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Reconstruction of the mid-Hirnantian palaeotopography in the Upper Yangtze region, South China

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Abstract. Reconstruction of the Hirnantian (Late Ordovician) palaeotopography in South China is important for understanding the distribution pattern of the Hirnantian marine depositional environment. In this study, we reconstructed the Hirnantian palaeotopography in the Upper Yangtze region based on the rankings of the palaeo-water depths, which were inferred according to the lithofacies and biofacies characteristics of the sections. Data from 374 Hirnantian sections were collected and standardized through the online Geobiodiversity Database. The Ordinary Kriging interpolation method in the ArcGIS software was applied to create the continuous surface of the palaeo-water depths, i.e. the Hirnantian palaeotopography. Meanwhile, the line transect analysis was used to further observe the terrain changes along two given directions.

The reconstructed palaeotopographic map shows a relatively flat and shallow epicontinental sea with three local depressions and a submarine high on the Upper Yangtze region during the Hirnantian. The water depth is mostly less than 60 m and the Yangtze Sea gradually deepens towards the north.

Key words: palaeotopography, palaeo-water depth, Hirnantian, Upper Yangtze region, South China, ArcGIS.

INTRODUCTION

The Hirnantian is an important geological time interval in the Late Ordovician, which recorded the end-Ordovician continental glaciation and mass extinction (Sheehan 2001; Saltzman & Young 2005; Finnegan et al. 2011; Melchin et al. 2013). The Hirnantian sediments are widely distributed and well preserved in South China, which has become one of the key study regions about the Hirnantian geological and biological events. Many aspects of the Hirnantian strata and fossils in South China have been studied for many decades, including dominant graptolite and brachiopod faunas (Rong 1979; Rong et al. 2002; Chen et al. 2005a; Zhan et al. 2010), the end-Ordovician mass extinction event (Chen et al. 2005b), stratigraphic classifications and correlations (Chen et al. 2000, 2006; Rong et al. 2010), geochemistry (Fan et al. 2009; Zhang et al. 2009; Gorjan et al. 2012), palaeogeography (Mu et al. 1981; Chen et al. 2004; Rong et al. 2011), etc. These previous studies provide a solid foundation and good opportunity to examine the palaeo-water depths and palaeotopographic characteristics in South China during the Hirnantian. Rong & Chen (1987) have briefly reconstructed the facies pattern of the time when the Kuanyinchiao Beds were deposited (basically equal to the mid-Hirnantian) based on the brachiopod assemblages in the form of hand-sketching. In the present study, based on a big collection of the Hirnantian sections, we use the ArcGIS software to reconstruct the mid-Hirnantian palaeotopography of South China in a quantitative and three-dimensional way. It is the first time to reconstruct the Hirnantian marine terrains in South China, which can be used in subsequent analysis such as predicting the palaeo-water depth in unknown regions and their biofacies and lithofacies characteristics, and inferring the patterns of ocean currents in the study area.

In this study, data of 374 Hirnantian sections of the Upper Yangtze region were collected through the Geobiodiversity Database (GBDB, http://www.geobiodiversity.com; Fan et al. 2013). The palaeo-water depths of those sections were ranked according to the lithofacies and biofacies characteristics. Using the ArcGIS software, we created the continuous surface of the mid-Hirnantian palaeotopography in the Upper Yangtze region and then examined its spatial patterns and the characteristics of terrain changes.

DATA AND METHODS

Study region and time interval

The Upper Yangtze region of the South China Palaeoplate was chosen as the study region. It mainly includes the eastern Sichuan, northern Guizhou, Hubei and northwestern Hunan provinces and Chongqing Municipality. The mid-Hirnantian, particularly the time interval in which the sediments of the Kuanyinchiao Beds were deposited, was selected as the study time interval. The strata and fossils of the Upper Yangtze region in this time interval have been intensively studied for decades and provide the necessary data and comprehensive background knowledge for our palaeotopographic reconstruction.

