Geochronological constraint on the Cambrian Chengjiang biota, South China

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Short title for the running headlines: Zircon U-Pb age of the Chengjiang biota
Abstract

The Cambrian Chengjiang biota of South China provided compelling fossil evidence for the rapid appearance of metazoan phyla in the Earth history (“Cambrian explosion”). However, the timing of the Chengjiang biota is poorly constrained due to lack of dateable rock materials within the Maotianshan Shale that yields the fossils. Here we integrate SIMS and CA-ID-TIMS U-Pb analyses of detrital zircons from the Maotianshan Shale to provide high precision geochronological constraint on the Chengjiang biota. The youngest group of SIMS U-Pb detrital zircon dates yields an age peak at 520 Ma. Six zircons from this group are further dated by CA-ID-TIMS U-Pb technique, but suggesting that they were not formed from a single zircon growth event. Thereby neither the age peak nor the weighted mean age defined by the youngest SIMS U-Pb dates could represent the maximum depositional age of Maotianshan Shale. Instead, the youngest CA-ID-TIMS U-Pb date, 518.03 ± 0.69/0.71 Ma (2σ, analytical uncertainty/ incorporates U-Pb tracer calibration uncertainty), provides the first robust maximum age of the Chengjiang biota. This new geochronological constraint on the Chengjiang biota indicates that the Cambrian explosion reached its major phase around 518.03 ± 0.69/0.71 Ma, demonstrating a protracted process (> 22 myr) of the Cambrian explosion.
The Chengjiang biota from the Cambrian Maotianshan Shale Member of the Yu’anshan Formation in South China, characterized by exceptionally well-preserved soft-bodied and weakly biomineralized fossils, shows the major phase of the Cambrian explosion of metazoans (e.g., Chen et al. 1996; Li et al. 2007; Shu 2008; Zhang & Shu 2014). This biota contains nearly all the present animal phyla including Chordata (e.g., Chen et al. 1999; Shu et al. 1999; Hou et al. 2017), providing a unique window into metazoan diversity and ecosystems in the early Cambrian Period (Zhao et al. 2010, 2012). Although it has been studied more than 30 years, there is no high precision geochronological constraint on the Chengjiang biota. The current Cambrian chronostratigraphic model does not help to provide direct age constraint on the Chengjiang biota either (Peng et al. 2012), ultimately hampering to estimate the rate of the Cambrian explosion process.

Owing to the lack of ash bed in the Yu’anshan Formation, several Rb-Sr, Ar-Ar and Pb-Pb analyses were conducted on the whole-rock and illite samples to directly determine the depositional age. These dating results range from ca. 560 Ma to ca. 534 Ma with large analytical errors (e.g., Chen et al. 2001; Chang et al. 2004). A SHRIMP (Sensitive High Resolution Ion Microprobe) zircon U-Pb age of 526.5 ± 1.1 Ma has been determined from an ash bed at the bottom of the underlying Shiyantou Formation (Fig. 1; Compston et al. 2008), providing the lower bracket of the age of Chengjiang biota. A breakthrough was made in recent years by analysing SIMS (Secondary Ion Mass Spectrometry) U-Pb ages of detrital zircons from basal Shiyantou Formation to the Maotianshan Shale Member, and the results demonstrate that the maximum age for the deposition of the Maotianshan Shale is ~520 Ma (Hofmann et al. 2016). However, taking into account of an external uncertainty of 1% (2 SD) for SIMS zircon U-Pb technique (e.g., Ireland & Williams 2003), the age
constraint on the Chengjiang biota needs to be refined further. Here we aim to get the high precision geochronological constraint on the Chengjiang biota using an integrated approach that includes SIMS and CA-ID-TIMS (Chemical Abrasion-Isotope Dilution-Thermal Ionization Mass Spectrometry) zircon U-Pb analytical methods. Our new results demonstrate that the age of the Chengjiang biota is not earlier than $518.03 \pm 0.69/0.71$ Ma, and the Cambrian explosion may have lasted more than 22 million years.

**Geological background and sampling**

The early Cambrian Chengjiang biota occurs in the Maotianshan Shale Member of the Yu’anshan Formation in eastern Yunnan Province, South China (Fig. 1). It has been discovered at numerous localities in eastern Yunnan Province, and the best-preserved fossils and quarries occur in Chengjiang-Haikou-Anning areas (Zhao et al. 2010). The studied Xiaolantian section is located about 6 km to the east of Chengjiang County town, and about 3 km away from the Maotianshan section where the Chengjiang biota was first discovered (Fig. 1).

The early Cambrian succession of the Xiaolantian section deposited in a shallow marine setting includes upward in order the Zhujiaqing, Shiyantou, and Yu’anshan formations (Fig. 1; Zhu et al. 2001). The Zhujiaqing Formation consists of three members in eastern Yunnan Province, upward in order, Daibu, Zhongyicun and Dahai members. In the Xiaolantian section, the Daibu Member is composed predominately of cherty dolostone. The Zhongyicun Member measures 37 meters thick and is composed of dolomitic phosphate with interlayered phosphate. The Dahai Member is absent in this section. Unconformably overlying the Zhujiaqing Formation is the Shiyantou Formation, which is about 52 meters thick and consists of siltstone. The
Yu’anshan Formation is 170 meters thick and consists of three members, namely the lower Black Shale Member, the middle Maotianshan Shale Member, and the upper Siltstone Member (Zhao et al. 2012). Regional stratigraphic correlation indicates that *Anabarites trisulcatus-Protohertzina anabarica* Assemblage Zone and *Paragloborilus subglobosus-Purella squamulosa* Assemblage Zone occur in the Daibu-lower middle Zhongyicun members and the upper Zhongyicun Member, respectively (Fig. 1; Yang et al. 2014, 2016a). *Sinosachites flabelliformis-Tannuolina zhangwentangi* Assemblage Zone occurs in the upper part of the Shiyantou Formation, and extends to the basal Yu’anshan formations; *Parabadiella* Zone occurs in the lower Yu’anshan Formation and *Eoredlichia-Wutingaspis* Zone occurs in the overlying Maotianshan Shale Member (Fig. 1; Zhu et al. 2001; Steiner et al. 2007; Yang et al. 2014, 2016a).

