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Identifying globally synchronous Permian–Triassic boundary levels in successions in China and Vietnam using Graphic Correlation

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ABSTRACT

Understanding the timing and correlation of significant global events in Earth history is facilitated by the Global Boundary Stratotype Section and Point (GSSP) concept, along with multi-proxy correlation techniques. As an example, the Permian–Triassic boundary (PTB) GSSP is used herein to correlate three PTB successions in east and southeast Asia. The PTB is defined using the First Appearance Datum (FAD) of the conodont *Hindeodus parvus* at the Meishan D section in China. By definition then, Meishan D is the only section on Earth where the FAD of *H. parvus* represents the beginning of the Triassic, at ~251.88 Ma, and thus the end of the Permian. Therefore, when correlating strata in any other section back to the PTB using biostratigraphic data, the local Lowest Observed Occurrence Point (LOOP) of *H. parvus* will probably not equate precisely to the defined FAD GSSP level (the PTB) for the beginning of the Triassic at Meishan D. The Graphic Correlation method, applied to PTB sites in China and Vietnam, is used herein to demonstrate that LOOPs of *H. parvus* in other successions are not equivalent in time to the PTB FAD. The LOOP and Highest Observed Occurrence Point (HOOP) for conodont data at two other successions studied, Huangzhishan in China, and Lung Cam in Vietnam, are used to determine the approximate level where the Triassic begins in these successions, resulting in high-resolution correlation among the sections and correlation back to the PTB GSSP level. It is demonstrated that when critical biostratigraphic data are missing, multiple proxy correlation techniques, geochemical, geophysical and, in some regional instances, unique lithostratigraphic information such as coeval ash beds, can be used to aid in locating the boundary in successions that are not the defining GSSP. LOOP and HOOP data are used to establish a Line of Correlation to differentiate between a defining PTB *H. parvus* FAD versus the *H. parvus* LOOP in secondary successions, and to project the PTB FAD into secondary sections to define the PTB at these localities. In addition, the timing of *H. parvus* arrivals at these sections is used to establish rough dispersal rates and patterns in the region.
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1. Introduction

Global correlation is a difficult problem in deep-time geology, but is critically important if we are to demonstrate that significant events in Earth history, such as large-magnitude extinctions, are either globally synchronous or not, and to determine if such events represent a very short amount of time, or not. To accomplish the correlations among various coeval successions, standards for global comparison are now being clearly established. Global Boundary Stratotype Sections and Points (GSSPs; Cowie, 1986) for all geologic stages have been defined or are in the process of being defined or redefined.

It has generally been agreed by the International Commission on Stratigraphy (ICS) that a GSSP section should be defined based on the First Appearance Datum (FAD) of a certain marine species within that succession. However, the ICS does allow other possibilities to be used, including the Last Appearance Datum (LAD; or Last Occurrence Datum [LOD]) of a species, a magnetic reversal, or a geochemical signal in a well-studied stratigraphic succession (Cowie, 1986; Romane et al., 1996). Today, most GSSPs are defined based on the FAD of some organism, although at a few localities, other criteria have been used, e.g., the carbon isotopic anomaly used to define the Paleocene–Eocene boundary (Aubry et al., 2007; Gradstein et al., 2012), and the LAD (or extinction) of representatives of the foraminifer family Hantkeninidae used to define the Eocene–Oligocene boundary (Silva and Jenkins, 1993; Gradstein et al., 2012).

A problem with the GSSP concept is that at any locality that is not identified as a GSSP, there has been a tendency for some workers to interpret a Lowest Observed Occurrence Point (LOOP) or Highest Observed Occurrence Point (HOOP) of the GSSP marker fossil within other than the GSSP succession, to be coeval with the equivalent GSSP

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FAD, or LAD when used as a GSSP marker event. Therefore, a LOOP (or HOOP) at localities other than the GSSP may improperly be assumed to be coeval with the FAD (or LAD) identified within the GSSP section (e.g., Landing et al., 2013).

A case in point is the important Permian–Triassic boundary (PTB), where the GSSP boundary point defining the beginning of the Triassic has been established by the ICS as the FAD of the conodont *Hindeodus parvus* within a specific geological succession, Section D at Meishan in China (Yin et al., 2001). This unique GSSP locality is the only place on Earth where the FAD of *H. parvus* defines the beginning of the Triassic. If elsewhere the LOOP of *H. parvus* is used to estimate the boundary location, where the arrival of *H. parvus* in secondary successions represents a delayed or earlier occurrence, the LOOP of *H. parvus* will not represent the PTB level in the secondary succession. Unfortunately, as a result the of the misunderstanding of the uniqueness of the GSSP FAD, the PTB is often incorrectly placed at the first occurrence of *H. parvus* in secondary sections (e.g., Nicoll et al., 2002; Krull et al., 2004; Son et al., 2007; Kolar-Jurkovšek et al., 2011; Yan et al., 2013; Zhao et al., 2013; Yin et al., 2014; Xu et al., 2017; and many others). Other serious problems also arise, (a) the boundary-defining fossil/s may not even be found in a studied succession (e.g., Newton et al., 2004; Son et al., 2007; Richoz et al., 2010), (b) the boundary may be based on lithostratigraphy (Heydari and Hassanzadeh, 2003; Son et al., 2007), or (c) the boundary interval may represent a disconformity (Lehrmann et al., 2003; Payne et al., 2007).