In the mid-Hirnantian, the Upper Yangtze region was covered with several different lithostratigraphic units (Fig. 1). The Kuanyinchiao Beds, mainly grey limestones or mudstones, are widely distributed over most of the Upper Yangtze region (area A in Fig. 2), and yield abundant benthic shelly fauna, including brachiopods (*Hirnantia* fauna, Rong 1979) and trilobites. In the southwestern Shaanxi Province, the Nanzheng Formation is composed of mudstones, siltstones and interbedded limestones, and yields graptolites and benthic shelly fossils (area B in Fig. 2, Li & Cheng 1988). In the southeastern Sichuan Province, the upper parts of the Tiezufeike and Daduhe formations (area C in Fig. 2, Mu et al. 1979, 1993; Hu 1980) consist of black shales/silty shales and thin-bedded limestones. At the bordering area between the Hunan and Guangxi provinces, the strata assigned to the mid-Hirnantian are parts of the Tianmashan and Tianlingkou formations (area D in Fig. 2, Chen et al. 1981, 2014; Liu & Fu 1984), which are composed of sandstones, siltstones and slates with some graptolites; these strata gradually changed to black shales towards the north (central Hunan Province).

Data set

Based on the analysis of rock composition, texture, structure and fossil characteristics, we ranked the water depths of each deposition area of the Upper Yangtze region (see Table 1).

A total of 374 sections were examined to reconstruct the palaeotopography. All the section data were collected from the GBDB online database. Then each section was assigned a rank value of palaeo-water depth according to the scheme in Table 1.

Palaeotopographic reconstruction

Although some ranks of water depth haven been assigned an estimated water depth (such as 10–30 m for Rank IV, see note for Table 1), the precision of the estimation is quite limited. For this reason, we used the ranks of water depth, instead of the water-depth values, to reconstruct the palaeotopography of the Upper Yangtze region. The palaeotopographic maps (Figs 2, 3) were created based on the ranks of palaeo-water depths by using the interpolation tools in ArcGIS 10. After comparing all the interpolation methods in the ArcGIS software, the Ordinary Kriging method in the Spatial Analyst tools was adopted for reconstructing the palaeotopography. Parameter settings are as follows: Kriging

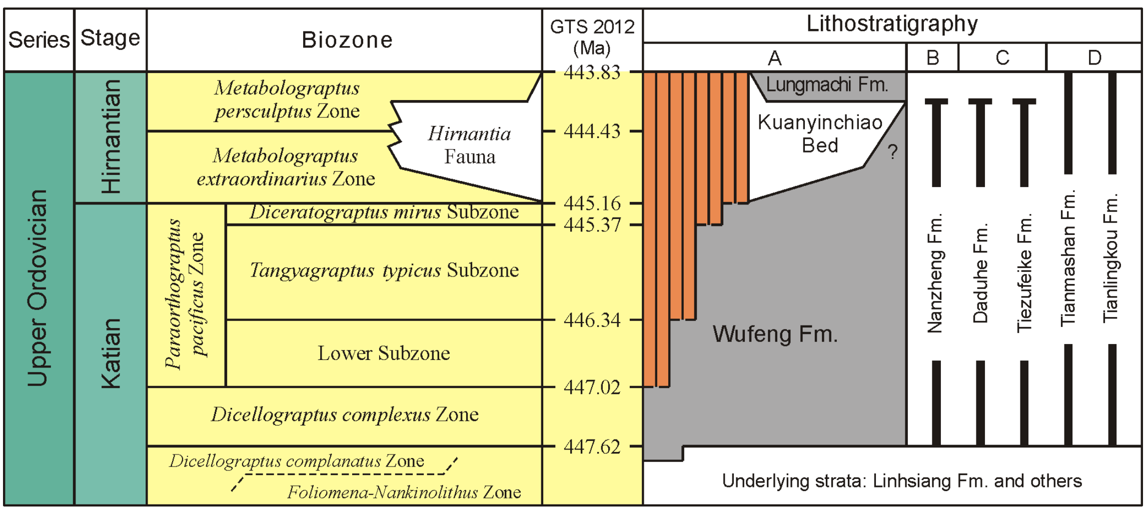

Fig. 1. Katian–Hirnantian lithostratigraphy and biozonation in the Upper Yangtze region (modified from Zhang et al. 2014). GTS 2012, The Geologic Time Scale 2012 (see the Ordovician chapter by Cooper & Sadler 2012).

