russian), 178-180 (in French);

Jiang, H., Aldridge, R.J., Lai, X., Yan, C., Sun, Y., 2011. Phylogeny of the conodont genera *Hindeodus* and *Isarcicella* across the Permian-Triassic boundary. Lethaia 44, 374–382. 10.1111/j.1502-3931.2010.00248.x.

Kaiser, S.I., 2009. The Devonian/Carboniferous boundary stratotype section (La Serre, France) revisited. Newsletters on Stratigraphy 43, 195–205.

Karpinsky, A.P., 1890. Ammonoids of Artinskian stage and some similar Carboniferous forms. Geological Committee of Russia (In Russian), Sankt-Petersburg.

Kauffman, E.G. and Hazel, J.E. (Eds.), 1977. Concepts and Methods of Biostratigraphy Dowden. Dowden, Hutchinson and Ross, Stroudsburg, Penn.,

Klapper, G., 2007. Conodont taxonomy and the recognition of the Frasnian/Famennian (Upper Devonian) State Boundary. Stratigraphy 4, 67–76.

Kleinpell, R.M., 1979. Criteria in correlation: relevant principles of science. Pacific Section. American Association of Petroleum Geologists, Bakersfield, CA, 1–44.

Korte, C. and Kozur, H.W., 2010. Carbon-isotope stratigraphy across the Permian–Triassic boundary: A review. Journal of Asian Earth Sciences 39, 215–235. 10.1016/j.jseaes.2010.01.005.

Kozur, H.W., 1996. The conodonts *Hindeodus*, *Isarcicella* and *Sweetohindeodus* in the Uppermost Permian and Lowermost Triassic. Geologia Croatia 49, 81–115.

Leonov, G.P., 1973. Principles of Stratigraphy. Moscow State University, Moscow.

