A refined late-Cryogenian – Ediacaran Earth history of South China: phosphorous-rich marbles of the Dabie and Sulu orogens

[1]Prave, A.R., [2]Meng, F., [3,4,5,6]Lepland, A., [5]Kirsmäe, K., [5]Kreitsmann, T., and [7]Jiang, C.Z.

[1]School of Earth and Environmental Sciences, University of St Andrews, St Andrews KY16 9AL Scotland/UK
[2]Nanjing Institute of Geology, Paleontology and Stratigraphy, 39 Beijing E Rd, Xuanwu Qu, Nanjing Shi, Jiangsu Sheng, China
[3]Geological Survey of Norway, 7491 Trondheim, Norway
[4]Centre for Arctic Gas Hydrate, Environment and Climate, University of Tromsø, 9037 Tromsø, Norway
[5]University of Tartu, Department of Geology, 50411 Tartu, Estonia
[6]Tallinn University of Technology, Institute of Geology, 19086 Tallinn, Estonia
[7]Department of Earth Sciences, Oxford University, South Park Road, Oxford OX1 3AN, UK

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Abstract

The late-Cryogenian – Ediacaran geological framework for South China is constructed principally from sedimentary successions preserved in the central and western regions of the Yangtze Block. New stratigraphic and carbonate-carbon isotope data allow us to extend that framework into the exhumed HP-UHP subduction complexes of the eastern Dabie and Sulu orogens that separate the South and North China cratons. Those data show that marble and phosphorous-rich (P-rich) units in those complexes were originally part of an Ediacaran shallow-marine shelf-carbonate platform. The basal pebbly schist (metadiamictite) and lowermost P-rich marble of the Jinping Formation (Haizhou Group) in the Sulu Orogen matches in both facies character and C-isotope profile that of the Marinoan-equivalent glacial-cap carbonate couplet of the Nantuo and Doushantuo formations. The Daxinwu Formation (Susong Group) in the eastern Dabie Orogen contains a marble unit that has, for several hundreds of metres, a strikingly uniform C-isotope profile of low $\delta^{13}C$ positive values and is overlain by a P-rich graphitic schist; these features match those of the late Ediacaran to early Cambrian Dengying Formation. These correlations establish that the HP-UHP metasedimentary rocks, many of which were once considered to be Palaeo- to Mesoproterozoic in age, are a Neoproterozoic-age cover sequence of the continental margin

of the Yangtze Block. Further, their widespread development limits their utility as indicators of offset across the Tan-Lu fault zone and, instead, favours tectonic models that interpret that feature as a continental-scale tear fault formed during the Mesozoic collision and suturing of the North and South China cratons.

Introduction

The South China region contains two iconic geological features. The first is a Neoproterozoic succession that archives the evolution of metazoa and the climatic extremes of Snowball Earth (e.g. Jiang et al. 2007; Xiao et al. 1998; Xiao 2004; Zhou et al. 2001; Zhou and Xiao 2007; Zhu et al. 2007, 2013). The second is an exhumed subduction complex, the Triassic-age high to ultra-high pressure (HP-UHP) Qinling-Dabie-Sulu orogen (e.g. Faure et al. 2001; Hacker et al. 1998; Xu et al. 2006; Zheng et al. 2005). Both features contain phosphorous-rich (P-rich) rocks; those in the former occur as phosphorites and have been studied extensively (e.g. She et al. 2013; Muscente et al. 2015; Cui et al. 2016) whereas those in the latter occur as apatite-rich units and are far less understood, as evident by the uncertainty in assigning their depositional age with estimates initially ranging from Palaeo- to Mesoproterozoic and now considered to be late Neoproterozoic (Longkang 1991; Pirajno 2013; Yang et al. 1986; see discussion by Xu et al. 2012).

Our interest was to refine understanding of the geology of the P-rich rocks and their associated marbles in two supracrustal successions in the Sulu and Dabie orogens, the Haizhou and Susong groups, respectively. These two units have figured prominently in efforts to construct the stratigraphic frameworks that link the sedimentary successions of the Yangtze Block to the metasedimentary rocks in the HP-UHP orogens (e.g. Wu et al. 2007; Xu et al. 2012) and in tectonic models to explain the Tan-Lu fault zone (e.g. Zhao et al. 2016, and references therein), the c. 700 km-long fault zone that separates the HP-UHP complexes from the sedimentary interior of the Yangtze Block (Fig. 1A-C). Here we report new stratigraphic and carbonate-carbon isotope data that are pertinent in assessing the Precambrian geological evolution proposed for South China. Our findings enable us to correlate the occurrences of the HP-UHP subduction complex marbles and associated P-rich rocks in the eastern Dabie and southern Sulu orogens to the late-Cryogenian – Ediacaran succession in the central and western parts of the Yangtze Block, and show that the marbles and P-rich rocks were originally part of an extensive carbonate shelf-platform that fringed the South China craton.

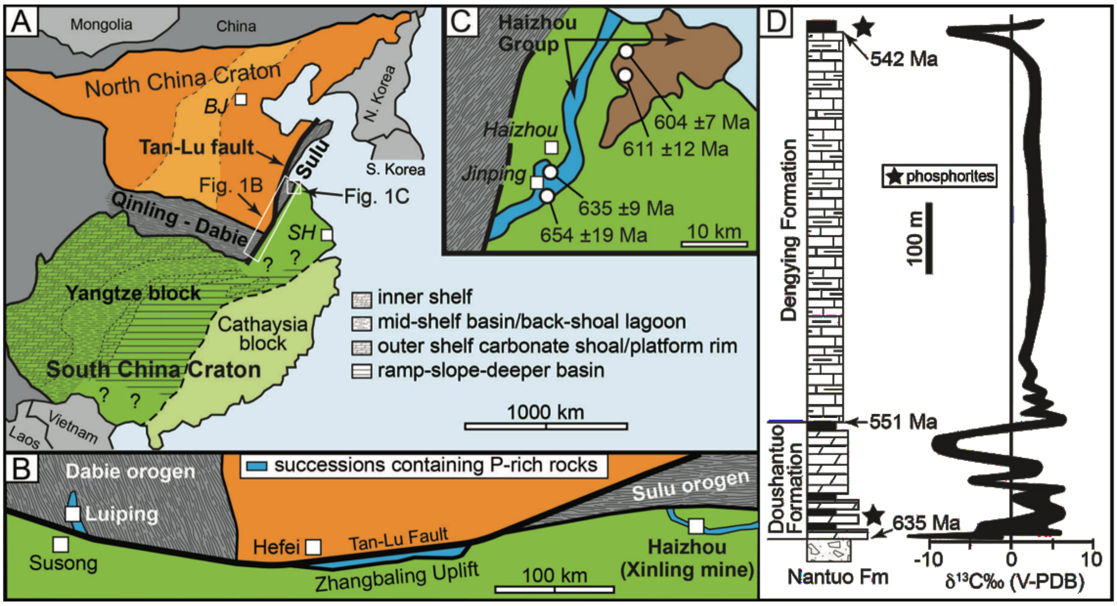

Figure 1. A. Tectonic components of the South China craton and location of the Qinling-Dabie-Sulu orogenic belts. BJ-Beijing, SH-Shanghai. **B.** Distribution of successions containing P-rich rocks adjacent to the Tan-Lu fault zone (from Longkang 1991). **C.** Simplified rock-distribution map of the Haizhou-Jinping area with location of U-Pb detrital zircon ages obtained by Zhou et al. (2012). **D.** Generalised Ediacaran stratigraphy of the Yangtze Block; C-isotope trend is based on many sources (see text for citations). Age constraints for the Doushantuo Formation are from Condon et al. (2005) and for the Dengying Formation from Chen et al. (2015).

Background

The South China craton was formed by the tectonic welding of the Yangtze and Cathasia blocks during the Tonian Jiangnan (or Sibao) orogeny (e.g. Cawood et al. 2017), although the exact nature of this suturing remains a subject of debate (e.g. Charvet 2013; see discussions in Yang et al. 2016 and Wang et al. 2014). Subsequent to that suturing, during the late Neoproterozoic, the Yangtze Block became an extensive shallow-marine carbonate platform-slope-basin (Fig. 1A), particularly well studied and represented by the Marinoan-equivalent Nantuo Formation glacial diamictite, its cap carbonate sequence, the Doushantuo Formation, and the overlying Dengying Formation (Fig. 1D; Cui et al. 2016; Han et al. 2015; Jiang et al. 2003, 2007, 2008, 2011; Li et al. 2013; Li et al. 2017; Ling et al. 2007; Lu et al. 2013; Muscente et al. 2015; Sato et al. 2016; Tahato et al. 2013; Wang et al. 2016; Xiao et al. 2014; Zhou and Xiao 2007; Zhou et al. 2001; Zhu et al. 2007, 2013). Those units also contain numerous ash beds and dating of those tuffs by U-Pb geochronology on zircon provides some of finest absolute age constraints for any late-Cryogenian – Ediacaran succession worldwide: the glacigenic Nantuo Formation is bracketed between 655 and 635 Ma in age (Condon et al. 2005; Zhang et al. 2005, 2008; Zhou et al. 2004), the basal Doushantuo Formation is 635 Ma in age (Condon et al. 2005), the contact between the Doushantuo and Dengying formations is 551 Ma in age (Condon et al. 2005), and the top of the Dengying Formation is near the Precambrian-Cambrian boundary at 542 Ma in age (Chen et al. 2015). Further, two stratigraphic intervals contain some of the best-developed and -preserved Ediacaran fossils and phosphorites: one is within the fossiliferous shelf-platform sections of the Doushantuo Formation and the other is the top of the Dengying Formation (Cui et al. 2016; Jiang et al. 2007; Li et al. 2013; Muscente et al. 2015; She et al. 2013; Xiao and Knoll 1999; Xiao et al. 1998; Zhou et al. 2001, 2007; Zhu et al. 2013).