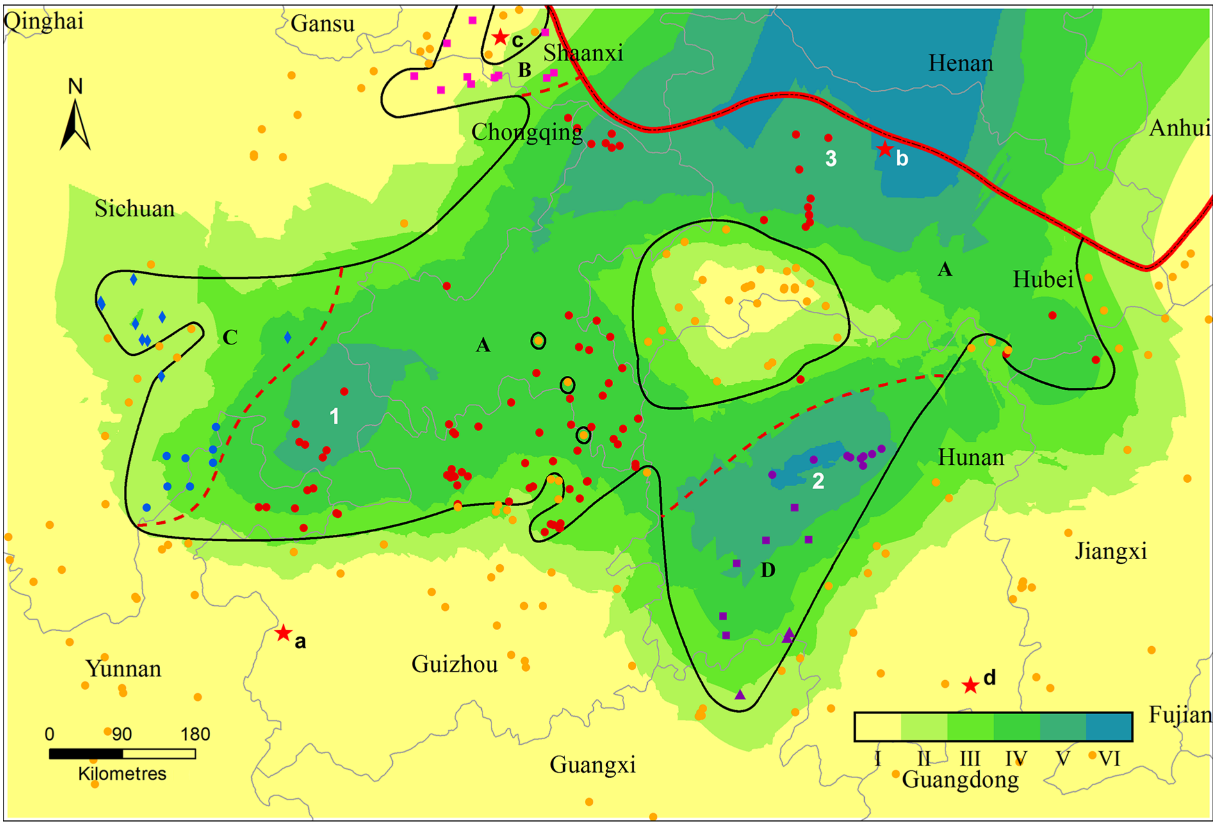

Fig. 2. Reconstructed palaeotopography of the Upper Yangtze region in the Hirnantian. Different colours indicate different ranks of water depths. The red solid line indicates the northern boundary of the South China Palaeoplate; black lines indicate the palaeo-coastlines and the outlines of the submarine highs; red dashed lines indicate the boundaries of different sedimentary facies. The dots are section locations: yellow dots indicate the localities without Hirnantian sediments; red dots indicate the localities deposited with the Kuanyinchiao Beds; ginger pink rectangles indicate the localities deposited with the Nanzheng Formation; blue diamonds indicate the localities deposited with the Daduhe Formation; blue dots indicate the localities deposited with the Tiezufeike Formation; purple rectangles indicate the localities deposited with the Tianmashan Formation; purple triangles indicate the localities deposited with the Tianlingkou Formation; purple dots indicate the localities deposited with black shales. Stars a, b, c and d represent the end points of the two transects in Fig. 4. The palaeo-coastlines and the outlines of the submarine highs are constrained by drawing lines to separate the sections with or without the Hirnantian sediments. The contour map was created by interpolating the water-depth ranks, which is likely affected by the quantity and distribution of the sections data. So, those lines and the boundaries in the contour map may not entirely fit each other in some regions with fewer data.

method is ‘Ordinary Kriging’, Output cell size is ‘2000’, Number of points of the search radius settings is ‘15’, and the other parameters are set as the default.

Based on the reconstructed palaeotopography, the line transect analysis was adopted to create two topographic profile graphs (Fig. 4), one from Point a to Point b and the other from Point c to Point d (Fig. 2), to observe the terrain changes along these two directions.