Lucas, S.G., 2013. We Need a New GSSP for the Base of the Permian. Permophiles, 8–13.
Lucas, S.G., 2018. The GSSP Method of Chronostratigraphy: A Critical Review. Frontiers in Earth Science 6, 1045. 10.3389/feart.2018.00191.
Lucas, S.G., Krainer, K., Tanner, L.H., Taylor, D.G., 2019. We need a new GSSP for the base of the Jurassic System. Volumina Jurassica XVII, 1–4.
Lyell, C., 1855. A Manual of Elementary Geology, 5th Edn. John Murray, London.
Macdonald, F.A., Schmitz, M.D., Crowley, J.L., Roots, C.F., Jones, D.S., Maloof, A.C., Strauss, J.V., Cohen, P.A., Johnston, D.T., Schrag, D.P., 2010. Calibrating the Cryogenian. Science (New York, N.Y.) 327, 1241–1243. 10.1126/science.1183325.
Malec, J., 2014. The Devonian/Carboniferous boundary in the Holy Cross Mountains (Poland). Geological Quarterly 58. 10.7306/gq.1142.
Marshall, J., 2018. Message from the Chairman. Subcommission on Devonian Stratigraphy Newsletter, 1–2.
Mattinson, J.M., 2005. Zircon U–Pb chemical abrasion (“CA-TIMS”) method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages. Chemical Geology 220, 47–66. 10.1016/j.chemgeo.2005.03.011.
Mazzocchi, F., 2008. Complexity in biology: EMBO reports VOL 9 | NO 1 | 2008. EMBO reports; 9.
McCann, T., 2008. The geology of central Europe. Geological Society, London.
McLaren, D.J., 1977. The Silurian-Devonian Boundary Committee. A final report. The Silurian-Devonian Boundary. In: Martinsson, A. (Ed.), The Silurian-Devonian Boundary. IUGS Series A. Schweizerbart, Stuttgart, 1–34
Melchin, M.J., Sadler, P.M., Cramer, B.D., Cooper, R.A., Gradstein, F.M., Hammer, O., 2012. Chapter 21 - The Silurian Period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), The Geologic Time Scale. Elsevier, Boston, 525–558.
Meyen, S.V., 1974. Introduction to the theory of stratigraphy. Geological Institute of Russian Academy of Sciences, Moscow, (In Russian).
Miller, K.G. and Wright, J.D., 2017. Success and failure in Cenozoic global correlations using golden spikes: A geochemical and magnetostratigraphic perspective. Episodes 40, 8–21. 10.18814/epiiugs/2017/v40i1/017003.
Mu, X., Kershaw, S., Li, Y., Guo, L., Qi, Y., Reynolds, A., 2009. High-resolution carbon isotope changes in the Permian–Triassic boundary interval, Chongqing, South China; implications for control and growth of earliest Triassic microbialites. Journal of Asian Earth Sciences 36, 434–441. 10.1016/j.jseaes.2007.08.004.
Murchison, R.I., 1841. First sketch of some of the principal results of a second geological survey of Russia. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 19, 417–422. 10.1080/14786444108650460.
Murchison, R.I., Verneuil, E. de, Keyserling, A. von, 1845. The Geology of Russia in Europe and the Ural Mountains. Murray, London.
Myrow, P.M., Ramezani, J., Hanson, A.E., Bowring, S.A., Racki, G., Rakociński, M., 2014. High-precision U-Pb age and duration of the latest Devonian (Famennian) Hangenberg event, and its implications. Terra Nova 26, 222–229. 10.1111/ter.12090.
Nemyrovska, T.I., 1999. Bashkirian conodonts of the Donets Basin, Ukraine. Scripta Geologica 119, 1–115.
Neumann, K.N. and Lippolt, H.J., 1981. Calibration of the Middle Triassic Time Scale by Conventional K-Ar and 40Ar/ 39Ar Dating of Alkali Feldspars. Journal of Geophysics 50, 73–88.
Nikitin, I.F. and Zhamoida, A.I. (Eds.), 1984. Practical Stratigraphy (In Russian). Nedra, Leningrad.
Novikoff, A.B., 1945. The concept of integrative levels and biology: Science 02 Mar 1945: Vol. 101, Issue 2618, pp. 209-215 DOI: 10.1126/science.101.2618.209.
Orchard, M.J. and Krystyn, L., 1998. Conodonts of the lowermost Triassic of Spiti, and new zonation based on Neogondolella successions. Risista Italiana di Paleontologia e Stratigrafia 104, 341–368.
Paproth, E., 1990. 4.1 Carboniferous subdivision proposals. Newsletter on Carboniferous stratigraphy 8, 5–6.
Paproth, E., Feist, R., Flajs, G., 1991. Decision on the Devonian一Carboniferous boundary stratotype. Episodes 14, 331–336.
Payne, J.L., Turchyn, A.V., Paytan, A., DePaolo, D.J., Lehrmann, D.J., Yu, M., Wei, J., 2010. Calcium isotope constraints on the end-Permian mass extinction. Proceedings of the National Academy of Sciences of the United States of America 107, 8543–8548. 10.1073/pnas.0914065107.
Plumb, K.A., 1991. New Precambrian time scale. Episodes 14, 139–140. 10.18814/epiiugs/1991/v14i2/004.
Racki, G., 1992. Brachiopod assemblages in the Devonian Kowala Formation of the Holy Cross Mountains. Acta Palaeontologica Polonica 37, 297–357.

Raup, D.M. and Sepkoski, J.J., 1982. Mass Extinctions in the Marine Fossil Record. Science, New Series 125, 1501–1503.

Remane, J., Bassett, M.G., Cowie, J.W., Cohrbandt, K.H., Lane, H.R., Michelsen, O., Wang, N., 1996. Revised guidelines for the establishment of global chronostratigraphic standards by the International Commission on Stratigraphy (ICS). Episodes 19, 77–81.

Renevier, E., 1873-1874. Tableau des terrains sedimentaires. Bulletin de la Société vaudoise des sciences naturelles XII-XIII.

Richards, B.C. and Task Group, 2009. Joint Task Group for Reappraisal of the Devonian-Carboniferous Boundary. Newsletter on Carboniferous stratigraphy 27, 7–9.

