SIMS U-Pb zircon geochronological constraints on the stratigraphic correlations of the upper Ediacaran in South China

Original Articles

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Short title for the running headlines: Zircon U-Pb dating of the Dengying Formation

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Abstract

Fossiliferous Ediacaran successions of South China, the Doushantuo and Dengying formations and their equivalents, are key to understanding bio- and geological evolution at the Neoproterozoic-Cambrian transition. However, their absolute ages, especially the upper Ediacaran successions, are poorly constrained. SIMS zircon U-Pb dating results in this study suggest that ash beds at the basal and middle parts of the Jiucheng Member (middle Dengying Formation) in eastern Yunnan Province were deposited at 553.6 ± 2.7/(3.8) Ma and 546.3 ± 2.7/(3.8) Ma, respectively. These new dates indicate that the age for the base of Dengying Formation in eastern Yunnan Province is similar to the 550.55 ± 0.75 Ma data, which is from an ash bed at the top of the Miaohe Member and has been regarded as the age for the base of Dengying Formation in Yangtze Gorges area. These dates do not permit a clear test of the two correlation models for the chronostratigraphic position of the Miaohe Member (uppermost Doushantuo Formation vs. middle Dengying Formation), thus suggesting requirement of further integrated intra-basinal stratigraphic correlations and more high-resolution chronological data in upper Ediacaran of South China. New dates of the Jiucheng Member constrain the age of the fossil biotas in the middle Dengying Formation, and extend the stratigraphic range of *Rangea*, *Hiemalora* and *Charniodiscus* to 546.3 ± 2.7/(3.8) Ma. The geochronology of the Dengying Formation implies that Ediacara-type fossils persevered in this formation are younger than the White Sea Assemblage, and temporally overlapping with the Nama Assemblage.

Keywords: Zircon U-Pb age, Ediacaran, Dengying Formation, Doushantuo Formation, Ediacara fossil, South China

1. Introduction

The Ediacaran Period spans a critical time interval during the Earth history, beginning with the termination of global Cryogenian glaciation and ending at the earliest occurrence of marine bilaterian animals on a global scale at the beginning of the Phanerozoic (Knoll *et al.* 2004). The successions during this interval record the dramatic fluctuations in the compositions of the ocean and atmosphere, such as the large excursions of the carbon isotope in seawater (e.g. Jiang, Kennedy & Christie-Blick, 2003; Le Guerroué, Allen, & Cozzi, 2006; Zhu, Zhang & Yang, 2007) and increasing oxygen levels (e.g. Och & Shelds-Zhou, 2012; Lyon *et al.* 2014; Chen *et al.* 2015). Broadly coincident is the rapid radiation of the complex, macroscopic multicellular organisms on the eve of the Cambrian explosion, including Ediacara-type soft-bodied fossils (e.g. Narbonne, 2005, Droser & Gehling, 2015), megascopic multicellular algal fossils (e.g. Xiao *et al.* 2002), trace fossils (e.g. Jensen *et al.* 2000; Chen *et al.* 2013), and weakly calcified metazoans (e.g. Hofmann & Mountjoy, 2001; Cai *et al.* 2015). Stratigraphic successions spanning the Ediacaran-Cambrian transition are well developed and exposed in South China (Zhu, Zhang & Yang, 2007). Previous studies on the litho-, chemo- and biostratigraphy of these successions have advanced significantly in understanding the evolution of life and environment during the Ediacaran (e.g. Jiang *et al.*, 2011; Zhu *et al.*, 2013; Liu *et al.* 2014). However, the Ediacaran stratigraphy of South China is complicated because of facies variation, thus hampering development of a global integrated stratigraphic model for life evolution and environmental changes at this critical interval.

Absolute dating (i.e. radio-isotopic geochronology) is the fundamental method for the developing and testing models of intra-basinal and global stratigraphic inter-comparison, and is the only way to quantify the rates of the geological and biological processes. The zircon ^{207}Pb-^{206}Pb age 550.55 ± 0.75 Ma from the top of the Miaohe Member in the west Huangling Anticline (Condon *et al.* 2005), which has been traditionally correlated to the Doushantuo Member IV in the Yangtze Gorges area, constrains the age of the Miaohe biota (Xiao *et al.* 2002) and is regarded as the age for the top of the Doushantuo Formation, i.e. the top of the DOUNCE (Doushantuo negative carbon isotope excursion, Zhu, Strauss & Shields, 2007)/Shuram δ^{13}C negative excursion and the base of the Dengying Formation (e.g. Ding *et al.* 1996; Wang *et al.*, 1998; Condon *et al.* 2005; Zhu, Zhang & Yang, 2007; Lu *et al.* 2013). This stratigraphic correlation recently was challenged by An *et al.* (2015), who suggested that Miaohe Member in the west Huangling Anticline is significantly younger than the Doushantuo Member IV in the Yangtze Gorges area, most likely time-equivalent with the lower Shibantan Member of the Dengying Formation which yields abundant Ediacara-type fossils (Chen *et al.* 2014). Therefore, the improvement of the chronostratigraphic framework is required for understanding of the DOUNCE/Shuram δ^{13}C negative excursion and its causal relation with the Miaohe biota and other Ediacaran fossils recorded in upper Ediacaran successions. One of the key issues to test those two competing models is to get absolute ages from the Dengying Formation. However no radiometric ages within the Dengying Formation or its equivalents have yet been reported. Meanwhile, the lack of the robust age constraints in the Dengying Formation hinders the biostratigraphic correlations between the Ediacara-type fossils discovered in South China and the three Ediacara-type fossil assemblages in other paleocontinents: the Avalon Assemblage (~575-560 Ma), the White Sea Assemblage (~560-550 Ma) and the Nama Assemblage (~550-541 Ma) (Grotzinger *et al.* 1995; Martin *et al.* 2000; Waggoner, 2003; Bowring *et al.* 2007; Xiao & Laflamme, 2009; Noble *et al.* 2015).

To achieve a better understanding of the geochronological framework of the Dengying Formation and the biostratigraphic correlations of the Ediacara-type fossils in South China, we scrutinise the SIMS zircon ^{238}U-^{206}Pb and ^{207}Pb-^{206}Pb data in order to derive robust age constraints, and present two new SIMS zircon U-Pb data sets, with a weighting towards the ^{207}Pb-^{206}Pb dates due to issues of open-system behavior (i.e. radiogenic Pb-loss) of the ash beds in the middle part of the Dengying Formation in eastern Yunnan Province, South China.