RESULTS AND DISCUSSIONS

Based on the reconstructed contour map (Fig. 2) and 3D stereogram (Fig. 3), we can see that, during the mid-Hirnantian, the Yangtze Sea mainly covered the area of the southeastern Sichuan, northern Guizhou, north-western Hunan and Hubei provinces, and the Chongqing Municipality in the Upper Yangtze region. The water depth did not exceed Rank V in most parts of the Yangtze Sea, which means that the water depth of the Yangtze Sea is mostly less than 60 m. On the whole, the Yangtze Sea gradually deepened towards the north. In the northern Hubei Province, the water depth reached the deepest rank, which may imply an open-sea environment. However, this is still uncertain because detailed stratigraphic records of the Hirnantian Stage near the northern margin of the South China Palaeoplate are lacking. It is notable that the main part of the Upper Yangtze region appears to be covered by a relatively flat and shallow epicontinental sea, which provided the

Table 1. Ranks of water depths of different facies

Area	Rank of water depth
Bordering area without coeval strata of the Kuanyinchiao Beds	I
Submarine high: area without deposition of the Kuanyinchaio Beds and the underlying *Paraorthograptus pacificus* and *Metabolograptus extraordinarius* zones of the Wufeng Formation	II
Submarine high: area without deposition of the Kuanyinchaio Beds and the underlying *M. extraordinarius* Zone of the Wufeng Formation	III
Area with deposition of the Kuanyinchiao Beds yielding shallow-water *Hirnantia* fauna	IV
Area with deposition of the Kuanyinchiao Beds yielding deeper-water *Hirnantia* fauna	V
Area with deposition of continuous black shales	VI
Area with deposition of the Tianmashan or Tianlingkou formations	IV–VI
Area with deposition of the Daduhe or Tiezufeike formations	III–IV
Area with deposition of the Nanzheng Formation	III–IV

Note: Rank I represents the oldland; from Rank II to VI, the water depth increases orderly. The areas of Rank II and Rank III have no depositions of the Kuanyinchiao Beds. However, there is no evidence of exposure weathering between overlying and underlying strata, so it is supposed to be a submarine gap (Chen et al. 2004), which means that Ranks II and III are deeper than Rank I, but shallower than Rank IV. The shallow-water *Hirnantia* fauna in the area of Rank IV is assigned to BA2, which indicates a water depth of 10–30 m (Rong et al. 1984; Rong 1986). The deeper-water *Hirnantia* fauna in Rank V is assigned to BA3, which indicates a water depth of 30–60 m (Rong et al. 1984; Rong 1986). The areas of Rank VI are deposited with continuous black shales (Bureau of Geology and Mineral Resources of Hunan Province 1988), which indicate a deeper-water environment.

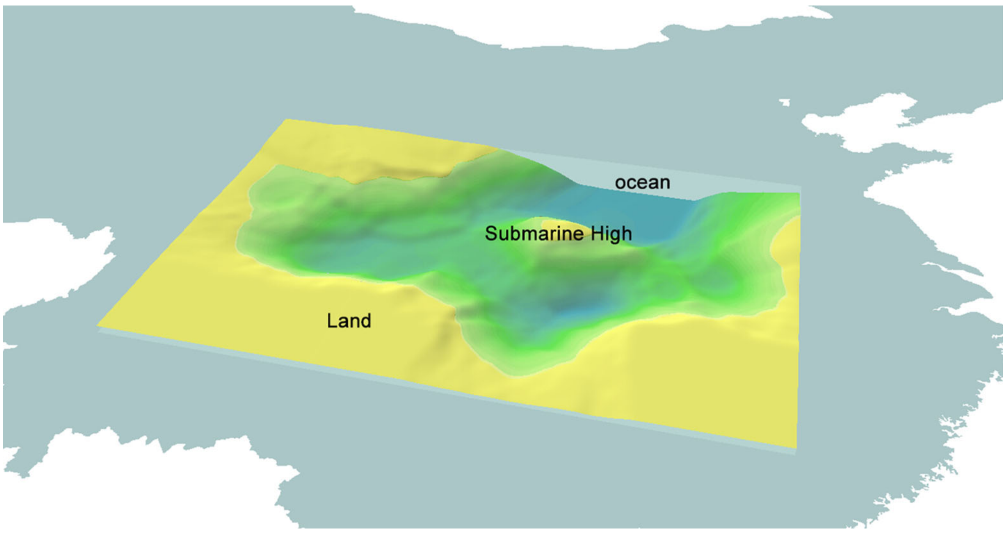

Fig. 3. 3D palaeotopography of the Upper Yangtze region during the Hirnantian. Note that the vertical scale is stretched out to show more details of the topographic profile.