Our work provides insight into extending and refining understanding of the Ediacaran geology of the Yangtze Block, from the well-studied areas concentrated in its central and west-central regions, into the Dabie and Sulu orogens. Those orogens formed during the early Mesozoic when the margin of the South China craton was subducted beneath the North China craton; the subduction complexes were subsequently exhumed to form the HP-UHP eclogitic-blueschist rocks of the Qinling-Dabie-Sulu orogens (e.g. Cawood et al. 2017; Chen et al. 2016; Xu et al. 2006; Zheng et al. 2005). In places, those rocks have microdiamonds and coesite, indicating peak metamorphic conditions as high as 2.5 GPa and 850º C that were reached at 240-220 Ma (e.g. Gao et al. 2011; Chen et al. 2016). In both the Dabie and Sulu orogens, successively lower-grade rocks occur in fault-bound slices outward from (i.e.

towards the non-subducted part of the Yangtze Block) the UHP rocks: the Susong Group in the Dabie Orogen and the Haizhou Group in the Sulu Orogen, and their correlatives, are two such examples. In many places, the exhumed HP-UHP complexes and areas adjacent to those are intruded by Mesozoic granitoids and overlain unconformably by Jurassic siliciclastic and Cretaceous volcaniclastic strata (e.g. Liu et al., 2011; Wang et al. 2017; Zheng et al. 2005). Thus, determining the age and provenance of the original protoliths of the rocks comprising those orogenic belts requires seeing through a Mesozoic tectonothermal overprint.

Methods

Standard sampling, mapping and section measuring techniques were employed to study the Haizhou and Susong group rocks in the field in their type areas. A total of 74 carbonate rock samples were collected for C-O stable isotope analyses. In that the rocks have experienced varied degrees of metamorphism, from lower blueschist facies for the Susong Group to upper greenschist-lower amphibolite facies for the Haizhou Group (based on our own observations and consistent with the published literature, see below), care was taken to sample rocks that were free of visible fractures, alteration zones and/or coarser spar textures.

Stable isotope analyses of $\delta^{18}O$ and $\delta^{13}C$ in calcite and dolomite were undertaken in the Stable Isotope Lab of the State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute for Geology, Paleontology and Stratigraphy (NIGPAS), Nanjing, China, and at the University of Tartu, Tartu, Estonia; the analyses were done independently using aliquots split from the same sample (see Table 1). Samples analysed at NIGPAS were first cut in half and cleaned and then microdrilled to obtain 0.03 mg of powder. These aliquots were then reacted and analysed using a Kiel IV Carbonate Device connected to a Thermo Fisher MAT-253. In Tartu University, stable isotope ratios were measured in micro-drilled powdered samples on a Thermo Scientific Delta V Advantage continuous flow isotope ratio mass spectrometer with precision (2σ) of 0.1‰. Reproducibility in both labs was better than ±0.1‰ for $\delta^{18}O$ and ±0.1‰ for $\delta^{13}C$. The results of carbonate mineral analyses are expressed in *per* *mil* deviation relative to the Vienna PeeDee Belemnite (VPDB) scale for oxygen and carbon. The δ^{18}O values are corrected for phosphoric acid fractionation factor for calcite and dolomite (Rosenbaum and Sheppard 1986).

Carbonate C-O isotope and XRD data

Results for both sample sets, and their geological implications, are discussed separately in the sections that follow. In brief, carbonate-carbon and -oxygen isotope plots and cross-plots (Fig. 2A-C) show that the Xinling Mine section (Jinping Formation, Haizhou Group, Sulu Orogen: mine entrance at 34.6417° 119.1725°) and the Luiping section (Daxinwu Formation, Susong Group, Dabie Orogen: base of section at 30.3416° 115.9458°) have distinctive and non-overlapping C-O isotope compositions. Further, the carbonate-carbon and -oxygen isotope data do not exhibit covariance (Fig. 2C). We use these two analytical findings to infer that the carbonate-C isotope compositions for both the Xinling Mine and Luiping sections record mostly original depositional values, as is typical for carbonate rocks that are usually well buffered against significant post-depositional modifications of their C-isotope composition. We interpret the low values for the oxygen isotopes of the Xinling Mine section (average

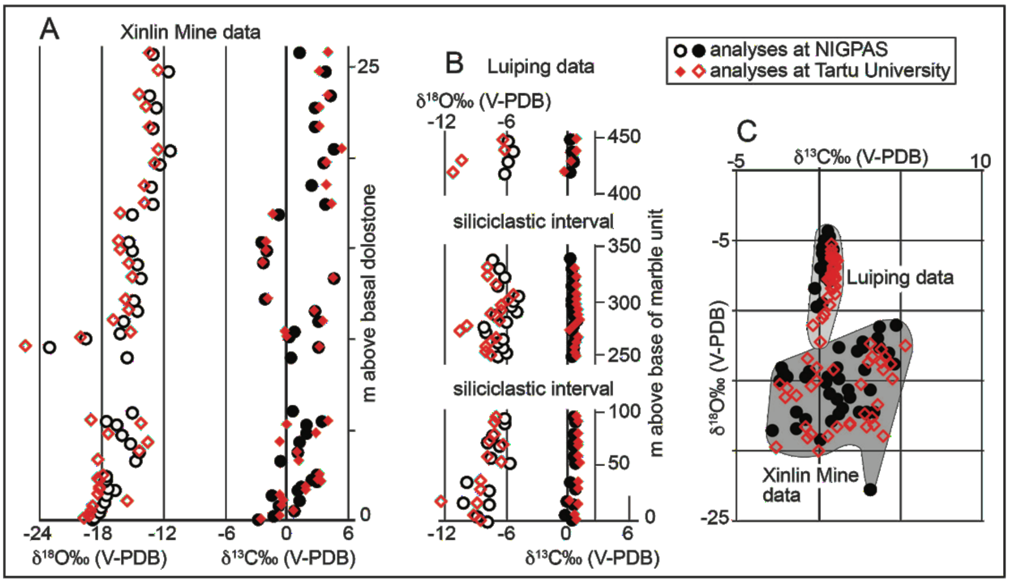

Figure 2. Cross-plot of C-O isotope data for the Jinping Formation (Haizhou Group) in the underground Xinling Mine section (39 samples) and the Daxinwu Formation (Susong Group) in the Luiping section (35 samples). NIGPAS-Nanjing Institute of Geology, Paleontology and Stratigraphy, Nanjing, China. Isotope data were obtained on split aliquots of the same sample that were analysed independently at NIGPAS and Tartu University, Tartu, Estonia.

$\delta^{18}O$ V-PDB of -16.3‰ and -17.2‰ from analyses at NIGPAS and Tartu University, respectively) to be a consequence of resetting of their depositional values during upper-greenschist to lower-amphibolite facies metamorphism associated with the Sulu orogeny. The lower oxygen isotope values of the Luiping section (average $\delta^{18}O$ V-PDB of -7.8‰ and -9.0‰ from analyses at NIGPAS and Tartu University, respectively) may archive original depositional values but most likely reflect lesser resetting (relative to the Haizhou Group) during the blueschist facies metamorphism experienced by this part of the Dabie Orogen.

The 74 samples were also analysed by X-ray diffractometry (XRD) at Tartu University (Table 2). Samples were pulverised by hand in an agate mortar, and unoriented preparations were made in standard steel sample holders. The preparations were scanned on a Bruker D8 Advance diffractometer using a Johannson-type Vario 1 focussing primary monochromator filtered Cu$K\alpha_1$ radiation and LynxEye positive sensitive detector in 2–70° 2 Θ range with step size 0.015° and counting time 1 s per step. The mineralogical composition of the samples was interpreted and modelled using the Rietveld algorithm-based code Topaz. The relative error of quantification is better than 10% for major phases (>5 wt%) and better than 20% for minor phases (<5 wt%).

The XRD analyses reveal two main P-rich intervals in the Xinling Mine section: one from 2-11 m above the base of the lower marble unit, in which apatite varies from 5-70 wt.%, and another at 17-26 m above the base with apatite varying between 8-50 wt.%. Further, 0.1-5 wt.% gypsum occurs from 1-3 m above the base and 0.5-10 wt.% barite from 3-17 m. The XRD analyses also confirm the observations made on the carbonate rocks whilst logging the section in the underground Xinling Mine: the basal 2-3 m and upper 15 m of the section are dominated by dolomitic marble with the intervening interval characterised by interlayered calcitic and dolomitic marbles. For the Daxinwu Formation in the Luiping section, XRD analyses confirm that the marbles are dolomitic.

Sulu Orogen, Xinling Mine section: Jinping Formation of the Haizhou Group

The Haizhou Group occurs discontinuously along the southern margin of the HP-UHP zone of the Sulu Orogen (Fig. 1C). It is at least several kilometres thick and garnetiferous amphibolites are indicative of upper greenschist to lower amphibolite facies metamorphism, consistent with the documentation of the adjacent blueschist facies rocks of the Sulu orogen (phengite, glaucophane and jadeite with P-T estimates of 0.7-0.85 GPa and 350º-450° C) that were retrogressed to upper greenschist facies during the late Triassic (Qiu et al. 2003; Wang et al. 2017; Xu et al. 2006). Whilst mapping the eponymous type area of the Hiazhou Group, Longkang (1991) identified four units (Fig. 3A): (i) migmatised granitoid and felsic orthogneiss; (ii) a discontinuously developed pebbly schist from 1-10 m in thickness that overlies unconformably the gneissic rocks; (iii) a unit of marble, P-rich marble and graphitic-pelitic schist; and (iv) interlayered quartz-albitic and amphibolitic schists. The first two metasedimentary units comprise the Jinping Formation and the third defines the Yuntai Formation (Zhou et al. 2012), which is in fault contact with the Jinping Formation and thought to represent a metamorphosed bimodal volcanic sequence (Longkang 1999).