Rivera, T.A., Schmitz, M.D., Crowley, J.L., Storey, M., 2014. Rapid magma evolution constrained by zircon petrochronology and 40Ar/39Ar sanidine ages for the Huckleberry Ridge Tuff, Yellowstone, USA. Geology 42, 643–646. 10.1130/G35808.1.

Rivera, T.A., Schmitz, M.D., Jicha, B.R., Crowley, J.L., 2016. Zircon Petrochronology and 40 Ar/ 39 Ar Sanidine Dates for the Mesa Falls Tuff: Crystal-scale Records of Magmatic Evolution and the Short Lifespan of a Large Yellowstone Magma Chamber. Journal of Petrology 198–199, egw053. 10.1093/petrology/egw053.

Ronov, A.B., 1993. Stratisphera or sedimentary cover of the Earth (quantitative investigation). Nauka, Moscow.

Renevier, E., 1896. CHRONOGRAPHE GÉOLOGIQUE. Compte-rendu du Congrès de Zurich 4.

Rubidge, B.S., Erwin, D.H., Ramezani, J., Bowring, S.A., Klerk, W.J. de, 2013. High-precision temporal calibration of Late Permian vertebrate biostratigraphy: U-Pb zircon constraints from the Karoo Supergroup, South Africa. Geology 41, 363–366. 10.1130/G33622.1.

Ruzhenzev, V.E., 1977. Biochronotype or Stratotype? Paleontological Zhurnal, 23–34 (In Russian).

Salvador, A. (Ed.), 2013. International Stratigraphic Guide. Geological Society of America, Electronic version.

Sageman, B.B., Kauffman E.G., Harries P.J., Elder W.P., 1997. Cenomanian/Turonian bioevent and ecostratigraphy in the Western Interior Basin: contrasting scales of local, regional, and global events. In: Brett C.E. and Baird G.C. (Eds.), Paleontological Events - Stratigraphic, Ecological and Evolutionary Implications. Columbia University Press, New York, 520–570.

Schenk, H.G. and Muller, S.W., 1941. Stratigraphic terminology. GSA Bulletin 52, 1419–1426.

Schindewolf, O.H., 1970. Stratigraphical principles. Newsletters on Stratigraphy 1, 17–24.

Schindewolf, O.H., 1970. Stratigraphie und stratotypus. Yerlag der Akademie der Wissenschaften und der Literatur, Mainz.

Schmitz, M.D., 2012. Chapter 6 - Radiogenic Isotope Geochronology. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G. (Eds.), The Geologic Time Scale 2012. Elsevier, Amsterdam, 115–126.

Schmitz, M.D. and Davydov, V.I., 2012. Quantitative radiometric and biostratigraphic calibration of the Pennsylvanian–Early Permian (Cisuralian) time scale and pan-Euramerican chronostratigraphic correlation. GSA Bulletin 124, 549–577. 10.1130/B30385.1;

Schmitz, M.D. and Kuiper, K., 2013. High-precision geochronology (in One hundred yeras of geochronology). Elements 9, 25–30.

Schoene, B., 2014. U–Th–Pb Geochronology. In: Holland, H.D. (Ed.), Treatise on geochemistry. Elsevier, Amsterdam, 341–378.

Schoene, B., Condon, D.J., Morgan, L., and Noah McLean, N., 2013. Precision and accuracy in geochronology. Elements 8, 19-24.

Shen, S., Cao, C., Zhang, H., Bowring, S.A., Henderson, C.M., Payne, J.L., Davydov, V.I., Chen, B., Yuan, D., Zhang, Y., Wang, W., Zheng, Q., 2013. High-resolution delta (super 13) C (sub carb) chemostratigraphy from latest Guadalupian through earliest Triassic in south China and Iran. Earth and Planetary Science Letters 375, 156–165. 10.1016/j.epsl.2013.05.020.