palaeogeographic setting for the deposition of the very thin Kuanyinchiao Beds with the widely distributed *Hirnantia* shelly fauna. The Hunan–Hubei Submarine High (Chen et al. 2004), reached its biggest coverage at that time, partly due to the concentration of continental glaciation around the South Pole (Fan et al. 2011). Meanwhile, three local depressions occurred in the southeastern corner of the Sichuan Province and southern Chongqing Municipality (Area 1 in Fig. 2), mid-western Hunan Province (Area 2 in Fig. 2) and the area north of the Hunan–Hubei Submarine High (Area 3 in Fig. 2).

From the two topographic profile graphs (Fig. 4), we investigated the lateral changes in palaeo-water depths. It is easy to see the terrain changes from Zunyi City to Yichang City (in the northeast) and from Anhua County to Xixiang County (in the north-northwest). It is clear that Zunyi City, Yanhe County, Yichang City, Anhua County and Chengkou County were relatively low-lying

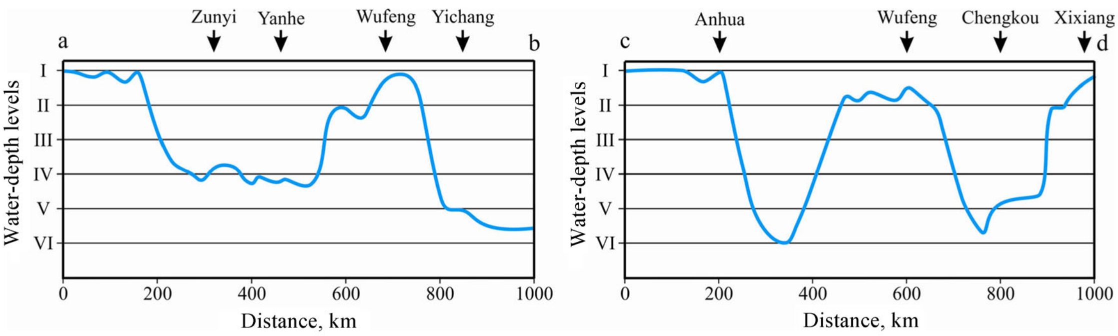

Fig. 4. Topographic profile graphs along two directions (Point a–b and Point c–d in Fig. 2) created using the line transect method. The arrows indicate the positions of cities. Note that the vertical scale is stretched out to show more details of the topographic profile.

regions in the Hirnantian, while Wufeng County and Xixiang County were high regions. From Point a to Point b, a local depression shows first, then the Hunan–Hubei Submarine High and finally an open-sea environment. From Point c to Point d, a deeper local depression shows, then the Submarine High and a depression, and finally an oldland. From these graphs, we can see that the rank of water depth of Point b is V–VI, which means the depth is deeper than 60 m. If we assume that the water depth of Point b is 70 m, we can estimate the average slope of the sea floor of the Upper Yangtze Sea by dividing the differences of the water depth between Point a and Point b by the distance between them. The average slope is 0.004°. Although there existed a submarine high at the bordering area of Hunan and Hubei (Figs 3, 4), the average slope of the Upper Yangtze region is obviously smaller than that of the modern continental shelf, which indicates a relatively flat terrain of the Upper Yangtze region. However, the areas in the Upper Yangtze region in different water depths yielded different biotic communities and rock types. If we take the rock fold into account, the distance between points a and b will be larger and the slope between them will become smaller, which means the Yangtze Sea will be more flat.

CONCLUSIONS

The online stratigraphic and palaeontological database provides the opportunity for palaeotopographic reconstrunction. In this paper, we estimated the water-depth ranks of 374 sections during the Hirnantian based on their lithofacies and biofacies and reconstructed 2D and 3D palaeotopographic maps using tools in the ArcGIS software.

The reconstructed topographic maps indicated that the Upper Yangtze region was a semi-closed, shallow epicontinental sea during the Hirnantian. It consisted of a small uplift (Hunan–Hubei Submarine High) and several local depressions. The Yangtze Sea gradually deepened towards the north and its water depth is mostly less than 60 m, showing a very gentle slope of the sea floor.

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