[Figure 1 here]

2. Geological background and sampling

As a part of the Rodinia supercontinent, the South China Block was formed by amalgamation of Yangtze and Cathaysia blocks along the Sibao orogen in the early Neoproterozoic (Fig. 1), although the timing of the amalgamation is still controversial (e.g. Li *et al*. 2002, 2009a; Zhou *et al*. 2002). Mantle plume was formed beneath the Rodinia supercontinent about 50 million years after the completion of its assembly, leading to the development of the continental rifting and the break-up of the supercontinent (Li *et al*. 2008a). Rift-related sedimentary successions and bimodal magmatic rocks dated at 0.85-0.72 Ga are widespread in South China, especially around the periphery of the Yangtze Block (e.g. Wang & Li, 2003; Li *et al*. 2008b; Yang *et al*. 2015). Overlying the rift-related sequences are the glacial and interglacial deposits, recording the two Neoproterozoic worldwide glaciations in South China (Shields-Zhou, Porter & Halverson, 2016). The Doushantuo Formation of the early Ediacaran is overlying the Nantuo (Marinoan-equivalent) glacial deposit, with the characteristic ‘cap carbonates’ at the base (Jiang, Kennedy & Christie-Blick, 2003;

Zhu, Zhang & Yang, 2007). The thin ash layer at the top of the cap carbonate was dated at 635.2 ± 0.6 Ma, constraining the terminal timing of the Nantuo glaciation in South China, which reflects the global Marinoan glaciation (Condon *et al*. 2005). The Doushantuo Formation is composed mainly of carbonate rocks and black shale. Large acanthomorphic acritarchs, multicellular algae, animal embryos and few animal fossils are presented in the Doushantuo Formation (e.g. Xiao *et al*. 1998; Chen *et al*. 2004; Liu *et al*. 2013; Yin *et al*. 2015). As the uppermost part of the Ediacaran in South China, the Dengying Formation (and its equivalents) consists mainly of carbonate rocks in the shallow water basin and cherts in the slope and deep water basin (Zhu *et al*. 2003, 2007). The Dengying Formation is known to contain abundant fossils, such as Ediacara-type soft-bodied fossils, trace fossils, macroalgal fossils, and some tubular fossils (e.g. Hua, Chen & Yuan, 2007; Chen *et al*. 2013, 2014, Cai *et al*. 2015). These terminal Ediacaran fossils are the central to our understanding of the animal evolution on the eve of the Cambrian explosion.

[Figure 2 here, in the landscape orientation]

The Ediacaran-Cambrian transitional strata with shallow marine facies are extensively developed and well exposed in eastern and northeastern Yunnan Province, South China (Zhu *et al*. 2001). We studied and sampled the middle part of the Dengying Formation in the Xiaolantian and Yinchangpo sections in the eastern Yunnan Province (Figs. 1, 2). The Xiaolantian section is located to the northeast of the Fuxian Lake, about 6 km to the east of the Chengjiang county town. This section is near the well-described Feidatian-Dongdahe section (Zhu, Zhang & Yang, 2007), and the lithostratigraphy of the Dengying Formation at the two sections is similar, so the horizon of the dated ash bed from Xiaolantian section is marked on the column of Feidatian-Dongdahe section (Fig. 2). The Xiaolantian section consists of four formations spanning upper Ediacaran to lower Cambrian, from bottom to top, namely Dengying, Zhujiaqing, Shiyantou and Yu'anshan formations. The Dengying Formation is divided into three members including, from bottom to top, the Donglongtan, Jiucheng and Baiyanshao members. The Donglongtan and Baiyanshao members are dominated by dolostone. The Jiucheng Member mainly consists of sandstone, muddy siltstone interbedded with laminated silty dolomite at the basal part. Overlying the Dengying Formation is the Zhujiaqing Formation which is composed of dolostone, phosphorite and interbedded phosphatic limestone. Numerous small shelly fossils (SSFs) were discovered from this formation (Qian *et al*. 1996). Unconformably overlying the Zhujiaqing Formation is the Shiyantou and Yu'anshan formations which are dominated by siltstone and shales. The famous Chengjiang biota occurs in the middle part of the Yu'anshan Formation (Zhang & Hou, 1985). The Yinchangpo section is located about 10 km to the northwest of the Huize county town. This section consists of two formations including Dengying and Zhujiaqing formations (Fig. 2). The Donglongtan Member of the Dengying Formation measures ca. 460 meters thick and is composed of thickly-bedded to massive dolostone. The Jiucheng Member is about 20 meters thick and consists of muddy siltstone and silty dolostone. The Baiyanshao Member consists of about 260 meters of medium- to thickly-bedded, laminated dolostone. Only the lower part of the Zhujiaqing Formation is outcropped in this section, composed of interbedded dolostone and chert (Fig. 2).

[Figure 3 here]

Two ash samples from the middle part of the Dengying Formation were collected for SIMS zircon U-Pb dating (Figs. 2, 3). Sample 14CJ07 was collected about 3.8 meters above the phosphorite layer at the base of the Jiucheng Member, Dengying Formation in the Xiaolantian section, and sample 14YCP02 was collected from the middle part of the Jiucheng Member, 471 meters above the base of the Dengying Formation in the Yinchangpo section.

3. SIMS zircon U-Pb dating method

Zircon crystals were separated from ca. 3 kg of each sample using conventional density and magnetic separation techniques. Together with zircon standards Plešovice, 91500, Penglai and Qinghu, zircon grains were mounted in an epoxy resin which was then polished to section the crystals in half for analysis. All zircon grains were documented with transmitted and reflected light photomicrographs and cathodoluminescence (CL) images to reveal their external and internal structures, and the mount was vacuum-coated with high-purity gold prior to secondary ion mass spectrometry (SIMS) analysis.

Measurements of U, Th and Pb isotopes were conducted using a Cameca 1280-HR SIMS at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS) in Beijing. The O_2^- primary ion beam was accelerated at −13 kV, with an intensity of 5~12 nA. The ellipsoidal spot is about 20 μm × 30 μm in size. Positive secondary ions were extracted with a 10 kV potential. Oxygen flooding was used to increase the O_2 pressure to about 5×10^{-6} Torr in the sample chamber, enhancing the secondary Pb^+ sensitivity to a value of 35 cps/nA/ppm for zircon. In the secondary ion beam optics, a 60 eV energy window was used to reduce the energy dispersion. To achieve a higher precision of SIMS U-Pb zircon geochronology, a dynamic multi-collector U-Pb dating method was used to take advantages of both mono-collector mode (high-precision determination of the ^{238}U-^{206}Pb age) and multi-collector mode (high-precision determination of the ^{207}Pb-^{206}Pb age). This new analytical protocol is able to achieve a higher precision for the ^{207}Pb-^{206}Pb age by a factor of two than the conventional mono-collector mode within the same working time, making it possible that simultaneously obtaining the ^{207}Pb-^{206}Pb age and ^{238}U-^{206}Pb age with comparable quality to effectively evaluate the concordance of the U-Pb system for Phanerozoic and late Precambrian samples (Liu *et al.* 2015). Each measurement consists of 7 cycles, and the total analytical time is about 14 minutes. More details for this method are described by Liu *et al.* 2015.

[Figure 4 here]

Analyses of the standard zircons were interspersed with those of unknown grains. Two successive sessions (session A and B) were conducted within a short time period, and the errors of the U/Pb calibration curve fitted by the standard zircons, 0.75% (1 SD, session A) and 0.55% (1 SD, session B), were propagated to the unknowns of the respective session (Fig. 4). The U-Th-Pb ratios were determined relative to the Plešovice standard zircon (Sláma *et al.* 2008), and the absolute abundances were calibrated to the standard zircon 91500 (Wiedenbeck *et al.* 1995). Measured Pb isotopic compositions were corrected for common Pb using the ^{204}Pb-method. Corrections are sufficiently small to be insensitive to the choice of common Pb composition, and an average of present-day crustal composition (Stacey & Kramers, 1975) is used for the common Pb assuming that the common Pb is largely surface contamination introduced during sample preparation. To be consistent with the published dates, the $^{238}U/^{235}U$ ratio of 137.88 (Steiger & Jaeger, 1977), ^{238}U and ^{235}U decay constants of Jaffey *et al*. (1971) are adopted in this study. Data reduction was carried out using the Isoplot/Exv. 4.15 program (Ludwig, 2003). Details for the calibration method are described by Li *et al*. 2009b. In order to monitor the external uncertainties of SIMS U-Pb measurements, analyses of zircon standard Qinghu were interspersed with unknowns. 12 analyses yielded a weighted mean ^{238}U-^{206}Pb age of 159.8 ± 0.6 Ma (2 SE, MSWD = 1.2), identical within errors to the reported age of 159.5 ± 0.2 Ma (Li *et al*. 2013a).