Deep weathering, thick vegetation and the extensive conurbations of Haizhou and Jinping restrict obtaining detailed field-based observations but we were granted permission to examine and sample along an adit several hundreds of metres below the surface in the underground Xinling phosphate mine that afforded access to a continuous section of the lower part of the Jinping Formation, from its contact with the orthogneiss through 30 m of its lowermost P-rich marble unit (Fig. 3B,C). In the adit, the base of the pebbly schist can be observed to be welded to the underlying granitic gneiss along an irregularly scalloped erosional surface (Fig. 4A). The pebbly schist is 15 m thick with clasts of gneiss, quartzite and rarer fine-grained siliciclastic (meta)sedimentary rocks that are dispersed widely through the matrix and commonly flattened by tectonic strain. Above this is 7 m of clast-poor graphitic-psammitic-pelitic schist and then, a sharp contact (Fig. 4B) with the lowermost P-

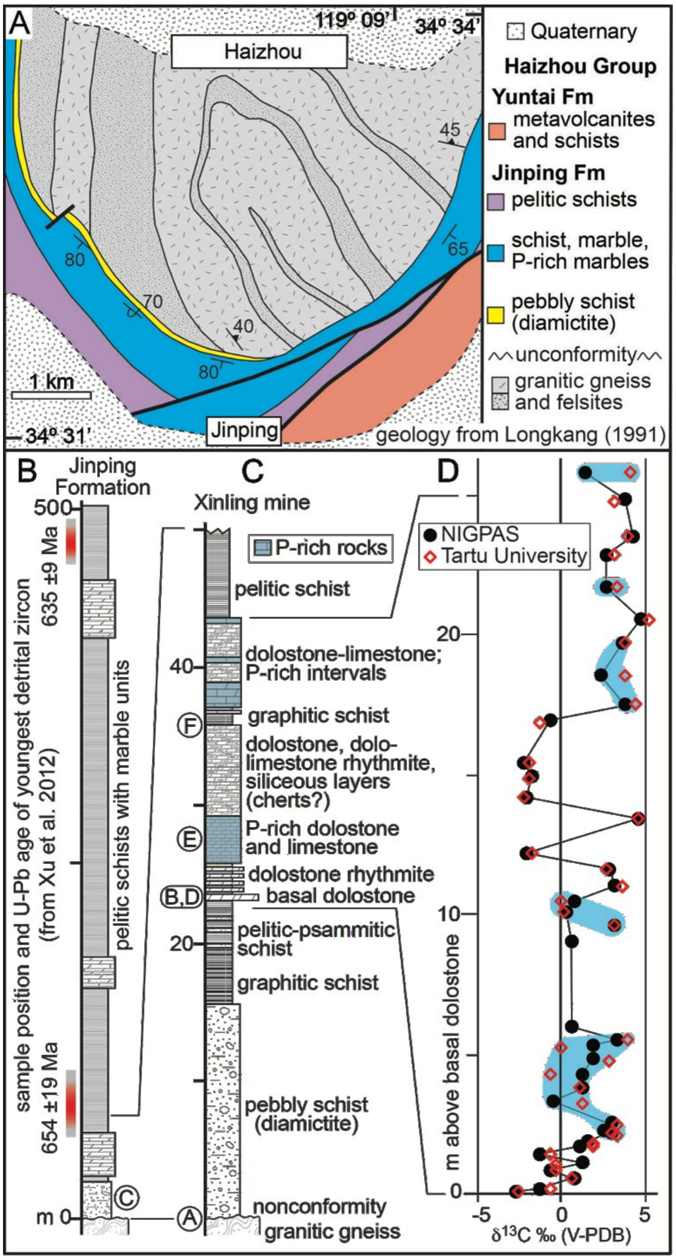

Figure 3. A. Simplified geological map of the Haizhou area, Sulu Orogen (after Longkang 1991). **B.** Generalised stratigraphy of the Jinping Formation; detrital zircon ages are from Zhou et al. (2012). **C.** Measured section of the Jinping Formation along the adit of the underground Xinling Mine; circled letters to left of the column are position of photographs in Figure 4. **D.** C-isotope profile for the Xinling Mine section. Isotope data were obtained on split aliquots of the same sample that were analysed independently at the Nanjing Institute of Geology, Paleontology and Stratigraphy (NIGPAS), Nanjing, China, and Tartu University, Tartu, Estonia.

rich marble unit of the Jinping Formation. The base of that unit is marked by a 0.5 -1.5 m thick dolomarble and freshly mined blocks of this rock reveal that its lower part is a sheet-cracked dolomicrite that passes upward into a dolostone with irregularly shaped, dolomite- and quartz-spar-filled vugs (Fig. 4D). Above the basal dolomarble is a 17-m thick succession of dolomitic-calcitic rhythmite, thin- to medium-bedded dolomitic-calcitic marbles with P-rich intervals, siliceous marbles and thin layers of pelitic and graphitic schists (Fig. 4E,F). The topmost 8 m is a variably P-rich dolomitic-calcitic marble with thin, discontinuous partings of schist overlain sharply by several metres of pelitic schist containing mm- to a few-cm-thick carbonate beds. The rest of the section was not accessible for examination. We obtained 39 samples along the mine adit and these yielded a carbonate-C-isotope profile marked by (Fig. 3D): (i) the basal dolostone exhibiting a trend in $\delta^{13}C$ from negative to positive values and (ii) a jagged pattern of mostly positive but also including negative $\delta^{13}C$ values through the remainder of the section.

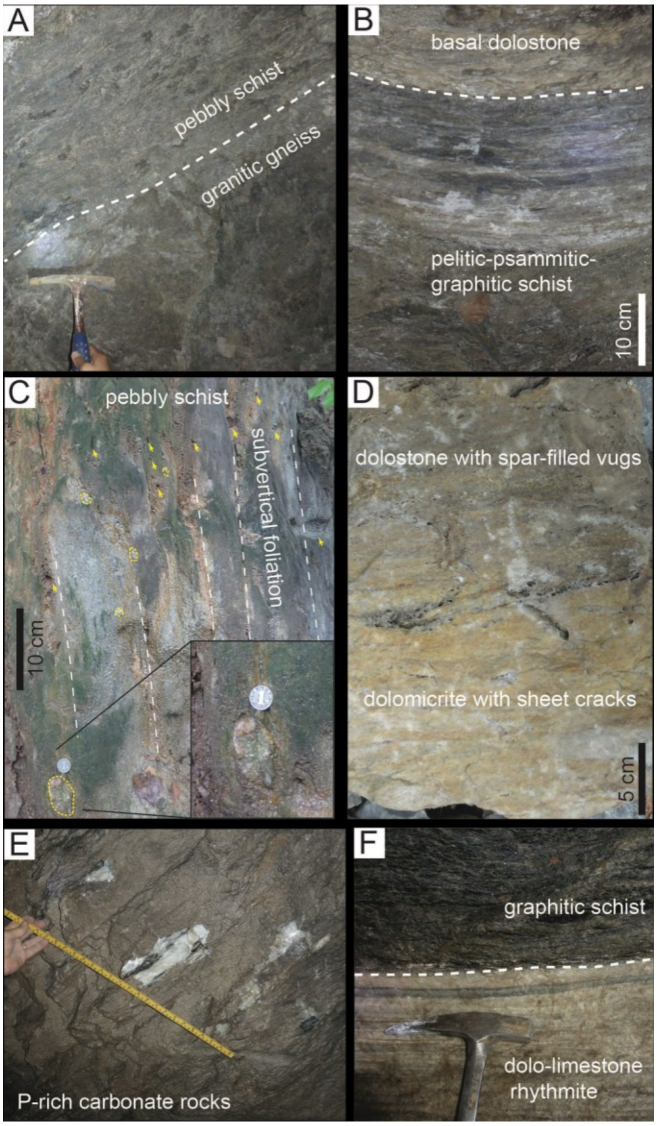

Figure 4. Photographs of Jinping Formation rocks; A, B, D-F are from the underground Xinling Mine. **A.** Unconformable contact between Proterozoic granitic gneiss basement and overlying pebbly schist. **B.** Clast-poor pelitic-psammitic-graphitic schists beneath the lowermost dolostone of the Jinping Formation, which is interpreted herein as a Marinoan-equivalent cap dolostone (scale of photo is the same as that for Fig. 4A). **C.** Pebbly schist in outcrop; deep weathering is typical of exposures in the region and the more obvious clasts are outlined by dashed lines and arrows point to cavities formed by weathered-out clasts; inset photo in bottom right shows a close-up of a granitoid clast. **D.** Block of basal dolostone from the Xinling Mine; lowermost portion is a tan-yellow dolomicrite with thin sheet cracks overlain by a dolostone containing dolo- and/or quartz-spar-filled vugs. **E.** P-rich dolo-limestone unit. **F.** Dolo-limestone rhythmite overlain by graphitic schist. See Figure 3 for stratigraphic position of photos.