Shen, S., Ramezani, R., Chen, J., Cao, C.-Q., Erwin, D.H., Zhang, H., Xiang, L., Schoepfer, S.D., Henderson, C.M., Zheng, Q.-F., Bowring, S.A., Wang, Y., Li, X.-H., Wang, X.-D., Yuan, D.-X., Zhang, Y.-C., Mu, L., Wang, J., Wu, Y.-S., 2019. A sudden end-Permian mass extinction in South China: /10 .1130 /B31909 .1. GSA Bulletin 131, 205–223. 10.1130/B31909.1.

Singor, P.W. and Lipps, J.H., 1982. Sampling bias, gradual extinction patterns and catastrophes in the fossil record. Geological Society of America Special Paper 190, 291–296.

Smith, W., 1815. A Memoir to the Map and Delineation of the Strata of England and Wales with part of Scotland. Cary, London.

Smith, W., 1816-1819. Strata Identified by Organized Fossils containing prints on colored paper of the most characteristic specimens in each stratum. W. Arding, London.

Smith, W., 1815. A Memoir to the Map and Delineation of the Strata of England and Wales with part of Scotland. Cary, London.

Smith, A.G., Barry, T., Brown, P., Cope, J., Gale, A., Gibbard, P., Gregory, J., Hounslow, M., Kemp, D., Knox, R., Marshall, J., Oates, M., Rawson, P., Powell J., Waters, C., 2015. GSSPs, global stratigraphy and correlation. In: Smith, D.G., Bailey, R.J., Burgess, P.M., Fraser, A.J. (Eds.), Strata and Time: Probing the Gaps in Our Understanding. Geological Society of London, London, 37–67.

Štorch, P., 2017. Chairman's corner. Silurian Times 25, 3–5.

Sungatullina, G.M., Davydov, V.I., Sungatullin, R.K., Barrick, J.E., Shilovsky, O.P., 2015. Usolka section. Middle Pennsylvanian (Moscovian-Kasimovain) succession. In: Southern Urals. Deep water successions of the Carboniferous and Permian. XVIII International congress on the Carboniferous and Permian. Pre-Congress A3 Trip, 6-10 August 2015., 70–86.

Twitchett, R.J., Looy, C. v., Morante, R., Visscher, H., Wignall, P., 2001. Rapid and synchronous collapse of marine and terrestrial ecosystems during the end-Permian biotic crisis. Geology 29, 351–354.

Ueno, K. and Task group, 2014. Report of the task group to establish the Moscovian–Kasimovian and Kasimovian–Gzhelian boundaries. Newsletter on Carboniferous stratigraphy 31, 36–40.

Ueno, K. and Task group, 2016. Report of the Task Group to establish the Moscovian–Kasimovian and Kasimovian–Gzhelian boundaries. Newsletter on Carboniferous stratigraphy 32, 33–37.

Utting, J., 1991. Minutes of combined meeting of the Permian Subcommission on Stratigraphy, The Carboniferous/Permian boundary Working Group and the Permian/Triassic boundary Working Group, August 1991, Perm, U.S.S.R. Permophiles, 2–5.

van Kranendonk, M.J., Contributors, Altermann, W., Beard, B.L., Hoffman, P.F., Johnson, C.M., Kasting, J.F., Melezhik, V.A., Nutman, A.P., Papineau, D., Pirajno, F., 2012. A Chronostratigraphic Division of the Precambrian. In: Gradstein, F.M. (Ed.), The geologic time scale 2012. Volume 2. Elsevier, Amsterdam, Boston, 299–392.

Villa, E., 1991. Project Group 5: Report on the base of the *Protriticites* zone. Newsletter on Carboniferous stratigraphy 9, 3.

Villa, E., 2000. General report of Working Group to establish GSSP close to the Moscovian-Kasimovian boundary. Newsletter on Carboniferous stratigraphy 18, 6-7.

Villa, E., 2001. Working Group to define a GSSP close to the Moscovian/Kasimovian boundary. Newsletter on Carboniferous stratigraphy 19, 8–11.

Villa, E. and a Task Group, 2008. Progress Report of the Task Group to establish the Moscovian-Kasimovian and Kasimovian-Gzhelian boundaries. Newsletter on Carboniferous stratigraphy 26, 12–13.