SIMS zircon U-Pb data are given in Table 1, and uncertainties on individual analysis are reported at 1σ level. Noteworthy is that the precision of the weighted mean ages is the standard error (SE), which will decrease with the increasing number of the zircon data that are included in weighted mean age calculation. Thus the external uncertainty of 1% (2 SD) for SIMS zircon ^{238}U-^{206}Pb age (e.g. Ireland & Williams, 2003; Yang *et al*. 2014) should be taken into consideration when comparing the SIMS zircon ^{238}U-^{206}Pb age with other published dates (e.g. the ID-TIMS date from Condon *et al*. 2005). The multi-collector SIMS determination of the ^{207}Pb-^{206}Pb age for the latest Neoproterozoic zircon has a comparable precision as the ^{238}U-^{206}Pb age (Li *et al*. 2009b), and the zircon ^{207}Pb-^{206}Pb age by SIMS measurement is independent on the matrix-matched U/Pb calibration. We assume that the external reproducibility for the multi-collector SIMS determination of latest Neoproterozoic zircon ^{207}Pb-^{206}Pb age is about 0.5% (2 SD) (Li *et al*. 2009b, 2010; Liu *et al*. 2015). The reported errors of the weighted mean ages in this study include two components, for example, Age ± X/(Y), where X represents the analytical error, and (Y) represents the analytical + external reproducibility. The calculation of (Y) is following the uncertainty propagation workflow in Horstwood *et al*. (2016). The MSWD (mean square of the weighted deviates) of the weighted mean age is calculated prior to the addition of the external uncertainties.

[Table 1 here, in the landscape orientation]

[Figure 5 here]

4. Results

4.a. Sample 14CJ07 at the base of the Jiucheng Member

Most zircons from this sample are 100-200 μm in length, and have aspect ratios of 3-5. They are euhedral and long-prismatic in morphology, with weakly oscillatory zoning under CL images (Fig. 5). A total of 50 analyses were conducted on 50 zircons. U and Th contents are between 57 and 545 ppm, 31 and 559 ppm, respectively, with Th/U ratios of 0.28-2.06 (mostly within 0.28-1.03), suggesting the magmatic origin. Except five sets of data from zircons with high common lead, all the others are considered to be reliable. The main population includes 44 grains, and their ^{238}U-^{206}Pb ages range from 539 ± 3 Ma to 561 ± 3 Ma (Fig. 6), yielding a weighted mean ^{238}U-^{206}Pb age of 549.5 ± 1.1/(5.6) Ma (2σ, n=44, MSWD = 2.6). Their weighted mean ^{235}U-^{207}Pb and ^{207}Pb-^{206}Pb ages are 550.4 ± 1.0 Ma (2σ, n=44, MSWD = 2.6) and 553.6 ± 2.7/(3.8) Ma (2σ, n = 44, MSWD = 0.77), respectively. The spot @22 yielded a ^{238}U-^{206}Pb age of 578 ± 3 Ma and a ^{207}Pb-^{206}Pb age of 568 ± 6 Ma. Its ^{238}U-^{206}Pb age is out of the main population and it is a little reverse discordant (discordance = 1.9%). So to be prudent, this grain was excluded in the weighted mean age calculation.

4.b. Sample 14YCP02 at the middle part of the Jiucheng Member

Zircons from sample 14CJ07 are 100-200 μm in length, and have aspect ratios of 2-4. They are euhedral and prismatic in morphology, showing oscillatory zoning under CL images (Fig. 5). A total of 50 analyses were conducted on 50 zircons, which are characterized by moderate U (47-853 ppm) and Th (42-1934 ppm) contents with Th/U ratios ranging from 0.09 to 10.56 (mostly within 0.36-2.81). The morphology and the Th/U ratios suggest that they are of magmatic origin. Except five sets of data from zircons with high common lead, all the others are considered to be reliable. The major population consists of 44 analyses, with their ^{238}U-^{206}Pb ages ranging from 525 ± 4 Ma to 556 ± 4 Ma. They yield a weighted mean ^{238}U-^{206}Pb age of 543.1 ± 1.2/(5.6) Ma (2σ, n=44, MSWD = 2.9, Fig. 6). Their weighted mean ^{235}U-^{207}Pb and ^{207}Pb-^{206}Pb ages are 543.8 ± 1.2 Ma (2σ, n=44, MSWD = 2.9) and 546.3 ± 2.7/(3.8) Ma (2σ, n = 44, MSWD = 0.58), respectively. Spot @27 gives a clearly older ^{238}U-^{206}Pb age of 584 ± 4 Ma and older ^{207}Pb-^{206}Pb age of 594 ± 8 Ma than the major population, suggesting a xenocrystal origin.

5. Discussion

5.a. Ages of the ash beds from middle Dengying Formation

Zircon U-Pb geochronology is the most widely used radiometric dating tool for determining geological ages and establishing time scales of processes in the Earth history. However the Pb-loss in zircons, arisen from the crystal lattice being damaged by the emission of alpha particles and alpha recoil processes, has often been recognised in U-Pb systematics of zircon (e.g. Nasdala *et al.* 2005). In micro-beam zircon U-Pb dating techniques, such as the LA-ICPMS and SIMS, it is possible to recognise the significant Pb-loss effect in the high-U zircons or zircons with old ages since their ^{238}U-^{206}Pb and ^{207}Pb-^{206}Pb dates can be resolved. However, Pb-loss can be cryptic and impossible to identify in the zircons with younger ages without reference to other techniques such as CA-ID-TIMS or ^{40}Ar-^{39}Ar dating (e.g. Kryza *et al*. 2012; Crowley *et al*. 2014; Watts *et al*. 2016). Thermal annealing and chemical abrasion ('CA') can minimise the effect of Pb-loss by removing the radiation-damaged parts of zircons, which have been widely used in thermal ionization mass spectrometry zircon U-Pb dating method (Mattinson, 2005). The SIMS ^{238}U-^{206}Pb ages of the CA-treated zircons are generally older than the results yielded from the untreated zircons from the same magmatic rock, even no discordance can be resolved from the latter analytical data set (Kryza *et al*. 2012; Watts *et al*. 2016).

The dynamic multi-collector U-Pb dating method we adopted in this study has the ability to measure the high-precision ^{207}Pb/^{206}Pb ratio as in the static multi-collector mode without trade off in the analytical precision of the ^{238}U/^{206}Pb ratio of the conventional peak-hopping mono-collector mode (Liu *et al*. 2015). This new method has potential to simultaneously produce higher precision ^{238}U-^{206}Pb and ^{207}Pb-^{206}Pb ages of zircon, providing reliable evaluation on the concordance of the zircon U-Pb system as young as 500 Ma (Liu *et al*. 2015). For the two samples in this study, their weighted mean ^{238}U-^{206}Pb age < ^{235}U-^{207}Pb age < ^{207}Pb-^{206}Pb age, indicating that they are discordant and most likely resulted from subtle radiogenic Pb-loss. The MSWD of the two weighted mean ^{238}U-^{206}Pb ages (2.6 and 2.9) are large and fall outside of the acceptable range of the MSWD values for a given population included in weighted mean age calculation (44 grains for each sample in this study, Fig. 6), implying that they do not represent a single population and their weighted mean ^{238}U-^{206}Pb ages are meaningless (Wendt & Carl, 1991). If the assumption that the analysed zircons have suffered subtle radiogenic Pb-loss is correct, we can explore a MSWD-based model to exclude the outliers. The model is that using the largest population of the oldest grains that yield an acceptable MSWD value to calculate the weighted mean ^{238}U-^{206}Pb ages. Thus the MSWD-based model weighted mean ^{238}U-^{206}Pb ages for the two samples are 551.9 ± 1.2/(5.6) Ma (Fig. 6c) and 545.5 ± 1.4/(5.6) Ma (Fig. 6d). We note however that the calculation of a MSWD with a value that is acceptable for *n* does not confirm a single age population.