As noted above, the Haizhou Group was originally inferred to be Palaeo-Mesoproterozoic in age and correlated with rocks in the Dabie Orogen that were thought to be of similar age (Longkang 1991; Yang et al. 1986; see discussions by Xu et al. 2012 and Zhou et al. 2012). U-Pb dating on detrital zircons recovered from the Haizhou Group, however, confirm that these units can be no older than Ediacaran (Fig. 1C): the youngest detrital zircons limit the maximum age of the lower and upper Jinping Formation to 654 ±19 Ma and 635 ±9 Ma (1σ), respectively (Xu et al. 2012). Thus, the Haizhou Group is a likely correlative to

Cryogenian-Ediacaran rocks preserved elsewhere on the Yangtze Block. In fact, the lowermost P-rich marble unit of the Jinping Formation in the Xinling Mine adit matches well the facies and C-isotope chemostratigraphic characteristics of the lower part (initial few tens of metres) of the shelf-platform sections of the Doushantuo Formation in the central and western regions of the Yangtze Block (see Fig. 7). There, four members have been identified (e.g. Jiang et al. 2011; Li et al. 2013; Ling et al. 2007; Muscente et al. 2015; Sato et al. 2016; Wang et al. 2016; Zhou et al. 2007; Zhu et al. 2007, 2013). The first is a basal, sheet-cracked to vuggy dolostone, 1-6 m thick, that is recognised as the Marinoan-equivalent cap carbonate with negative $\delta^{13}C$ values that trend into positive values (the dolostone can exhibit many tens-of-*per-mil* variations over cm-scale vertical distances; Jiang et al. 2003; Sato et al. 2016); the basal dolostone of the Jinping Formation displays such features. The second member is a unit of thin- to medium-bedded carbonate rocks with variably organic- and P-rich intervals (e.g. phosphorites, phosphatic fossils) and a jagged $\delta^{13}C$ profile of mostly positive, but also negative, $\delta^{13}C$ values (e.g. Jiang et al. 2008; Zhou and Xiao 2007; Zhu et al. 2013); this is matched by the P-rich marble unit of the Jinping Formation. The other two members of the Doushantuo Formation, medium- to thick-bedded carbonate rocks typically containing a negative $\delta^{13}C$ excursion that has been equated to the Ediacaran Shuram anomaly (e.g. Wang et al. 2012, 2016; Lu et al. 2013; although this correlation is complicated by the presence of slumped units, e.g. Lu et al. 2013) and an organic-rich shale, may be present in the Jinping Formation but we were unable to access the part of the adit that exposed the remainder of the Formation. Nonetheless, based on their shared traits, we interpret the lowermost part of the lower P-rich marble unit of the Jinping Formation as being correlative with the lower part of the Doushantuo Formation cap carbonate.

What is more difficult to determine is if the pebbly schist and schistose rocks that comprise the basal part of the Jinping Formation can be interpreted reasonably as a metamorphosed correlative of the end-Cryogenian glacigenic Nantuo Formation. Our observations showed, like those made by previous workers (e.g. Longkang 1991), that the pebbly schist is marked by a fine-grained micaceous-quartzitic matrix containing numerous, widely dispersed clasts of gneissic rocks, quartzites and rare fine-grained (meta)sedimentary clasts, all from 1 cm to more than 50 cm in size. In other words, it is a metamorphosed diamictite. That, though, does not make it glacial in origin and the deformational overprint combined with deep weathering (see Fig. 4C) hinders identifying glacigenic features such as dropstones or multiply striated bullet-shaped clasts. However, interpreting the basal pebbly schist of the Jinping Formation as a correlative of the end-Cryogenian Nantuo Formation glacigenic diamictite is consistent and compatible with the recognition of the overlying P-rich marble unit as the Marinoan-equivalent cap carbonate. Thus, we conclude that the lower part of the Jinping Formation is the metamorphosed equivalent of the Nantuo-Doushantuo glacial-cap carbonate couplet.

Dabie Orogen, Luiping section: Daxinu Formation of the Susong Group

In the eastern part of the exhumed subduction complex of the Dabie Orogen, rocks attributed to the South China craton can be categorised into four main terranes (Zheng et al. 2005; Li et al. 2011), from north to south: UHP migmatised granulites, UHP eclogites, HP-UHP eclogitic blueschists, and the low-grade metasedimentary Susong Group and its correlatives (an outstanding summary of the latter is given by Xu et al. 2012). As noted previously, many of the metasedimentary sequences and para- and ortho-gneiss complexes in the Dabie Orogen were originally thought to be Palaeo-Mesoproterozoic in age but U-Pb geochronology has shown that to be mistaken. In brief, U-Pb dating of magmatic zircon obtained from mid-upper crustal granitoid gneisses throughout the Dabie orogen produce ages that range mostly from 800-720 Ma (e.g. Ames et al., 1996; Hacker et al. 1998; Hu et al. 2010; Rowley et al. 1997; Wu et al. 2007; Xie et al. 2004) with somewhat older ages of 860-760 Ma obtained for the cores of magmatic zircons derived from lower-crustal granulites in the UHP terrains in the northern part of the orogen (e.g. Ling et al. 2003; Liu et al. 2007, 2011; Wu et al. 2012; Xu et al. 2016). In other words, the protoliths that define the underlying basement for the metasedimentary sequences in the Dabie Orogen are mostly Tonian to Cryogenian in age, which makes their supracrustal cover sequences that age or younger. Many workers have noted this and have suggested that the P-rich marbles, whether they occur in the HP-UHP complexes in the central and northern parts of the Dabie Orogen or in the Susong and Hong'an groups in the eastern and western Dabie Orogen, respectively, and Zhangbaling Group in the eponymous Uplift area (see Fig. 1B), are the metamorphosed equivalents of the Cryogenian-Ediacaran ('Sinian') sedimentary successions and underlying Proterozoic basement of the Yangtze Block (e.g. Rumble et al. 2000; Zheng et al. 1998, 2005; Wu et al. 2007; Xu et al. 2012). Our work focussed on trying to refine that proposed correlation.

The Luiping area contains one of the best developed exposures of the Susong Group (Fig. 5A,B). The geology of that area in the eastern Dabie Orogen consists of a granitic gneiss basement (Dabie Complex), the unconformably overlying Daxinwu Formation, the P-rich Luiping Formation, and the Hutashi Formation. Our stratigraphic mapping and sampling transect provide additional details (Fig. 5C). The base of the Daxinwu Formation defines an irregularly scalloped, erosive unconformity surface on the underlying foliated granite of the Dabie Complex and above which is a variably developed coarse to pebbly arkose (meta)sandstone. The (meta)arkose unit fines upward over 30-40 m into micaceous (meta)sandstone and fine psammitic metapelites. The next 150-200 m is a patchily exposed pelitic-psammitic-white mica schist interval that passes gradational into a finer-grained white-mica schist. This siliciclastic interval is overlain sharply by the first of two finely crystalline to lutitic, white dolomarble units. Both marble units are exposed poorly: the lower one is about 100 m thick and the upper one about 150 m thick, and they are separated by a similarly

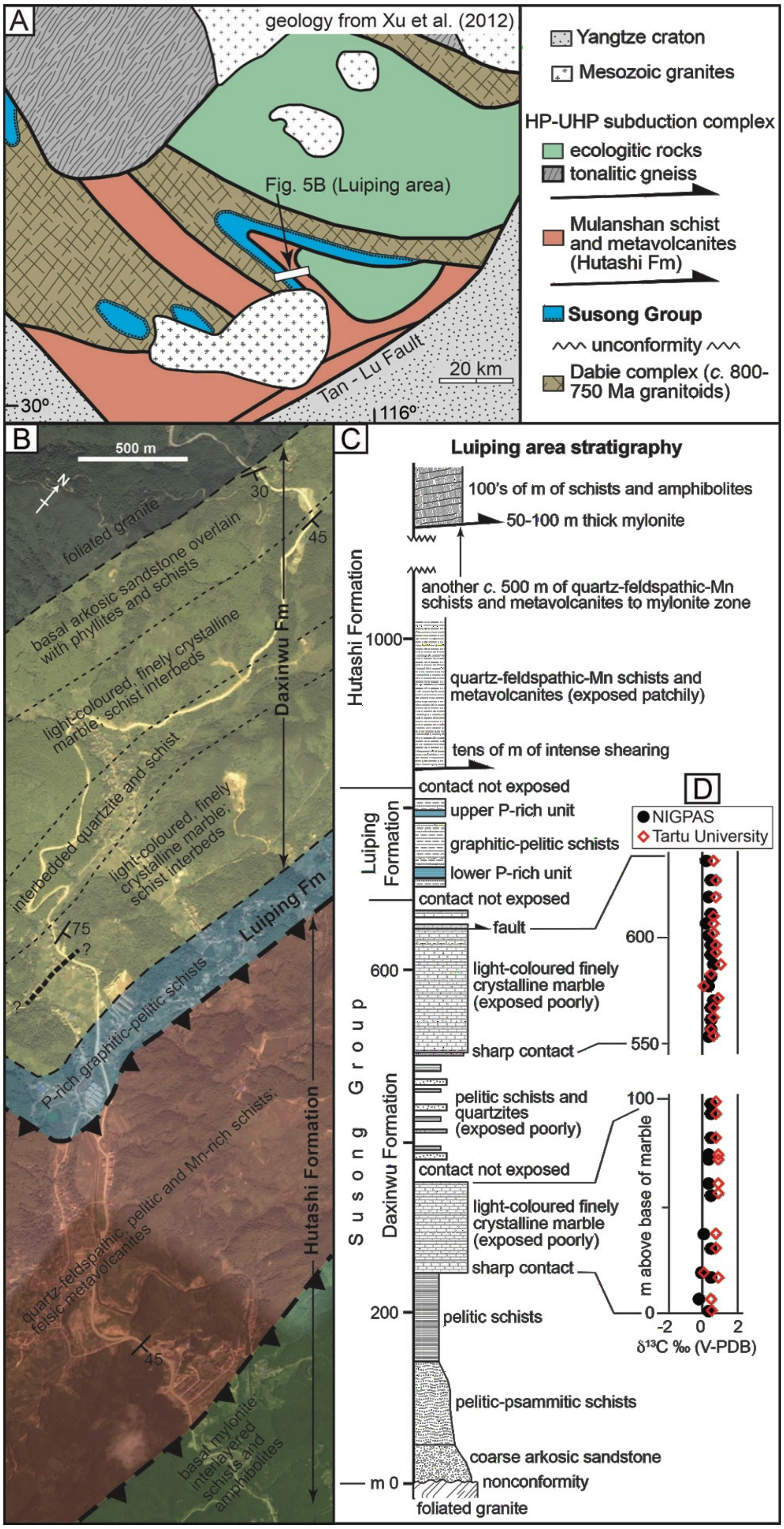

Figure 5. A. Simplified geological map of the eastern part of the Dabie Orogen (after Xu et al. 2012). **B-C.** Simplified geological map and stratigraphy based on our work in the Luiping area. **D.** C-isotope profile of the Daxinwu Formation. Isotope data were obtained on split aliquots of the same sample that were analysed independently at the Nanjing Institute of Geology, Paleontology and Stratigraphy (NIGPAS), Nanjing, China, and Tartu University, Tartu, Estonia.

