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Quantitative stratigraphy of the Wufeng and Lungmachi black shales and graptolite evolution during and after the Late Ordovician mass extinction

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ABSTRACT

Graptolite-bearing black shales are widely distributed on the Yangtze Platform in South China. Based on 19 sections systematically studied recently, we conducted a quantitative stratigraphic analysis of the graptolite biodiversity change during and after the Late Ordovician mass extinction. The combination of graphic correlation and rarefaction methods make it possible to evaluate the effect of sampling intensity on biodiversity estimates. Graptolite diversity reached its peak in the *Dicellograptus complexus* Chron, and then a gradual decline to the *P. pacificus* Chron. It was followed by a two-step mass extinction, the first and major phase occurred in the *Metabolograptus extraordinarius* Chron, and the second and minor phase in the latest *M. persculptus* Chron. The second phase of the extinction was mostly represented by the elimination of the Diplograptina survivors from the major extinction event, but did not show significant decline in standardized diversity curve. Thereafter, a moderate increase in richness appeared in the early and mid *Parakidograptus acuminatus* Chron, which was followd by a considerable decrease of graptolite richness in the late *P. acuminatus* Chron and early *C. vesiculosus* Chron. The present study also indicates slow and uneven sedimentation rates in the studied sections from mid-Katian to early Rhuddanian, including a relatively slower sedimentation rate during the Hirnantian Epoch. The latter, and the hiatus at the Honghuayuan and Guanwu sections, probably reflect the effects of the Hirnantian glaciation and regional tectonic movements.

1. Introduction

The Late Ordovician mass extinction, the second largest (in terms of species lost) of the five major events in the Phanerozoic, is estimated to have eliminated 86% of species (Jablonski, 1991). Recent studies from South China also indicate that this event eliminated at least 75% of genera of marine animals (Rong et al., 2007). The patterns and processes of mass extinction of graptolites (Chen et al., 2004a, 2005a; Fan and Chen, 2007) have been described based on high-resolution sampling in South China and quantitative biostratigraphic methods. However, there are still several key issues to be addressed, one of which is the effect of sampling intensity on the diversity curves, and the second is the patterns and processes of graptolite recovery from the mass extinction. When we conducted the analyses published in 2005 and 2007 (Chen et al., 2005a; Fan and Chen, 2007), the graptolite fauna in lower Rhuddanian strata in South China had not yet been systematically studied (see p. 84, Fan and Chen, 2007), so we were unable to make meaningful interpretations of graptolite evolution in the early Rhuddanian, even though the curves were already extended into that interval.

In the present paper, we present data from 19 late Katian–Rhuddanian sections from South China as a composite section. The graptolite faunas from late Katian to early Rhuddannian have been systematically studied and described by Chen et al. (2005b) and the present authors, and the recent systematic work by Štorch et al. (2011) and Melchin et al. (2011) is utilized in the present study as well. We also make significant improvements to a program for graphic correlation, SinoCor, so that we can conduct the compositing more efficiently (Fan et al., in review). The new program also provides some useful analytical functions, such as calibrating both the composite and the 19 individual sections to a geochronologic scale, generating a taxonomic richness curve based on the composite or calibrated composite, and creating a fence diagram showing the correlation between the composite and the individual sections. We also design a new method to run rarefaction analysis based on the 19 calibrated sections.

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2. Localities and descriptions

For the present study, we employ a large compilation of ranges of graptolite species and genera based on data from 19 densely sampled sections in the Yangtze region of South China archived in the Geobiodiversity Database (GBDB, http://www.geobiodiversity.com; Fan et al., 2013) (Fig. 1, Table 1).

Shaw proposed the term "species level" to measure the thoroughness of sampling at a section (p. 187, Shaw, 1964), which is equal to the term "species occurrence" used herein. Among the 19 sections, the Honghuayuan section is the section which spans the longest duration in age, and the Wangjiawan North section is the one that contains the most occurrences of graptolite species (Table 1).