Present-day radiogenic Pb-loss of zircon will not affect the accuracy of the ^{207}Pb-^{206}Pb age. Zircon ^{207}Pb-^{206}Pb age by SIMS measurement is independent on the matrix-matched U/Pb calibration, and its uncertainty is derived predominantly from the uncertainty of the measured ^{207}Pb/^{206}Pb ratio and the common Pb correction. For all the zircons included in the weighted mean age calculation, they have ^{206}Pb/^{204}Pb ratios > 10000, indicating that the common Pb correction has only little contribution to the final ^{207}Pb-^{206}Pb age uncertainty (Li *et al.* 2009b). As mentioned above, the new analytical protocol we adopted is able to achieve a higher precision for the ^{207}Pb-^{206}Pb age by a factor of two than the conventional mono-collector mode within the same working time (Liu *et al.* 2015). Thus we suggest that the weighted mean ^{207}Pb-^{206}Pb ages, 553.6 ± 2.7/(3.8) Ma and 546.3 ± 2.7/(3.8) Ma, are the best estimates of the crystallization ages for the two ash samples in the middle Dengying Formation in eastern Yunnan Province, South China. This suggestion is also supported by that the weighted mean ^{207}Pb-^{206}Pb age is identical within errors to its corresponding MSWD-based model weighted mean ^{238}U-^{206}Pb age.

[Figure 6 here]

5.b. Geochronological constraints on the Dengying Formation

The Dengying Formation is divided into three parts in South China, although they have been called different names in different areas (Fig. 2). The three lithostratigraphic units of the Dengying Formation in eastern Yunnan Province (in upwards order, Donglongtan, Jiucheng and Baiyanshao members) are traditionally correlated to those in other areas of the Yangtze Platform (Zhu, Zhang & Yang, 2007), such as the Yangtze Gorges area (Hamajing, Shibantan and Baimatuo members) and southern Shaanxi Province (Algal Dolostone, Gaojiashan and Beiwan members).

Although numerous studies have been carried out on the lithostratigraphy, chemostratigraphy and paleontology within the Dengying Formation, less achievement on geochronology has been made. No zircon U-Pb data have been directly obtained from the Dengying Formation or its equivalents, hampering the attempts to verify the chronostratigraphic framework. The Miaohe Member, which consists of black siliceous and carbonaceous shales and contains the famous Miaohe biota in west Huangling Anticline, Yangtze Gorges area, has long been considered as the uppermost part of the Doushantuo Formation ('traditional correlation model', e.g. Ding *et al*. 1996; Wang *et al*., 1998; Zhu, Zhang & Yang, 2007). Thus the zircon ^{207}Pb-^{206}Pb age 550.55 ± 0.75 Ma for the ash bed at the top of the Miaohe Member from the Jijiawan section in the west Huangling Anticline has been widely accepted as the maximum age for the base of the Dengying Formation (Condon *et al*. 2005). However some researchers recently argued that the Miaohe Member is most likely time-equivalent to the lower Shibantan Member (equivalent to the Jiucheng Member in eastern Yunnan, Fig. 2) of the Dengying Formation in the Yangtze Gorges area, suggesting that the base of the Dengying Formation, i.e., top of the Doushantuo Formation and the top of the DOUNCE/Shuram Carbon isotope excursion, should be much older than 550.55 ± 0.75 Ma (An *et al*. 2015).

In this study, the ash beds from the basal and middle parts of the Jiucheng Member of the Dengying Formation in the Xiaolantian and Yinchangpo sections are dated at 553.6 ± 2.7/(3.8) Ma and 546.3 ± 2.7/(3.8) Ma, respectively, indicating that the base of the Dengying Formation is older than 553.6 ± 2.7/(3.8) Ma in eastern Yunnan Province. It seems that the age for the base of the Dengying Formation there is older than the age for the top of the Miaohe Member in the Yangtze Gorges area (zircon ^{207}Pb-^{206}Pb age 550.55 ± 0.75 Ma, Condon *et al.* 2005), contradicting with the traditional correlation model but agree with An *et al.* (2015)'s correlation model. There are three possible interpretations for the controversial correlations. 1, considering the sequence boundary at the base of the Jiucheng Member and the thick Donglongtan dolostone unit in the lower part of the Dengying Formation, it is possible that the base of Dengying Formation in eastern Yunnan Province is older than 550.55 ± 0.75 Ma. That is not unexpected as the lithostratigraphic boundaries in different sedimentary basins can be diachronous, and the base of the Dengying Formation in the Yangtze platform represents initiation of a highstand system tract. 2, the traditional correlation model is incorrect and implies a lateral facies changes of the Dengying Formation among the basins of the Yangtze Platform, therefore supporting An *et al.* (2015)'s correlation model that the base of the Dengying Formation is below the Miaohe Member in the west Huangling Anticline, and 550.55 ± 0.75 Ma for the top of the Miaohe Member in this area represents the age of the middle Dengying Formation (Fig. 2). This interpretation is least likely because this correlation model violates the field observations, chemostratigraphy and sedimentary model of the Dengying Formation over the entire Yangtze Platform (Zhu, Zhang & Yang, 2007; Lu *et al.* 2013; Zhu *et al.* 2013) and stratigraphic correlations between South China, Namibia and Oman (Grotzinger *et al.* 1995; Bowring *et al.* 2007). 3, it is beyond the precision of these two SIMS zircon ^{207}Pb-^{206}Pb ages to exactly determine the age for the base of Dengying Formation in eastern Yunnan Province. Within errors the age 553.6 ± 2.7/(3.8) Ma for the base of the Jiucheng Member is similar to the age 550.55 ± 0.75 Ma for the top of the Miaohe Member in west Huangling Anticline in Yangtze Gorges area. Besides, because of the update of the U-Pb tracer calibration (Condon *et al*. 2015; McLean *et al*. 2015), there may be a bias between the new ^{238}U-^{206}Pb date derived from new parameters and the legacy ID-TIMS data in the published literatures (e.g. Burgess, Bowring & Shen, 2014). The analyses above demonstrate that the two SIMS zircon ^{207}Pb-^{206}Pb ages from the Jiucheng Member in eastern Yunnan Province do not permit a clear test of the two correlation models for the chronostratigraphic position of the Miaohe Member in the Yangtze Gorges area (uppermost Doushantuo Formation vs. middle Dengying Formation, Fig. 2). Thus, higher precision geochronology on the upper Doushanuo and Dengying formations, including recalibration of the published dates, is needed to further test and refine the stratigraphic correlation of the upper Ediacaran in South China.