poorly exposed interval, 100-150 m thick, of pelitic-psammitic schists and fine-grained quartzites. P-rich graphitic-pelitic schists of the Luiping Formation overlie the Daxinwu marble interval, but the contact is not exposed. Above the Luiping Formation are the quartz-feldspathic-Mn schists, metafelsites and amphibolites of the Hutashi Formation; the contact between the formations is also not exposed. We defer further description of those units until they can be better studied but we highlight two aspects. Firstly, prior to being metamorphosed, the Luiping Formation would have been variably organic- and P-rich fine-grained siliciclastic rocks that followed deposition of carbonates (i.e. the marble units in the Daxinwu Formation). Secondly, the lowermost exposures of both the quartz-feldspathic-Mn schist-metafelsite unit of the lower Hutashi Formation and the amphibolite-metafelsite interval in the upper part of the Hutashi Formation are zones of intense shearing and mylonitisation that are many tens of metres thick. Thus, the Hutashi Formation is not in stratigraphic continuity with the underlying Susong Group rocks (Luiping and Daxinwu formations) and is itself dissected by major mylonitised shear zones.

We took 35 samples of the two marble units in the Daxinwu Formation (14 from the lower unit and 21 from the upper unit) and the resulting carbonate-C isotope profile is remarkable (Fig. 5D): invariantly flat $\delta^{13}C$ values of 0 to 1‰ over the entire stratigraphic thickness (200-300 m) of both marble units. As explained above, the metasedimentary successions in the Dabie Orogen must be younger than their underlying basement rocks, which are mostly 860-700 Ma in age. Thus, the lithostratigraphic and C-isotope chemostratigraphic characteristics of the marble-dominated portion of the Daxinwu Formation suggest that it is a metamorphosed equivalent of the late Ediacaran Dengying Formation, which is known to be 551-542 Ma (e.g. Condon et al. 2005) in age and is the only Ediacaran-early Cambrian unit to be marked by a consistently flat C-isotope profile of low positive $\delta^{13}C$ values like that of the Daxinwu's (see Fig. 7).

Zhangbaling Uplift

The Zhangbaling Uplift occurs along the southeast margin of the Tan-Lu fault zone approximately midway between the Luiping and Jinping regions (Figs. 1, 6A,B). Zhao et al. (2014, 2016) have studied in detail the geology of the Uplift and have defined three

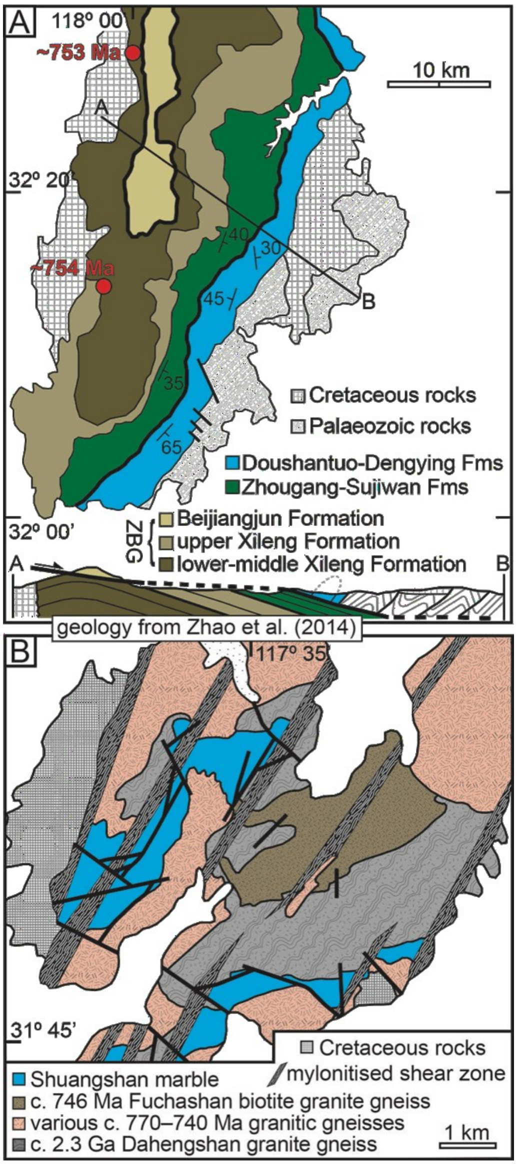

Figure 6. Simplified geological maps of the Zhangbaling Uplift: **(A)** southern portion of the north segment of the Uplift and **(B)** southern portion of the south segment of the Uplift (ZBG – Zhangbaling Group). Geology is from Zhao et al. (2014).

subdivisions. The first, the Feidong Complex, is limited to the southern segment of the Uplift and consists of amphibolite-facies ortho- and paragneiss, schist, marble and amphibolite. The second is the upper-greenschist facies metavolcanic rocks of the Xileng Formation, the pelitic-psammitic schists of the Beijiangjun Formation (these two formations define the Zhangbaling Group), the phyllite and metasandstone of the Zhougang Formation, and the metadiamictite (pebbly phyllite) of the Sujiwan Formation, which has been correlated to 'Sinian tillites' in the non-metamorphosed parts of the Yangtze Block (Zhao et al. 2014). The third subdivision is the lesser-deformed dolostones and limestones identified as being correlative with the Doushantuo and Dengying formations (Zhao et al. 2014). Lower Palaeozoic rocks are also present, but are minor, and in many places the Uplift is intruded by Cretaceous granites and overlain unconformably by Cretaceous silici- and volcaniclastic rocks. Two key geochronological constraints have been established by Zhao et al. (2014): weighted mean U-Pb SHRIMP ages of *c*. 754 Ma, with several grains as young as 722-709 Ma, for the intermediate to felsic metavolcanites of the Xileng Formation, and 800-745 Ma protolith ages for the Feidong Complex, such as the Fuchashan and Dahengshan metagranites. Thus, these ages confirm that the metasedimentary rocks in the Uplift can be no older than late Tonian, and likely younger, in age.

We examined in reconnaissance fashion the P-rich interval in the Shuangshan marble of the Feidong Group in the southern segment of the Uplift (Fig. 6B). There, much faulting and mylonitisation have compromised obtaining meaningful stratigraphic relationships but what is revealing is that the P-rich intervals are associated with thick calcitic-dolomitic marble sequences. Given that Ediacaran rocks are known for the northern segment of the Uplift and that, as highlighted herein, other P-rich rocks adjacent to and within the Dabie-Sulu orogens are Ediacaran in age, then it is reasonable to conclude that the Shuangshan P-rich marble is also Ediacaran in age. Considering, then, correlations to the non-metamorphosed succession on the Yangtze Block, P-rich rocks there have two distinct facies associations. The first typifies the phosphorites in the Doushantuo Formation, which occur as thin interbeds in organic-rich shale and carbonate rocks. The second is found in the Dengying Formation: dark, P-rich shales above a thick dolostone-limestone succession (e.g. the Zhongyicun Member; Li et al. 2013). The character of the P-rich marbles in the Zhangbaling Uplift match better the latter facies association, i.e. thick marbles overlain by P-rich rocks associated with graphitic-quartz-feldspathic schists. Thus, we conclude that the P-rich marbles in the Zhangbaling Uplift are the deformed correlatives of the carbonate-phosphorite interval that occurs near the top of the Dengying Formation.

The Zhangbaling Uplift rocks contain no evidence for blueschist or UHP metamorphism, the geochronological data and identification of the Doushantuo-Dengying formations in the northern segment of the Uplift (Zhao et al. 2014, 2016), and our inferred correlation of the P-rich marble units in the southern segment of the Uplift to the Dengying Formation, concur with the findings of Zhao et al. (2014). Thus, the metasedimentary rocks of the Zhangbaling Uplift are part of the late Ediacaran shelf-platform succession of the Yangtze Block.

Discussion: Ediacaran palaeogeography and the nature of the Tan-Lu fault zone

Our new data allow us to infer that the subduction complexes in the exhumed HP-UHP Dabie and Sulu orogens and the areas adjacent to those are the deformed Ediacaran carbonate shelf-platform rocks that typify the central and western regions of the Yangtze Block. This conclusion is supported by our carbonate-C isotope data for the Jinping Formation of the Haizhou Group in the Sulu Orogen and the Daxinwu Formation of the Susong Group in the Dabie Orogen (Fig. 7). The $\delta^{13}C$ profiles for the former matches well the lower part of the Doushantuo Formation in its shelf-platform settings and is distinct from the Doushantuo's slope-basin $\delta^{13}C$ trend. Likewise, the flat $\delta^{13}C$ profile of the Daxinwu Formation matches that of the Dengying Formation. Further, the basal pebbly schist of the Jinping Formation can be interpreted reasonably as the metamorphosed correlative of the end-Cryogenian Nantuo Formation glacigenic diamictite.