All the graptolite samples come from the Wufeng and Lungmachi Formations or contemporaneous sediments. The Wufeng Formation (Fig. 2), mostly comprises black graptolitic shales, and yields an abundant and diverse Katian and early Hirnantian graptolite fauna. In most localities, a thin bed of argillaceous limestone yielding a typical *Hirnantia* Fauna, the Kuanyinchiao Beds (Rong, 1979, 1984), lie conformably on the Wufeng Formation. The black graptolitic shales of the lower part of the Lungmachi Formation, which span the Ordovician and Silurian boundary and may extend into lower Telychian in some localities, lie conformably on the Kuanyinchiao Beds, or disconformably on the Wufeng Formation or overlying strata of earlier age (Fan et al., 2011).

We follow the graptolite biozonation reported by Chen et al. (2000, 2006) and Fan et al. (2011). In ascending order, the graptolite zones are the *Dicellograptus complanatus*, *Dicellograptus complexus*, *Paraorthograptus pacificus* (subdivided into the Lower Subzone, *Tangyagraptus typicus* Subzone and *Diceratograptus mirus* Subzone), *Metabolograptus extraordinarius* (referred to as the *Normalograptus extraordinarius–N. ojsuensis* Zone in Chen et al., 1999, 2000 and *N. extraordinarius* Zone in Chen et al., 2006), *Metabolograptus persculptus* Zone (referred to as the *Normalograptus persculptus* Zone in Chen et al., 2006), *Akidograptus ascensus*, *Parakidograptus acuminatus* and *Cystograptus vesiculosus* zones (Fig. 2).

3. Methodology

3.1. Graphic correlation

It is the geologists' task to make the best use of the fossil range data in the strata and to construct a temporal metric with the most sensitive, precise, and accurate scale attainable (Mann and Lane, 1995). Quantitative biostratigraphic methods provide the methodology to use the order and position of biostratigraphic events in local sections to reconstruct an estimate of their actual original sequence (Agterberg, 1990). There are several quantitative methods presently available, such as Graphic Correlation (such as GraphCor and SinoCor; Hood, 1986 and Fan et al., 2002 respectively), Constrained Optimization (CONOP; Kemple et al., 1995), Ranking and Scaling (RASC; Gradstein et al., 1985, 1999; Agterberg and Gradstein, 1999), Unitary Associations (UAs; Guex, 1991), and Horizon Annealing (HA; Sheets et al., 2012). The graphic correlation method was first described by Shaw (1964), updated by Miller (1977) and Edwards (1984, 1989), and is widely applied in stratigraphic analysis (e.g., Sweet, 1984; Kleffner, 1989; Cooper and Lindholm, 1990; Cooper, 1992; Mann and Lane, 1995; Zhang, 1995; Finney et al., 1996; Sweet and Tolbert, 1997; Benoist, 2000; Chen et al., 2006), the