[Figure 7 here]

5.c. Geochronological constraints on the biostratigraphic correlation

Abundant fossils have been discovered from the Ediacaran successions in South China, especially from the Dengying Formation and its equivalents (e.g. Hua, Chen & Yuan, 2007; Chen *et al*. 2013, 2014). Most of them, such as the Gaojiashan biota in the southern Shaanxi Province, the Xilingxia biota in the Yangtze Gorges area and the Jiangchuan biota in the Yunnan Province (Fig. 2), are preserved in the middle part of the Dengying Formation with some fossils extending to the upper part of the formation. They are mainly composed of macroscopic multicellular algae, Ediacara-type fossils, tubular fossils and trace fossils (Zhu, 2010 and references therein). Our new zircon ^{207}Pb-^{206}Pb age of 553.6 ± 2.7/(3.8) Ma for the ash bed from the basal Jiucheng Member in eastern Yunnan Province provides constraint on the maximum age of the biotas in the middle part of the Dengying Formation. The zircon ^{207}Pb-^{206}Pb age of 555.3 ± 0.3 Ma for the ash bed from the lower part of sequence B of the Ust-Pinega Formation represents the minimum age for the oldest Ediacara-type fossils in the White Sea region (Fig. 7; Martin *et al.* 2000). The SIMS zircon ^{207}Pb-^{206}Pb age for the basal Jiucheng Member is slightly younger than, or within errors identical to the age from the White Sea region, indicating that the Ediacara-type fossil assemblage preserved in the Dengying Formation is younger than the White Sea Assemblage.

The zircon ^{207}Pb-^{206}Pb age of 546.3 ± 2.7/(3.8) Ma for the ash bed from the middle part of the Jiucheng Member constrains the ages of the Ediacara-type fossils, trace fossils and some tubular fossils in the middle part of the Dengying Formation (Fig. 7). This age is identical within errors to the zircon ^{207}Pb-^{206}Pb age of 549.34 ± 0.82 Ma for the ash bed from the middle part of the Kuibis subgroup of the Nama Group, which provides the minimum age for the Ediacara-type fossils and *Cloudina* in Namibia (Grotzinger *et al.* 1995; Bowring *et al.* 2007). The δ^{13}C negative excursion at the lowermost Cambrian starts at the top of the Dengying Formation in eastern Yunnan Province (Li *et al.* 2013b), and the onset of this globally significant biogeochemical event was constrained at 541.00 ± 0.13 Ma in Oman (Amthor *et al.* 2003; Bowring *et al.* 2007). If this δ^{13}C negative excursion can be correlated between South China and Oman, the age for the top of the Dengying Formation in eastern Yunnan Province would be ca. 541 Ma, which is similar with the age for the top of the Spitskopf Member of the Nama Group (bracketed by zircon ^{207}Pb-^{206}Pb ages 543.3 ±

1 Ma and 539.4 ± 1 Ma, Grotzinger *et al.* 1995). Comparison between the newly obtained zircon ^{207}Pb-^{206}Pb ages and those from the Nama Group indicates that the Ediacara-type fossils in the middle Dengying Formation in South China can be temporally correlated to the Nama Assemblages in Namibia. This result is consistent with the affinity between the Dengying and Nama assemblages based on the same Ediacara genera such as the *Pteridinium* and *Rangea*, the presence of the *Cloudina* and *Sinotubulites*, and the abundance of trace fossils in the two assemblages (Chen *et al.* 2014). *Pteridinium* is one of the youngest Ediacara fossils, extending to the uppermost Ediacaran (younger than 543.3 ± 1 Ma, Grotzinger *et al.* 1995). The *Rangea* ranges from 558 Ma to 549 Ma, and the *Hiemalora* and *Charniodiscus* are usually discovered in the strata older than 550 Ma (Xiao & Laflamme, 2009; Noble *et al.* 2015). The discovery of these fossils in the middle Dengying Formation (Chen *et al.* 2014) extends their stratigraphic ranges to as young as 546.3 ± 2.7/(3.8) Ma.

Assigning the Ediacara-type fossils in the Dengying Formation to the Nama Assemblage significantly extend their taphonomic ranges. The Ediacara-type fossils in Namibia were mostly preserved as casts and molds in siliciclastic rocks, similar to the preservation in the Flinders Ranges area in Australia, where the fossils were restricted to the Ediacara Member of the Rawnsley Quartzite (e.g. Gehling & Droser, 2013). The Ediacara-type fossils with a limestone taphonomic window in the Dengying Formation in South China represent a distinct taphonomic pathway, extend their ecological range and prove that these Ediacara organisms were marine organisms rather than terrestrial lichens or microbial colonies (Xiao *et al.* 2005; Chen *et al.* 2014).

6. Conclusions

The following conclusions about the geochronology of the upper Ediacaran in

South China can be made by SIMS zircon U-Pb dating of the ash beds from the Jiucheng Member, Dengying Formation in the eastern Yunnan Province, South China.

(1) Excess ‘scatter’ in U-Pb data sets is interpreted to reflect subtle radiogenic Pb-loss in the analysed zircons, and the two weighted mean ^{207}Pb-^{206}Pb ages, 553.6 ± 2.7/(3.8) Ma and 546.3 ± 2.7/(3.8) Ma, are considered as the best estimates of the crystallization ages for the two ash samples from the basal and middle part of the Jiucheng Member, Dengying Formation in eastern Yunnan Province, South China.

(2) The age for the base of the Dengying Formation in eastern Yunnan Province is older than, or within errors identical to, that in the Yangtze Gorges area. The two SIMS zircon ^{207}Pb-^{206}Pb ages from the Jiucheng Member do not permit a clear test of the two correlation models for the chronostratigraphic position of the Miaohe Member (uppermost Doushantuo Formation vs. middle Dengying Formation).

(3) The Ediacara-type fossils preserved in the Dengying Formation in South China are temporally correlated to the Nama Assemblage. Their exceptional limestone taphonomic window in South China sheds new light on the diversity and paleoecology of the macroscopic Ediacaran life forms.

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Declaration of Interest

None

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Figure captions

Figure 1. (Colour online) Simplified palaeogeographic map of the Yangtze Block during the Precambrian-Cambrian transition interval (modified after Zhu *et al.* 2003). The dots represent the cities or the areas, and the triangles represent the sections.

Figure 2. (Colour online) Stratigraphic column of the Yinchangpo section in the eastern Yunnan Province, and its lithostratigrahic correlation to the Ediacaran-Cambrian transition successions in eastern Yunnan Province (Zhu, Zhang & Yang, 2007; Li *et al*. 2013b), southern Shaanxi Province (Zhu, Zhang & Yang, 2007) and Yangtze Gorges area (Condon *et al*. 2005; Jiang *et al*. 2007; Lu *et al*. 2013; Zhu *et al*. 2013; An *et al*. 2015). The biostratigraphy is based on Tang *et al*. 2006; Hua, Chen & Yuan, 2007; Zhu, 2010; Chen *et al*. 2013, 2014; Zhang, Hua & Zhang, 2015. The dot lines represent the lithostratigraphic boundaries. KY = Kunyang Group, NT = Nantuo Formation, ZJQ = Zhujiaqing Formation, KCP = Kuanchuanpu Formation, YJH = Yanjiahe Formation, SJT = Shuijingtuo Formation, JC = Jiucheng Member, DB = Daibu Member, GJS = Gaojiashan Member, Fm = Formation, Mb = Member.

Figure 3. (Colour online) (a) Field photo showing the sampling site of the ash bed 14CJ07. (b) Field photo showing the sampling site of the ash bed 14YCP02. (c) Photomicrograph of sample 14CJ07 showing it is composed mainly of mud, epidote and quartz. (d) Photomicrograph of sample 14YCP02 showing it is composed mainly of mud, epidote and quartz.