Those correlations enable us to extrapolate the geochronological constraints established for the non-metamorphosed Ediacaran successions to the rocks of the Dabie (DO) and Sulu (SO) orogens and Zhangbaling Uplift (ZU) (Fig. 7): (i) the pebbly schist/phyllite at the base of the Jinping Formation (SO), and probably also the diamictite of the Sujiwan Formation (ZU), are correlative with the end-Cryogenian Marinoan glacial that has been bracketed between c. 639-635 Ma in age (Zhang et al. 2008; Prave et al. 2016); (ii) the lower Jinping Formation P-rich marbles (SO) are a Marinoan-equivalent cap carbonate, known to be 635 Ma in age (Condon et al. 2005; Hoffmann et al. 2005); and the (iii) Daxinwu Formation marble units (DO) through the P-rich rocks of the Luiping Formation (DO) and the Shuangshan P-rich marbles (ZU) would be between c. 551 Ma to early Cambrian in age,

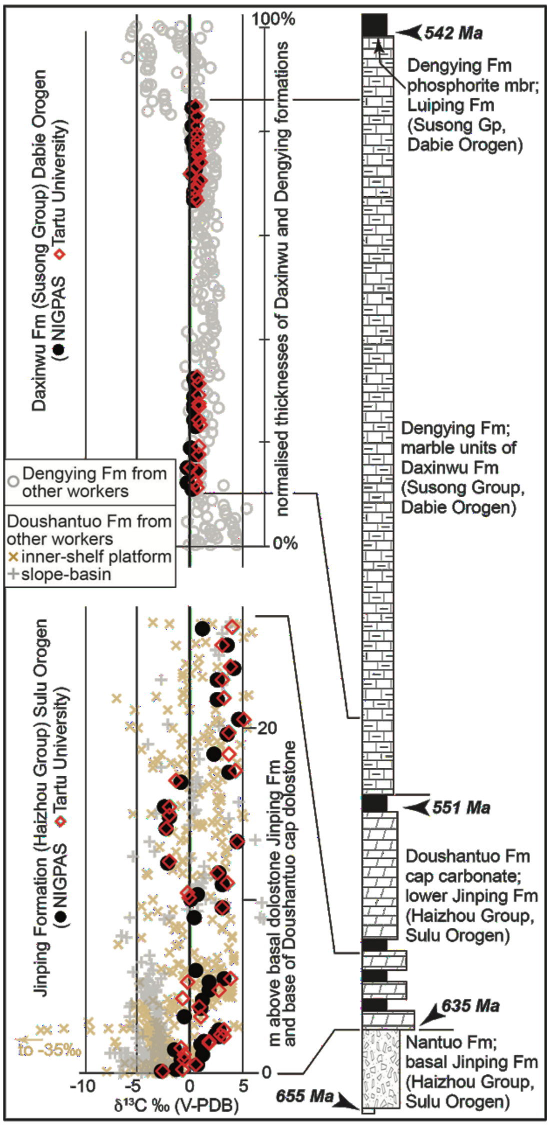

Figure 7. Proposed lithostratigraphic and C-isotope chemostratigraphic correlations of the metasedimentary rocks of the Jinping Formation (Haizhou Group, Sulu Orogen) and Daxinwu Formation (Susong Group, Dabie Orogen) to the late-Cryogenian – Ediacaran succession on the Yangtze Block. C-isotope data for the latter are from Jiang et al. (2003, 2007, 2008), Li et al. (2013), Tahata et al. (2013), Wang et al. (2016), Wang et al. (2017), Zhou and Xiao (2007) and Zhu et al. (2013). Isotope data for the Jinping and Daxinwu formations were obtained on split aliquots of the same sample that were analysed independently at the Nanjing Institute of Geology, Paleontology and Stratigraphy (NIGPAS), Nanjing, China, and Tartu University, Tartu, Estonia. Age constraints are from Zhang et al. (2008) for the base of the Nantuo Formation, Condon et al. (2005) for the Doushantuo Formation and Chen et al. (2015) for the Dengying Formation.

given their inferred correlation with the Dengying Formation (Condon et al. 2005; Chen et al. 2015;Li et al. 2013). We are uncertain how to explain the apparent absence of the Marinoan-equivalent glacial-cap carbonate couplet in the Susong Group but offer two possibilities: either the Susong Group is younger than the Marinoan glaciation or the Marinoan glacial-cap carbonate couplet is present but was overlooked due to poor exposure. Assessing which is the correct answer requires additional field study.

Our findings also provide insights into and assessment of tectonic models of the Tan-Lu fault zone. The Tan-Lu fault trends northeast for hundreds of kilometres along the juncture of the North and South China cratons (Fig. 1A). The general interpretation is that it is a sinistral strike-slip fault with as much as 500 km or more of offset (e.g. Xu and Zhu 1994; Zheng et al. 2005). In this model, the occurrence of P-rich marbles juxtaposed with blueschist facies rocks in both the Dabie and Sulu orogens was used to infer that the two HP-UHP orogenic belts were once a linearly contiguous belt of rocks that became dismembered by the Tan-Lu fault. Noteworthy is that in this interpretation the displaced rocks, specifically the Haizhou and Susong Groups, were thought to be Palaeo-Mesoproterozoic in age (e.g. Longkang 1991; Pirajno 2013; Yang et al. 1986; see discussions by Xu et al. 2012 and Zhou et al. 2012). In contrast, Zhou et al. (2016) interpret the Tan-Lu fault zone as a continental-scale tear fault formed by the indentation of a rigid promontory of the North China craton into the South China craton during the Mesozoic suturing of the two cratons. In this model, the present distribution of HP-UHP rocks along the Tan-Lu fault represents differential exhumation and preservation of the now dismembered but once widespread continental margin of the Yangtze Block. Our data indicate that the Susong Group rocks in the eastern Dabie Orogen and the Haizhou Group rocks in the Sulu Orogen, along with the rocks of the Zhangbaling Uplift, were indeed part of an extensive carbonate shelf-platform that fringed the entire margin of the Yangtze Block during Ediacaran time (Fig. 8). Because these rocks had an extensive distribution, rather than restricted to a single linear orogenic belt, they cannot be used as pierce points for determining magnitude-of-offset. This finding refutes a key line of evidence for strike-slip interpretations but is compatible with the rigid indenter-tear fault model for the origin of the Tan-Lu fault zone.

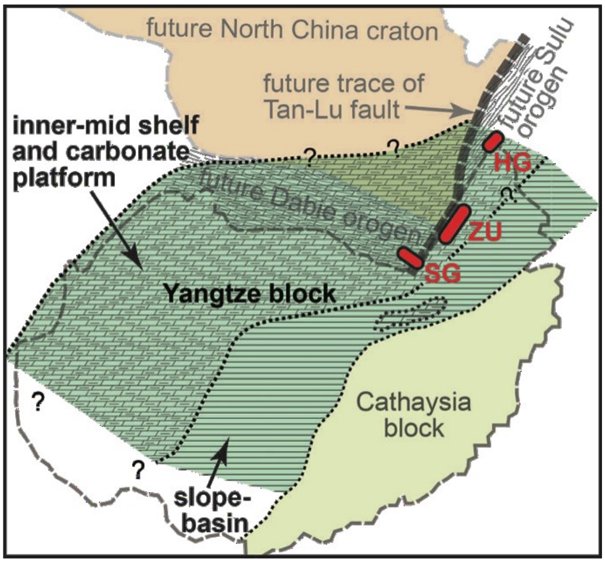

Figure 8. Proposed early Ediacaran palaeogeographic framework of the Yangtze Block using the data for the Susong Group (SG), Zhangbaling Uplift (ZU) and Haizhou Group (HG); see Figure 1A for comparison.

Summary

New stratigraphic and carbonate-C isotope chemostratigraphic data for the Susong and Haizhou Groups of the Dabie and Sulu orogens, respectively, show that they are correlative to the end-Cryogenian through Ediacaran Nantuo-Doushantuo-Dengying successions that typify the central and western portions of the Yangtze Block. A metadiamictite (pebbly schist) at the base of the Jinping Formation of the Haizhou Group in the Sulu Orogen can be reasonably interpreted as correlative with the glacigenic Marinoan-equivalent Nantuo Formation. Further, the lowermost P-rich marble interval of the Jinping Formation matches in lithofacies character and $\delta^{13}C$ profile the lower part of the Doushantuo Formation cap carbonate sequence in its shallow shelf-platform settings. In the Dabie Orogen, the marble units of the Daxinwu Formation and the P-rich rocks of the Luiping Formation of the Susong Group are correlatives of the late Ediacaran – early Cambrian Dengying Formation. This correlation is supported by the remarkably invariant carbonate-C isotope profiles (low positive $\delta^{13}C$ values for hundreds of metres of section) exhibited by both the Daxinwu and Dengying formations. These findings indicate that the shallow-marine shelf-carbonate platform that characterised the central and western portions of the Yangtze Block during Ediacaran time can be extended into and across the eastern Dabie and Sulu orogens and Zhangbaling Uplift, as proposed by Wu et al. (2007) and Xu et al. (2012). Our findings also support the tectonic model that the Tan-Lu fault zone is a continental-scale tear fault formed by the impingement of a rigid promontory of the North China craton into the South China craton during the Mesozoic suturing of the two cratons, as proposed by Zhao et al. (2016).