1.1. Time versus time stratigraphic nomenclature and the critical need to differentiate between FAD versus LOOP

There is some confusion in the literature that results from abbreviations used to represent the position in a stratigraphic succession where a fossil organism is found. Stratigraphers think in terms of height, position or 'point' in the section where the organism is first observed during sampling, not in terms of specific time. The terms lowest and highest are stratigraphic terms that are independent of time. It is useful within a GSSP, to establish a First Appearance Datum (FAD) to identify the time-stratigraphic fixed point in a succession, as is commonly used to define GSSPs. However, if a lower (earlier in time) occurrence of the marker fossil is found in the GSSP succession, then this new lowest observed point can be differentiated from the defining FAD by using the LOOP to identify this lower occurrence. For this and other reasons, the terms LOOP and HOOP as time independent stratigraphic terms have been introduced (Wardlaw et al., 2015; Nestell et al., 2015).

Stratigraphic boundary successions, where these are condensed, where there is reworking of faunal elements, or where there are various depositional settings, also pose significant problems for interpretation and correlation. Therefore, when correlating to a given GSSP section, it is necessary to use all available information in an attempt to identify the boundary level in all non-GSSP secondary successions. This difficult problem is well-known in stratigraphy; thus, additional tools are needed for correlation, but such tools often relate to other fossils that carry with them the same problems as do the defining fossils, or to geochemical or geophysical indices that may not be well constrained in time.

The Graphic Correlation method is a useful tool often employed to overcome some of these problems in stratigraphy, and for comparing a GSSP succession to individual secondary successions to identify the boundary level in those sections. Graphic Correlation (Shaw, 1964; Mann and Lane, 1995) has been used for many years for the purpose of developing fossil ranges, but herein, Graphic Correlation is applied to PTB boundary successions only for the purpose of identifying specific PTB boundary locations within secondary PTB successions. Other correlation methods have also been used in identifying the PTB in other than the GSSP succession (Brosse et al., 2016).

2. Previous work

It has long been known that time differences exist between the stratigraphic occurrences of the same organism when found at different localities (e.g., Hedberg, 1965). A species originates only at one place and at one point in time. Very simplistically, any new organism must migrate or be dispersed from its source locality to all other locations. This concept is illustrated in Fig. 1, a time-distance cartoon modified from work by Hedberg (1965) and Eicher (1968), and further developed in the recent work of Landing et al. (2013) in their review of Cambrian successions. The point of origin of an organism is labeled as the 'origination point' in Fig. 1. This event occurs at a specific time, Time 1 in Fig. 1, and the new organism then begins to disperse/migrate away from the point of origin. In the example presented, the organism reaches Locality B after traveling for a relatively short period of time, Time 2 (Fig. 1). Millions of years later, a geologist collecting the succession at Locality B, can potentially find the LOOP of the organism at Time 2 within the section. Or, the geologist may miss the actual arrival points due to poor fossil preservation, thus introducing a larger difference in time within the B succession than would be expected from the location of the actual origination point in time (Fig. 1). Dispersal of this organism may eventually take it to localities A, C, D, and E, at Times 4, 3, 5, and 8, respectively, but, as discussed above, the actual arrival points within these successions may be missed in the LOOP reported, when not 'observed' in the section, although the organism may actually have 'appeared' at that locality. Also, because of an unfavorable environmental facies, the organism may seem to disappear from the geological record in the A and B successions at Times 6 and 7, respectively, seemingly representing HOOPs at those times, but then the organism reappears later in these successions at Times 11 and 9, respectively, as 'Lazarus' taxa. These comments assume that each succession is collected at a high enough resolution to resolve LOOPs and HOOPs. Due to an unconformity within successions A and B (Fig. 1), the HOOP for this organism will occur at Times 13 and 14, respectively. Local extinctions will create a HOOP for the organism in successions D and E at Times 12 and 10, respectively. If an estimate for geological time through the time-interval of interest is known, using either numerical dates or time-series analysis, then timing for the LOOPs or HOOPs of this organism can be estimated.

An important question is, if the LOOPs or HOOPs are not coeval at different sites, how can these sites be correlated back to the FAD point in the GSSP section? This establishment of correlation can be difficult. Ideally, once the boundary point has been identified, a signal or proxy that is globally synchronous can be used for correlation. Earth's magnetic field reversals, changes in eustasy, climate cyclicity, or certain atmospherically controlled processes are essentially instantaneous (in a geologic sense), and therefore, global correlation efforts in some instances, can use geochemical or geophysical proxies, provided a method like Graphic Correlation is used that can account for uncertainties in the data. Included as possible proxies are geochemical events that are known to be near-global in character such as the Cretaceous–Paleogene iridium anomaly attributed to a bolide impact at that time (Alvarez et al., 1980), or the carbon isotope (δ^{13}C) anomaly associated with the onset of the Paleocene–Eocene Thermal Maximum (PETM) that is used to define the base of the Ypresian Stage, and thus the base of the Eocene Series (Aubry et al., 2004).

2.1. Permian–Triassic examples

The time interval that includes the latest Permian to earliest Triassic contains massive world-wide extinctions of biota, when more than 95% of terrestrial and marine species went to extinction through this interval (Raup, 1979; Hallam and Wignall, 1997). It is important to correctly identify the boundary in many localities to resolve, with high precision, the succession of events that preceded and succeeded these extinctions. In the case of the latest Permian, extinction affected tabulate and rugose corals, several classes of echinoderms and also some groups of

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