Figure 4. (Colour online) Logarithmic U-Pb calibration graphs. Curve (A) is applied to sample 14YCP02 and 14CJ07@01-20, and curve (B) is applied to 14CJ07@21-50.

Figure 5. (Colour online) Photomicrographs of representative zircons analysed in this study. The ellipses indicate the SIMS U-Pb analytical spots with 30 microns in length for scale. Zircon ^{207}Pb-^{206}Pb ages are quoted.

Figure 6. (Colour online) (a) U-Pb Concordia diagram of sample 14CJ07. (b) U-Pb Concordia diagram of sample 14YCP02. (c) The plot of the weighted mean

^{238}U-^{206}Pb ages versus their MSWD versus the number of the oldest grains included in the weighted mean age calculation for sample 14CJ07. (d) The plot of the weighted mean ^{238}U-^{206}Pb ages versus their MSWD versus the number of the oldest grains included in the weighted mean age calculation for sample 14YCP02. The gray area represents the range of the acceptable MSWD (Wendt & Carl, 1991).

Figure 7. (Colour online) Temporal distribution of the Ediacara-type fossils and the representative biomineralized animals in South China (Hua, Chen & Yuan, 2007; Chen *et al.* 2013, 2014), Namibia (Grotzinger *et al.* 1995; Bowring *et al.* 2007), Oman (Amthor *et al.* 2003; Bowring *et al.* 2007) and White Sea (Martin *et al.* 2000). The thicknesses of the lithostratigraphic units are not in scale. DST = Doushantuo Formation, N = Nomtsas Formation, Fm = Formation, Gr = Group, and the red bars represent the locations of the ash beds in the columns.

Table 1. SIMS zircon U-Pb data of ash samples from Dengying Formation in eastern Yunnan Province

Sample/ spot #	Session Number	U ppm	$\frac{Th}{U}$	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{206}Pb}$	±1σ %	$\frac{^{207}Pb}{^{235}U}$	±σ %	$\frac{^{206}Pb}{^{238}U}$	±σ %	$\frac{^{207}Pb}{^{206}Pb}$	±σ	$\frac{^{207}Pb}{^{235}U}$	±σ	$\frac{^{206}Pb}{^{238}U}$	±σ	Disc. % conv.
14CJ07@01	A	163	0.66	29291	0.0585	0.50	0.719	1.13	0.0891	1.01	549.1	10.9	550.0	4.8	550.2	5.3	0.2
14CJ07@02	A	87	0.59	12145	0.0590	0.57	0.722	0.97	0.0887	0.79	568.4	12.4	552.0	4.2	548.0	4.1	-3.8
14CJ07@03	A	73	0.42	20706	0.0587	0.79	0.727	1.09	0.0898	0.75	555.8	17.1	554.6	4.7	554.3	4.0	-0.3
14CJ07@04	A	218	0.28	50149	0.0589	0.36	0.736	0.84	0.0906	0.76	563.7	7.8	560.1	3.6	559.2	4.1	-0.8
14CJ07@05	A	76	0.45	32927	0.0588	0.63	0.733	1.03	0.0904	0.82	559.3	13.7	558.0	4.4	557.7	4.4	-0.3
14CJ07@06	A	545	0.75	73313	0.0588	0.23	0.714	0.79	0.0881	0.75	559.9	5.1	547.3	3.3	544.3	3.9	-2.9
14CJ07@07	A	88	0.89	19430	0.0586	0.62	0.706	0.98	0.0874	0.76	554.1	13.4	542.6	4.1	539.9	3.9	-2.7
14CJ07@08	A	115	0.62	16979	0.0583	0.67	0.708	1.01	0.0880	0.75	540.9	14.6	543.4	4.3	543.9	3.9	0.6
14CJ07@09	A	237	0.83	43849	0.0584	0.57	0.714	0.99	0.0886	0.80	546.6	12.5	547.3	4.2	547.4	4.2	0.2
14CJ07@10	A	130	0.62	21554	0.0587	0.47	0.720	1.02	0.0891	0.91	554.5	10.3	550.9	4.4	550.0	4.8	-0.8
14CJ07@11	A	278	0.78	63783	0.0587	0.32	0.730	0.85	0.0901	0.79	557.1	7.0	556.4	3.7	556.3	4.2	-0.2
14CJ07@12	A	85	0.59	25308	0.0587	0.70	0.718	1.03	0.0887	0.76	554.7	15.2	549.4	4.4	548.1	4.0	-1.2
14CJ07@13	A	120	0.78	20451	0.0584	0.49	0.714	0.96	0.0887	0.83	543.2	10.7	547.2	4.1	548.1	4.4	0.9
14CJ07@14	A	82	0.59	13003	0.0591	0.57	0.738	0.97	0.0905	0.78	570.6	12.3	561.0	4.2	558.6	4.2	-2.2
14CJ07@15	A	150	0.72	29693	0.0590	0.46	0.730	1.00	0.0898	0.89	566.8	10.0	556.6	4.3	554.2	4.7	-2.3
14CJ07@16	A	178	0.63	12595	0.0582	0.47	0.704	0.91	0.0877	0.78	537.4	10.1	541.0	3.8	541.9	4.1	0.9
14CJ07@17	A	90	0.60	19189	0.0593	0.62	0.728	1.03	0.0890	0.82	577.6	13.5	555.2	4.4	549.7	4.3	-5.0
14CJ07@18	A	57	0.59	14968	0.0582	0.72	0.701	1.10	0.0873	0.82	538.3	15.7	539.4	4.6	539.7	4.3	0.3
14CJ07@19	A	276	0.99	51605	0.0585	0.34	0.713	0.84	0.0884	0.77	546.7	7.3	546.4	3.6	546.3	4.0	-0.1
14CJ07@20	A	174	0.68	32148	0.0584	0.45	0.718	0.90	0.0892	0.79	544.5	9.7	549.4	3.8	550.6	4.2	1.2
14CJ07@21	B	158	0.72	42537	0.0583	0.47	0.711	0.79	0.0884	0.64	542.4	10.2	545.3	3.4	546.0	3.4	0.7
~~14CJ07@22~~	B	~~314~~	~~1.13~~	~~44559~~	~~0.0590~~	~~0.29~~	~~0.763~~	~~0.64~~	~~0.0938~~	~~0.57~~	~~567.7~~	~~6.4~~	~~575.8~~	~~2.8~~	~~577.8~~	~~3.1~~	~~1.9~~
14CJ07@23	B	76	0.60	19871	0.0588	0.62	0.726	0.88	0.0895	0.63	560.6	13.5	554.4	3.8	552.8	3.3	-1.4
14CJ07@24	B	127	0.61	27966	0.0585	0.49	0.711	0.75	0.0882	0.57	549.7	10.6	545.6	3.2	544.7	3.0	-1.0
14CJ07@25	B	103	0.57	11814	0.0589	0.54	0.725	0.91	0.0893	0.73	562.0	11.8	553.4	3.9	551.3	3.9	-2.0
~~14CJ07@26~~	B	~~352~~	~~0.87~~	~~2732~~	~~0.0581~~	~~0.76~~	~~0.730~~	~~0.94~~	~~0.0911~~	~~0.55~~	~~533.6~~	~~16.5~~	~~556.4~~	~~4.0~~	~~561.9~~	~~3.0~~	~~5.5~~