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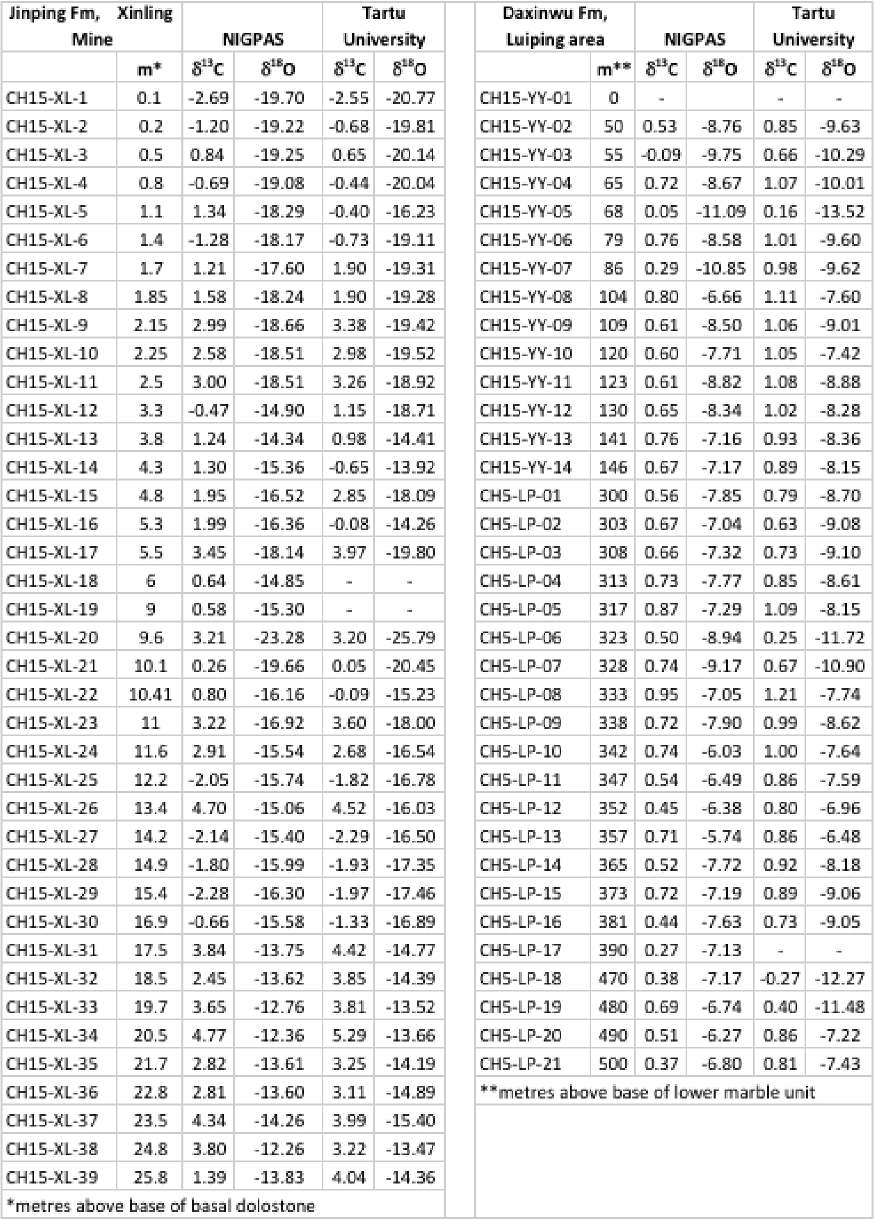
Table 1. C and O isotope data in *per mil* relative to the Vienna PeeDee Belemnite (‰ VPDB) standard for samples of the Jinping Formation (Haizhou Group, Sulu Orogen) and Daxinwu Formation (Susong Group, Dabie Orogen). Isotope data were obtained on split aliquots of the same sample that were analysed independently at the Nanjing Institute of Geology, Paleontology and Stratigraphy (NIGPAS), Nanjing, China, and Tartu University, Tartu, Estonia.



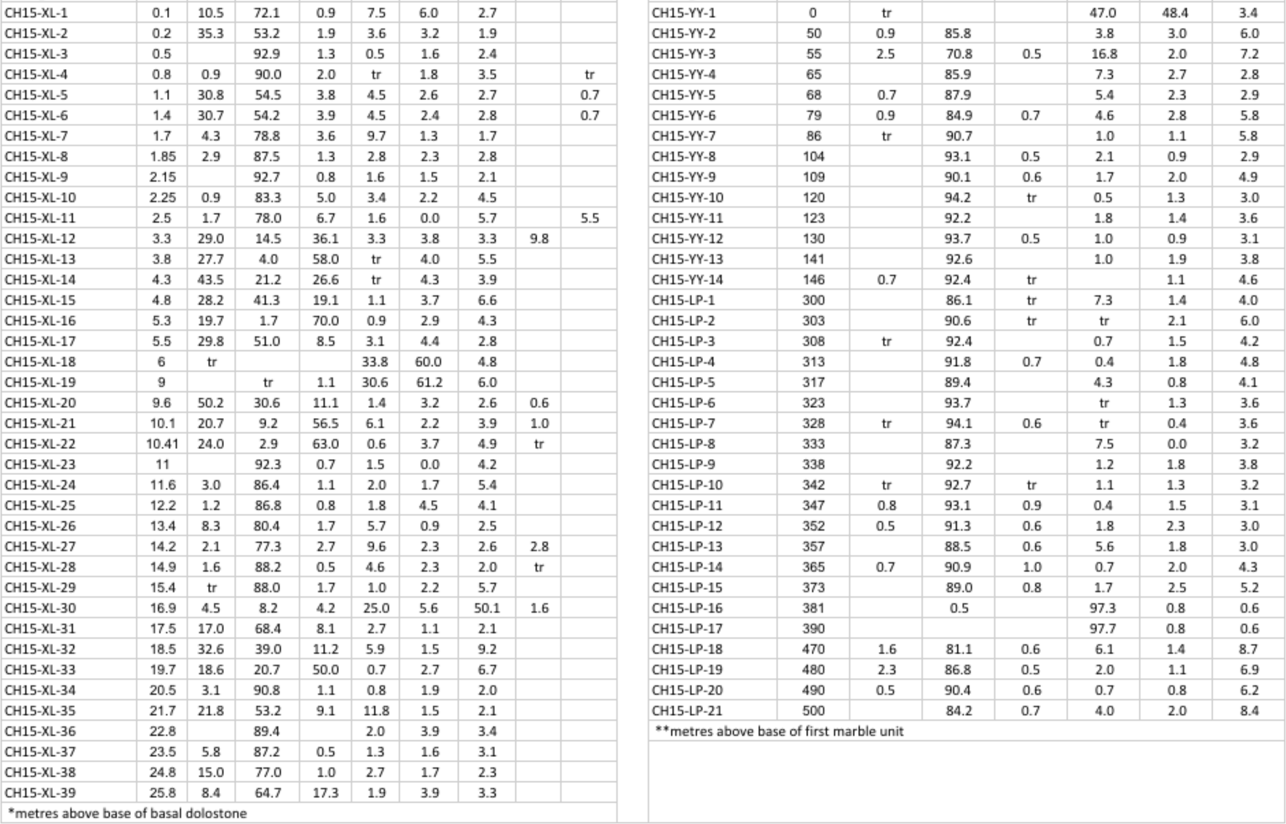
Jinping Fm, Xinling Mine		NIGPAS		Tartu University	
	m*	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$
CH15-XL-1	0.1	-2.69	-19.70	-2.55	-20.77
CH15-XL-2	0.2	-1.20	-19.22	-0.68	-19.81
CH15-XL-3	0.5	0.84	-19.25	0.65	-20.14
CH15-XL-4	0.8	-0.69	-19.08	-0.44	-20.04
CH15-XL-5	1.1	1.34	-18.29	-0.40	-16.23
CH15-XL-6	1.4	-1.28	-18.17	-0.73	-19.11
CH15-XL-7	1.7	1.21	-17.60	1.90	-19.31
CH15-XL-8	1.85	1.58	-18.24	1.90	-19.28
CH15-XL-9	2.15	2.99	-18.66	3.38	-19.42
CH15-XL-10	2.25	2.58	-18.51	2.98	-19.52
CH15-XL-11	2.5	3.00	-18.51	3.26	-18.92
CH15-XL-12	3.3	-0.47	-14.90	1.15	-18.71
CH15-XL-13	3.8	1.24	-14.34	0.98	-14.41
CH15-XL-14	4.3	1.30	-15.36	-0.65	-13.92
CH15-XL-15	4.8	1.95	-16.52	2.85	-18.09
CH15-XL-16	5.3	1.99	-16.36	-0.08	-14.26
CH15-XL-17	5.5	3.45	-18.14	3.97	-19.80
CH15-XL-18	6	0.64	-14.85	-	-
CH15-XL-19	9	0.58	-15.30	-	-
CH15-XL-20	9.6	3.21	-23.28	3.20	-25.79
CH15-XL-21	10.1	0.26	-19.66	0.05	-20.45
CH15-XL-22	10.41	0.80	-16.16	-0.09	-15.23
CH15-XL-23	11	3.22	-16.92	3.60	-18.00
CH15-XL-24	11.6	2.91	-15.54	2.68	-16.54
CH15-XL-25	12.2	-2.05	-15.74	-1.82	-16.78
CH15-XL-26	13.4	4.70	-15.06	4.52	-16.03
CH15-XL-27	14.2	-2.14	-15.40	-2.29	-16.50
CH15-XL-28	14.9	-1.80	-15.99	-1.93	-17.35
CH15-XL-29	15.4	-2.28	-16.30	-1.97	-17.46
CH15-XL-30	16.9	-0.66	-15.58	-1.33	-16.89
CH15-XL-31	17.5	3.84	-13.75	4.42	-14.77
CH15-XL-32	18.5	2.45	-13.62	3.85	-14.39
CH15-XL-33	19.7	3.65	-12.76	3.81	-13.52
CH15-XL-34	20.5	4.77	-12.36	5.29	-13.66
CH15-XL-35	21.7	2.82	-13.61	3.25	-14.19
CH15-XL-36	22.8	2.81	-13.60	3.11	-14.89
CH15-XL-37	23.5	4.34	-14.26	3.99	-15.40
CH15-XL-38	24.8	3.80	-12.26	3.22	-13.47
CH15-XL-39	25.8	1.39	-13.83	4.04	-14.36