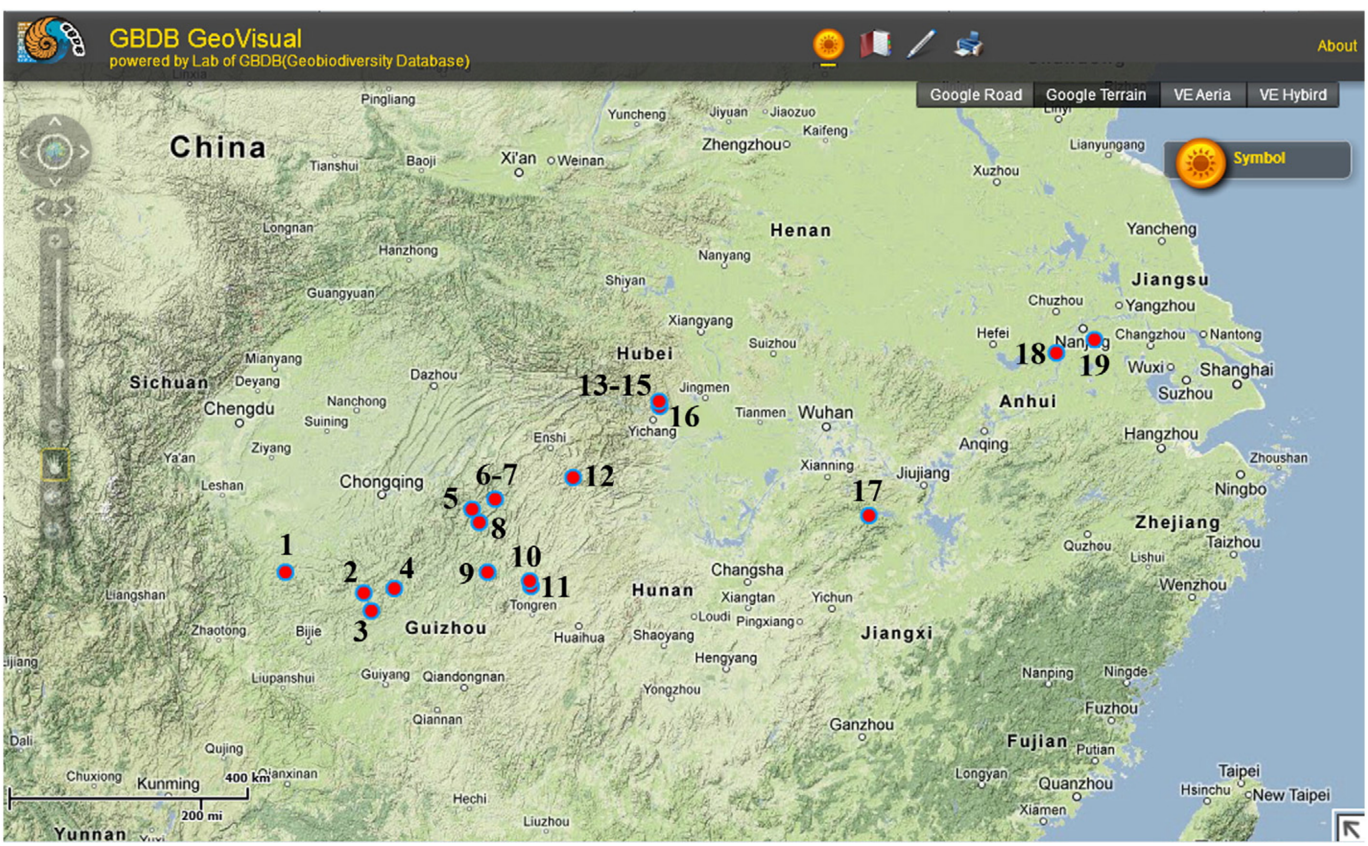

Fig. 1. Geographic map showing the localities. The map was generated through the online function for geographic visualization, GeoVisual 1.0. 1. Qinglongzui, Changning County, Sichuan Province; 2. Bainida–Sanhuai, Xishui County, Guizhou Province; 3. Yangliugou, Renhuai City, Guizhou Province; 4. Honghuayuan, Tongzi County, Guizhou Province; 5. Lanmaxiang South, Qianjiang District, Chongqing Municipality; 6–7. Miaolinwan West and Central, Qianjiang District, Chongqing Municipality; 8. Lujiao, Pengshui County, Chongqing Municipality; 9. Shichang'ao, Yanhe County, Guizhou Province; 10. Fengxiangqiao, Huangfan Township, Guizhou Province; 11. Ludiping, Songtao County, Guizhou Province; 12. Guanwu, Hefeng County, Hubei Province; 13–15. Wangjiawan North, South and Riverside, Yichang City, Hubei Province; 16. Fenxiang, Yichang City, Hubei Province; 17. Guantangyuan, Wuning County, Jiangxi Province; 18. Xiaotan, He County, Anhui Province; 19. Gaojiabian, Jurong County, Jiangsu Province.