14CJ07@27	B	266	0.73	42690	0.0585	0.36	0.719	0.66	0.0891	0.56	547.7	7.7	549.8	2.8	550.3	2.9	0.5
14CJ07@28	B	227	0.63	16860	0.0590	1.06	0.726	1.20	0.0892	0.57	565.7	23.0	554.0	5.2	551.1	3.0	-2.7
14CJ07@29	B	141	0.61	37134	0.0587	0.42	0.735	0.70	0.0909	0.56	555.3	9.2	559.5	3.0	560.6	3.0	1.0
~~14CJ07@30~~	B	~~182~~	~~0.74~~	~~391~~	~~0.0582~~	~~3.79~~	~~0.721~~	~~3.83~~	~~0.0899~~	~~0.55~~	~~537.1~~	~~80.8~~	~~551.3~~	~~16.4~~	~~554.8~~	~~2.9~~	~~3.4~~
14CJ07@31	B	303	0.84	31211	0.0585	0.37	0.718	0.67	0.0890	0.55	549.5	8.2	549.4	2.8	549.4	2.9	0.0
14CJ07@32	B	183	0.74	41113	0.0584	0.38	0.712	0.70	0.0884	0.58	546.3	8.4	545.9	3.0	545.8	3.1	-0.1
14CJ07@33	B	295	0.88	13812	0.0588	0.30	0.713	0.67	0.0880	0.60	559.4	6.5	546.6	2.8	543.5	3.1	-3.0
14CJ07@34	B	191	0.75	23098	0.0586	0.38	0.712	0.67	0.0882	0.56	551.9	8.2	546.1	2.9	544.7	2.9	-1.4
14CJ07@35	B	545	1.03	32548	0.0587	0.24	0.730	0.61	0.0903	0.55	555.2	5.3	556.8	2.6	557.2	3.0	0.4
14CJ07@36	B	166	0.75	15392	0.0589	0.41	0.723	0.79	0.0890	0.68	564.2	8.9	552.3	3.4	549.4	3.6	-2.7
~~14CJ07@37~~	B	~~247~~	~~0.96~~	~~3166~~	~~0.0588~~	~~0.62~~	~~0.716~~	~~1.00~~	~~0.0883~~	~~0.78~~	~~559.3~~	~~13.4~~	~~548.3~~	~~4.2~~	~~545.6~~	~~4.1~~	~~-2.5~~
~~14CJ07@38~~	B	~~152~~	~~0.79~~	~~9925~~	~~0.0577~~	~~0.54~~	~~0.691~~	~~0.78~~	~~0.0868~~	~~0.56~~	~~517.8~~	~~11.9~~	~~533.1~~	~~3.3~~	~~536.7~~	~~2.9~~	~~3.8~~
14CJ07@39	B	179	2.06	18990	0.0589	0.39	0.730	0.75	0.0899	0.64	562.0	8.5	556.5	3.2	555.1	3.4	-1.3
14CJ07@40	B	367	0.83	23684	0.0586	0.27	0.735	0.62	0.0909	0.56	553.7	6.0	559.4	2.7	560.7	3.0	1.3
14CJ07@41	B	238	0.53	44655	0.0585	0.54	0.712	0.77	0.0884	0.55	546.8	11.7	546.1	3.3	545.9	2.9	-0.2
14CJ07@42	B	67	0.60	10299	0.0590	0.64	0.721	0.85	0.0887	0.56	566.9	13.8	551.5	3.6	547.7	2.9	-3.5
14CJ07@43	B	187	1.03	41999	0.0585	0.39	0.720	0.70	0.0893	0.58	546.9	8.6	550.5	3.0	551.3	3.0	0.8
14CJ07@44	B	128	0.62	27603	0.0586	0.49	0.719	0.75	0.0890	0.57	552.6	10.6	550.3	3.2	549.8	3.0	-0.5
14CJ07@45	B	179	0.66	36561	0.0586	0.38	0.726	0.74	0.0898	0.63	553.8	8.4	554.1	3.2	554.2	3.4	0.1
14CJ07@46	B	454	0.94	17212	0.0585	0.26	0.720	0.78	0.0892	0.73	549.8	5.8	550.7	3.3	550.9	3.9	0.2
14CJ07@47	B	301	0.64	63740	0.0585	0.30	0.719	0.63	0.0891	0.56	549.9	6.6	550.0	2.7	550.0	2.9	0.0
14CJ07@48	B	87	0.56	17976	0.0583	0.63	0.701	0.84	0.0872	0.55	540.3	13.7	539.2	3.5	538.9	2.9	-0.3
14CJ07@49	B	154	0.68	21791	0.0582	0.46	0.705	0.72	0.0879	0.56	536.9	10.0	542.0	3.0	543.2	2.9	1.2
~~14CJ07@50~~	B	~~202~~	~~0.71~~	~~4663~~	~~0.0625~~	~~0.65~~	~~0.896~~	~~0.88~~	~~0.1039~~	~~0.60~~	~~692.9~~	~~13.8~~	~~649.7~~	~~4.2~~	~~637.4~~	~~3.6~~	~~-8.4~~
14YCP02@01	A	180	1.50	35519	0.0583	0.47	0.708	0.89	0.0881	0.75	539.6	10.3	543.5	3.8	544.5	3.9	0.9
14YCP02@02	A	129	1.26	24768	0.0580	0.79	0.694	1.10	0.0868	0.76	529.2	17.2	535.1	4.6	536.4	3.9	1.4
14YCP02@03	A	132	1.09	60566	0.0583	0.52	0.700	0.92	0.0871	0.75	540.0	11.4	538.7	3.8	538.4	3.9	-0.3
14YCP02@04	A	89	1.73	29577	0.0586	0.84	0.707	1.14	0.0875	0.77	551.3	18.1	542.7	4.8	540.6	4.0	-2.0
14YCP02@05	A	149	1.48	35862	0.0585	0.51	0.713	0.94	0.0883	0.78	549.3	11.2	546.3	4.0	545.5	4.1	-0.7