Vleeschouwer, D. de, Rakociński, M., Racki, G., Bond, D.P.G., Sobień, K., Claeys, P., 2013. The astronomical rhythm of Late-Devonian climate change (Kowala section, Holy Cross Mountains, Poland). Earth and Planetary Science Letters 365, 25–37. 10.1016/j.epsl.2013.01.016.

Walliser, O.H., 1984. Pleading for a natural D/C-boundary. Courier Forschungsintitut Senckenberg 67, 241–246.

Walsh, S.L., 1998. Fossil datum and paleobiological event terms, paleontostratigraphy, chronostratigraphy, and the definition of land mammal "age" boundaries. Journal of Vertebrate Paleontology 18, 150–179.

Walsh, S.L., Gradstein, F.M., Ogg, J.G., 2004. History, philosophy, and application of the Global Stratotype Section and Point (GSSP). Lethaia 37, 201–218. 10.1080/00241160410006500.

Wang Chengyuan, 1996. Conodont evolutionary lineage and zonation for the latest Permian and the earliest Triassic. Permophiles, 30–36.

Wang, X., 2018. Annual report to ICS for 2017-2018. Newsletter on Carboniferous stratigraphy 34, 8–12.

Watson, E.B., Wark, D.A., Thomas, J.B., 2006. Crystallization thermometers for zircon and rutile. Contributions to Mineralogy and Petrology 151, 413–433. 10.1007/s00410-006-0068-5.

Webby, B.D., 1998. Steps towards a global standard for Ordovician stratigraphy.: Webby, B.D., 1998. Steps towards a global standard for Ordovician stratigraphy. Newsletters in Stratigraphy 36, 1-33.

Wolf, Y.I., Katsnelson, M.I., Koonin, E.V., 2018. Physical foundations of biological complexity. Proceedings of the National Academy of Sciences of the United States of America 115, E8678-E8687.

Wrzołek, T., 1992. Rugose corals from the Devonian Kowala Formation of the Holy Cross Mountains. Acta Palaeontologica Polonica 37, 217–254.

Yin, H., Zhang, K., Tong, J., Yang, Z., Wu Shunbao, 2001. The Global Stratotype Section and Point (GSSP) of the Permian-Triassic Boundary. Episodes 24, 102–114.

Yuan, D.-X., Chen, J., Zhang, Y.-C., Zheng, Q.-f., Shen, S.-z., 2015. Changhsingian conodont succession and the end-Permian mass extinction event at the Daijiagou section in Chongqing, Southwest China. Journal of Asian Earth Sciences 105, 234–251. 10.1016/j.jseaes.2015.04.002.

Yuan, D.-X., Shen, S.-z., Henderson, C.M., Chen, J., Zhang, H., Zheng, Q.-f., Wu, H., 2019. Integrative timescale for the Lopingian (Late Permian): A review and update from Shangsi, South China. Earth-Science Reviews 188, 190–209. 10.1016/j.earscirev.2018.11.002.

Zeng, J., Cao, C., Davydov, V.I., Shen, S., 2012. Carbon isotope chemostratigraphy and implications of palaeoclimatic changes during the Cisuralian (Early Permian) in the southern Urals, Russia. Gondwana Research 21, 601–610. 10.1016/j.gr.2011.06.002.

Zhang, L., Orchard, M.J., Algeo, T.J., Chen, Z.-Q., Lyu, Z., Zhao, L., Kaiho, K., Ma, B., Liu, S., 2019. An intercalibrated Triassic conodont succession and carbonate carbon isotope profile, Kamura, Japan. Palaeogeography, Palaeoclimatology, Palaeoecology 519, 65–83. 10.1016/j.palaeo.2017.09.001.

Zinovyev, A., 2015. Overcoming Complexity of Biological Systems: from Data Analysis to Mathematical Modeling. Mathematical modeling of Natural Phenomena 10, 186–205. 10.1051/mmnp/201510314.