*metres above base of basal dolostone

Daxinwu Fm, Luiping area		NIGPAS		Tartu University	
	m**	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$
CH15-YY-01	0	-		-	-
CH15-YY-02	50	0.53	-8.76	0.85	-9.63
CH15-YY-03	55	-0.09	-9.75	0.66	-10.29
CH15-YY-04	65	0.72	-8.67	1.07	-10.01
CH15-YY-05	68	0.05	-11.09	0.16	-13.52
CH15-YY-06	79	0.76	-8.58	1.01	-9.60
CH15-YY-07	86	0.29	-10.85	0.98	-9.62
CH15-YY-08	104	0.80	-6.66	1.11	-7.60
CH15-YY-09	109	0.61	-8.50	1.06	-9.01
CH15-YY-10	120	0.60	-7.71	1.05	-7.42
CH15-YY-11	123	0.61	-8.82	1.08	-8.88
CH15-YY-12	130	0.65	-8.34	1.02	-8.28
CH15-YY-13	141	0.76	-7.16	0.93	-8.36
CH15-YY-14	146	0.67	-7.17	0.89	-8.15
CH5-LP-01	300	0.56	-7.85	0.79	-8.70
CH5-LP-02	303	0.67	-7.04	0.63	-9.08
CH5-LP-03	308	0.66	-7.32	0.73	-9.10
CH5-LP-04	313	0.73	-7.77	0.85	-8.61
CH5-LP-05	317	0.87	-7.29	1.09	-8.15
CH5-LP-06	323	0.50	-8.94	0.25	-11.72
CH5-LP-07	328	0.74	-9.17	0.67	-10.90
CH5-LP-08	333	0.95	-7.05	1.21	-7.74
CH5-LP-09	338	0.72	-7.90	0.99	-8.62
CH5-LP-10	342	0.74	-6.03	1.00	-7.64
CH5-LP-11	347	0.54	-6.49	0.86	-7.59
CH5-LP-12	352	0.45	-6.38	0.80	-6.96
CH5-LP-13	357	0.71	-5.74	0.86	-6.48
CH5-LP-14	365	0.52	-7.72	0.92	-8.18
CH5-LP-15	373	0.72	-7.19	0.89	-9.06
CH5-LP-16	381	0.44	-7.63	0.73	-9.05
CH5-LP-17	390	0.27	-7.13	-	-
CH5-LP-18	470	0.38	-7.17	-0.27	-12.27
CH5-LP-19	480	0.69	-6.74	0.40	-11.48
CH5-LP-20	490	0.51	-6.27	0.86	-7.22
CH5-LP-21	500	0.37	-6.80	0.81	-7.43

**metres above base of lower marble unit

Table 2. XRD data in weight percent (wt.%) for samples of the Jinping Formation (Haizhou Group, Sulu Orogen) and Daxinwu Formation (Susong Group, Dabie Orogen). Samples were analysed at Tartu University, Estonia.



Jinping Formation Xinling Mine section	m*	calcite	dolomite	apatite	quartz	feldspar	phyllo-silicates	barite	gypsum
CH15-XL-1	0.1	10.5	72.1	0.9	7.5	6.0	2.7		
CH15-XL-2	0.2	35.3	53.2	1.9	3.6	3.2	1.9		
CH15-XL-3	0.5		92.9	1.3	0.5	1.6	2.4		
CH15-XL-4	0.8	0.9	90.0	2.0	tr	1.8	3.5		tr
CH15-XL-5	1.1	30.8	54.5	3.8	4.5	2.6	2.7		0.7
CH15-XL-6	1.4	30.7	54.2	3.9	4.5	2.4	2.8		0.7
CH15-XL-7	1.7	4.3	78.8	3.6	9.7	1.3	1.7		
CH15-XL-8	1.85	2.9	87.5	1.3	2.8	2.3	2.8		
CH15-XL-9	2.15		92.7	0.8	1.6	1.5	2.1		
CH15-XL-10	2.25	0.9	83.3	5.0	3.4	2.2	4.5		
CH15-XL-11	2.5	1.7	78.0	6.7	1.6	0.0	5.7		5.5
CH15-XL-12	3.3	29.0	14.5	36.1	3.3	3.8	3.3	9.8	
CH15-XL-13	3.8	27.7	4.0	58.0	tr	4.0	5.5		
CH15-XL-14	4.3	43.5	21.2	26.6	tr	4.3	3.9		
CH15-XL-15	4.8	28.2	41.3	19.1	1.1	3.7	6.6		
CH15-XL-16	5.3	19.7	1.7	70.0	0.9	2.9	4.3		
CH15-XL-17	5.5	29.8	51.0	8.5	3.1	4.4	2.8		
CH15-XL-18	6	tr			33.8	60.0	4.8		
CH15-XL-19	9		tr	1.1	30.6	61.2	6.0		
CH15-XL-20	9.6	50.2	30.6	11.1	1.4	3.2	2.6	0.6	
CH15-XL-21	10.1	20.7	9.2	56.5	6.1	2.2	3.9	1.0	
CH15-XL-22	10.41	24.0	2.9	63.0	0.6	3.7	4.9	tr	
CH15-XL-23	11		92.3	0.7	1.5	0.0	4.2		
CH15-XL-24	11.6	3.0	86.4	1.1	2.0	1.7	5.4		
CH15-XL-25	12.2	1.2	86.8	0.8	1.8	4.5	4.1		
CH15-XL-26	13.4	8.3	80.4	1.7	5.7	0.9	2.5		
CH15-XL-27	14.2	2.1	77.3	2.7	9.6	2.3	2.6	2.8	
CH15-XL-28	14.9	1.6	88.2	0.5	4.6	2.3	2.0	tr	
CH15-XL-29	15.4	tr	88.0	1.7	1.0	2.2	5.7		
CH15-XL-30	16.9	4.5	8.2	4.2	25.0	5.6	50.1	1.6	
CH15-XL-31	17.5	17.0	68.4	8.1	2.7	1.1	2.1		
CH15-XL-32	18.5	32.6	39.0	11.2	5.9	1.5	9.2		
CH15-XL-33	19.7	18.6	20.7	50.0	0.7	2.7	6.7		
CH15-XL-34	20.5	3.1	90.8	1.1	0.8	1.9	2.0		
CH15-XL-35	21.7	21.8	53.2	9.1	11.8	1.5	2.1		
CH15-XL-36	22.8		89.4		2.0	3.9	3.4		
CH15-XL-37	23.5	5.8	87.2	0.5	1.3	1.6	3.1		
CH15-XL-38	24.8	15.0	77.0	1.0	2.7	1.7	2.3		
CH15-XL-39	25.8	8.4	64.7	17.3	1.9	3.9	3.3		

*metres above base of basal dolostone

Daxinwu Formation Luiping section	m**	calcite	dolomite	apatite	quartz	feldspar	phyllo-silicates
CH15-YY-1	0	tr			47.0	48.4	3.4
CH15-YY-2	50	0.9	85.8		3.8	3.0	6.0
CH15-YY-3	55	2.5	70.8	0.5	16.8	2.0	7.2
CH15-YY-4	65		85.9		7.3	2.7	2.8
CH15-YY-5	68	0.7	87.9		5.4	2.3	2.9
CH15-YY-6	79	0.9	84.9	0.7	4.6	2.8	5.8
CH15-YY-7	86	tr	90.7		1.0	1.1	5.8
CH15-YY-8	104		93.1	0.5	2.1	0.9	2.9
CH15-YY-9	109		90.1	0.6	1.7	2.0	4.9
CH15-YY-10	120		94.2	tr	0.5	1.3	3.0
CH15-YY-11	123		92.2		1.8	1.4	3.6
CH15-YY-12	130		93.7	0.5	1.0	0.9	3.1
CH15-YY-13	141		92.6		1.0	1.9	3.8
CH15-YY-14	146	0.7	92.4	tr		1.1	4.6
CH15-LP-1	300		86.1	tr	7.3	1.4	4.0
CH15-LP-2	303		90.6	tr	tr	2.1	6.0
CH15-LP-3	308	tr	92.4		0.7	1.5	4.2
CH15-LP-4	313		91.8	0.7	0.4	1.8	4.8
CH15-LP-5	317		89.4		4.3	0.8	4.1
CH15-LP-6	323		93.7		tr	1.3	3.6
CH15-LP-7	328	tr	94.1	0.6	tr	0.4	3.6
CH15-LP-8	333		87.3		7.5	0.0	3.2
CH15-LP-9	338		92.2		1.2	1.8	3.8
CH15-LP-10	342	tr	92.7	tr	1.1	1.3	3.2
CH15-LP-11	347	0.8	93.1	0.9	0.4	1.5	3.1
CH15-LP-12	352	0.5	91.3	0.6	1.8	2.3	3.0
CH15-LP-13	357		88.5	0.6	5.6	1.8	3.0
CH15-LP-14	365	0.7	90.9	1.0	0.7	2.0	4.3
CH15-LP-15	373		89.0	0.8	1.7	2.5	5.2
CH15-LP-16	381		0.5		97.3	0.8	0.6
CH15-LP-17	390				97.7	0.8	0.6
CH15-LP-18	470	1.6	81.1	0.6	6.1	1.4	8.7
CH15-LP-19	480	2.3	86.8	0.5	2.0	1.1	6.9
CH15-LP-20	490	0.5	90.4	0.6	0.7	0.8	6.2
CH15-LP-21	500		84.2	0.7	4.0	2.0	8.4

**metres above base of first marble unit