14YCP02@06	A	459	0.09	83406	0.0584	0.35	0.714	0.84	0.0888	0.77	543.0	7.5	547.3	3.6	548.4	4.0	1.0
14YCP02@07	A	83	1.48	14430	0.0587	0.73	0.720	1.06	0.0889	0.77	556.1	15.9	550.6	4.5	549.3	4.1	-1.3
14YCP02@08	A	149	2.45	27030	0.0587	0.55	0.712	0.93	0.0880	0.75	554.6	11.9	545.8	3.9	543.7	3.9	-2.0
14YCP02@09	A	243	2.28	16148	0.0586	0.52	0.707	0.91	0.0875	0.75	553.7	11.3	543.1	3.8	540.6	3.9	-2.5
~~14YCP02@10~~	A	~~179~~	~~0.79~~	~~142~~	~~0.0584~~	~~19.08~~	~~0.729~~	~~19.10~~	~~0.0906~~	~~0.86~~	~~543.8~~	~~370.2~~	~~556.3~~	~~85.3~~	~~559.3~~	~~4.6~~	~~3.0~~
14YCP02@11	A	191	1.70	28771	0.0586	0.69	0.717	1.02	0.0889	0.76	550.7	15.0	549.2	4.4	548.8	4.0	-0.4
14YCP02@12	A	275	2.81	59470	0.0585	0.39	0.718	0.84	0.0889	0.75	549.8	8.4	549.4	3.6	549.3	3.9	-0.1
14YCP02@13	A	714	0.48	114013	0.0586	0.22	0.724	0.78	0.0897	0.75	551.3	4.8	553.3	3.3	553.8	4.0	0.5
~~14YCP02@14~~	A	~~158~~	~~6.48~~	~~3004~~	~~0.0580~~	~~5.62~~	~~0.572~~	~~9.40~~	~~0.0716~~	~~7.53~~	~~528.2~~	~~118.7~~	~~459.5~~	~~35.4~~	~~445.9~~	~~32.5~~	~~-16.1~~
14YCP02@15	A	236	0.36	44621	0.0585	0.39	0.714	0.87	0.0885	0.77	549.7	8.6	547.1	3.7	546.5	4.0	-0.6
14YCP02@16	A	171	1.99	33233	0.0584	0.48	0.694	0.91	0.0861	0.77	545.9	10.4	535.0	3.8	532.5	4.0	-2.6
~~14YCP02@17~~	A	~~184~~	~~1.13~~	~~7356~~	~~0.0588~~	~~1.09~~	~~0.682~~	~~1.32~~	~~0.0842~~	~~0.75~~	~~559.7~~	~~23.5~~	~~528.2~~	~~5.4~~	~~521.0~~	~~3.8~~	~~-7.2~~
14YCP02@18	A	171	2.06	34179	0.0584	0.44	0.720	0.89	0.0895	0.77	543.8	9.7	550.9	3.8	552.7	4.1	1.7
14YCP02@19	A	560	2.04	68824	0.0584	0.25	0.712	0.80	0.0885	0.76	543.1	5.4	546.1	3.4	546.8	4.0	0.7
14YCP02@20	A	187	1.33	27453	0.0583	0.43	0.715	0.87	0.0889	0.76	541.6	9.3	547.5	3.7	549.0	4.0	1.4
14YCP02@21	A	241	1.01	53854	0.0585	0.42	0.718	0.86	0.0889	0.75	550.1	9.2	549.5	3.7	549.3	4.0	-0.1
14YCP02@22	A	74	0.94	20550	0.0584	0.67	0.700	1.01	0.0870	0.75	544.5	14.7	539.1	4.2	537.8	3.9	-1.3
14YCP02@23	A	198	0.76	33761	0.0585	0.41	0.708	0.87	0.0878	0.76	548.2	9.0	543.7	3.7	542.6	4.0	-1.1
14YCP02@24	A	69	0.91	21565	0.0579	0.69	0.693	1.10	0.0869	0.85	525.7	15.1	534.8	4.6	536.9	4.4	2.2
14YCP02@25	A	144	1.35	49199	0.0584	0.50	0.688	1.07	0.0854	0.94	545.8	10.9	531.6	4.4	528.3	4.8	-3.3
14YCP02@26	A	280	1.63	27889	0.0585	0.61	0.699	1.06	0.0867	0.87	547.5	13.3	538.3	4.5	536.1	4.5	-2.2
~~14YCP02@27~~	A	~~251~~	~~1.67~~	~~66634~~	~~0.0597~~	~~0.36~~	~~0.781~~	~~0.86~~	~~0.0948~~	~~0.79~~	~~594.0~~	~~7.7~~	~~585.9~~	~~3.9~~	~~583.8~~	~~4.4~~	~~-1.8~~
14YCP02@28	A	256	1.45	63527	0.0584	0.36	0.714	0.84	0.0886	0.76	545.1	7.8	546.8	3.6	547.2	4.0	0.4
14YCP02@29	A	140	1.29	26676	0.0584	0.59	0.713	0.96	0.0886	0.76	543.5	12.9	546.3	4.1	547.0	4.0	0.7
14YCP02@30	A	241	1.35	40168	0.0585	0.38	0.708	0.85	0.0879	0.76	546.9	8.3	543.9	3.6	543.1	4.0	-0.7
~~14YCP02@31~~	A	~~47~~	~~1.56~~	~~8596~~	~~0.0585~~	~~0.83~~	~~0.689~~	~~1.33~~	~~0.0854~~	~~1.04~~	~~549.5~~	~~18.0~~	~~532.2~~	~~5.5~~	~~528.2~~	~~5.3~~	~~-4.0~~
14YCP02@32	A	114	1.35	28170	0.0585	0.52	0.710	0.94	0.0881	0.78	548.9	11.4	545.0	4.0	544.0	4.1	-0.9
14YCP02@33	A	152	2.54	29242	0.0580	0.50	0.678	0.94	0.0849	0.80	528.7	11.0	525.7	3.9	525.0	4.0	-0.7
14YCP02@34	A	347	2.53	55309	0.0586	0.30	0.726	0.82	0.0898	0.76	553.6	6.6	554.4	3.5	554.6	4.0	0.2
14YCP02@35	A	236	0.80	61510	0.0583	0.42	0.697	1.16	0.0868	1.08	540.0	9.1	537.1	4.8	536.4	5.6	-0.7

14YCP02@36	A	176	1.93	17264	0.0586	0.41	0.728	0.88	0.0901	0.78	551.5	9.0	555.1	3.8	556.0	4.2	0.9
14YCP02@37	A	460	1.57	74944	0.0584	0.26	0.705	0.79	0.0876	0.75	544.4	5.7	541.7	3.3	541.1	3.9	-0.6
14YCP02@38	A	183	10.56	47554	0.0582	0.41	0.699	0.86	0.0871	0.75	538.3	9.0	538.3	3.6	538.3	3.9	0.0
14YCP02@39	A	109	0.99	27207	0.0583	0.61	0.706	0.97	0.0879	0.75	539.9	13.3	542.5	4.1	543.1	3.9	0.6
14YCP02@40	A	91	1.26	25455	0.0585	0.70	0.710	1.03	0.0880	0.75	547.9	15.3	544.6	4.3	543.7	3.9	-0.8
14YCP02@41	A	136	2.00	32791	0.0586	0.48	0.714	0.91	0.0884	0.77	552.1	10.4	547.4	3.8	546.3	4.0	-1.1
14YCP02@42	A	121	1.50	29885	0.0579	0.53	0.687	0.93	0.0861	0.75	524.5	11.7	530.9	3.8	532.4	3.9	1.6
14YCP02@43	A	302	0.66	81276	0.0582	0.37	0.700	0.84	0.0872	0.75	536.9	8.2	538.7	3.5	539.2	3.9	0.4
14YCP02@44	A	853	1.24	50917	0.0586	0.20	0.719	0.78	0.0890	0.76	552.3	4.4	550.0	3.3	549.5	4.0	-0.5
14YCP02@45	A	224	1.56	49367	0.0582	0.41	0.691	0.86	0.0862	0.75	536.3	8.9	533.7	3.6	533.1	3.9	-0.6
14YCP02@46	A	81	1.23	29362	0.0589	0.66	0.702	1.03	0.0864	0.79	564.5	14.3	539.8	4.3	533.9	4.0	-5.6
~~14YCP02@47~~	A	~~147~~	~~2.16~~	~~9635~~	~~0.0580~~	~~0.70~~	~~0.709~~	~~1.04~~	~~0.0887~~	~~0.76~~	~~529.9~~	~~15.3~~	~~544.3~~	~~4.4~~	~~547.8~~	~~4.0~~	~~3.5~~
14YCP02@48	A	348	0.84	71703	0.0587	0.33	0.713	0.85	0.0882	0.78	554.3	7.2	546.7	3.6	544.9	4.1	-1.8
14YCP02@49	A	123	1.80	37266	0.0584	0.63	0.707	1.10	0.0879	0.89	543.7	13.8	543.2	4.6	543.1	4.7	-0.1
14YCP02@50	A	268	1.84	47745	0.0584	0.33	0.716	0.82	0.0889	0.75	543.8	7.3	548.1	3.5	549.1	4.0	1.0