Two SIMS zircon U-Pb ages of 535.2 ± 1.7 Ma and 526.5 ± 1.1 Ma have been dated from ash beds in the middle Zhongyicun Member and at the base of the Shiyantou Formation in the Meishucun section in the same area, respectively (Fig. 1; Compston et al. 2008; Zhu et al. 2009).

Two samples (14CJ-2 and 14CJ-3) from the lower part of Maotianshan Shale Member in the Xiaolantian section (24°40′53″N, 102°58′50″E) were collected for SIMS and CA-ID-TIMS zircon U-Pb dating (Fig. 1). Sample 14CJ-2 is a fine-grained siltstone, and sample 14CJ-3 is a mudstone which locates about 60 cm above 14CJ-2 (Fig. 2).

**Zircon U-Pb dating methods**

Separated zircon crystals were mounted in an epoxy resin together with zircon standards Plešovice, 91500, Penglai and Qinghu. All zircon grains were documented with transmitted and reflected light photomicrographs and cathodoluminescence
images to reveal their external and internal structures, and the mount was vacuum-coated with high-purity gold prior to SIMS U-Pb analysis. Measurements of U, Th and Pb isotopes were conducted using a Cameca 1280HR SIMS at the Institute of Geology and Geophysics, Chinese Academy of Sciences. A single electron multiplier was used in ion-counting mode to measure secondary ion beam intensities by peak jumping. Each measurement consists of 7 cycles, and the total analytical time is about 12 minutes. Detailed SIMS zircon U-Pb analytical method is described by Li et al. (2009). Analyses of standard zircon grains were interspersed with those unknown grains. A long-term uncertainty of 1.5% (1 RSD) for $^{206}\text{Pb}^{238}\text{U}$ measurements of the standard zircon was propagated to the unknowns (Li et al. 2010), because all the analysed grains are detrital zircons. 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 $^{204}\text{Pb}$-method. Corrections are sufficiently small to be insensitive to the choice of common Pb composition. 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. Data reduction was carried out using the Isoplot/Exv. 4.15. More details for calibration methods are described by Li et al. (2009). In order to monitor the external uncertainties of SIMS U-Pb measurements, analyses of zircon standard Qinghu were interspersed with unknowns. 20 analyses yielded a weighted mean $^{238}\text{U}^{206}\text{Pb}$ age of 159.4 ± 1.1 Ma (MSWD = 0.44, 95% confidence interval), identical within errors to the reported age of 159.5 ± 0.2 Ma (Li et al. 2013).

Zircons of the youngest $^{238}\text{U}^{206}\text{Pb}$ date population were micro-drilled off from the
SIMS mount for CA-ID-TIMS analysis in the NERC Isotope Geosciences Laboratory (NIGL), British Geological Survey. Zircons were annealed in a muffle furnace at 900°C for ~60 hours in quartz beakers before being transferred to 3 ml Hex Savillex beakers. After ultrasonic bath and rinsing by 30% HNO₃, zircons were transferred to 300 μl Teflon PFA microcapsules, leached in ~5:1 mix of 29M HF + 30% HNO₃ for 12 hours at 180°C (Mattinson 2005). Then the acid solution was removed, and zircons were rinsed again by 30% HNO₃ and 6M HCl before spiking with the mixed EARTHTIME ²³⁵U-²³³U-²⁰⁵Pb tracer (Condon et al. 2015). The single zircons were dissolved in ~ 120 μl of 29M HF with a trace amount of 30% HNO₃ at 220°C for 48 hours. After converting the dried fluorides into chlorides in 3M HCl at ~180°C overnight, U and Pb were separated using standard HCl-based anion-exchange chromatographic procedures on 0.05 ml PTFE columns. Pb and U were loaded together on a single Re filament in a silica-gel/phosphoric acid mixture, and analysed by the Thermo-Electron Triton Thermal Ionisation Mass-Spectrometer in NIGL. Pb isotopes were measured by peak-hopping on a single SEM detector. U isotope measurements were made in static Faraday mode or on a single SEM detector, based on the uranium content. Age calculations and uncertainty estimation were made using the Tripoli and ET_Redux (Bowring et al. 2011).

Both SIMS and CA-ID-TIMS U-Pb dates are calculated using the ²³⁵U and ²³⁴U decay constants of Jaffey et al. (1971). SIMS and CA-ID-TIMS zircon U-Pb data are given in the Appendix Table 1 and Table 2, respectively, and uncertainties on individual analysis are reported at 2σ level in the main text. The CA-ID-TIMS ²³⁸U-²⁰⁶Pb date uncertainties are presented as ± X/Y in this study, where X is the uncertainty arising solely from internal or analytical uncertainty, and Y includes X and the tracer calibration uncertainty. The systematic uncertainty associated with ²³⁸U
decay constant also needs to be propagated if it is compared with other chronometers such as Ar-Ar or astrochronology. For interpretation of the zircon ages only concordant or nearly concordant (<10% discordant) data were included. The measured $^{207}\text{Pb}^{206}\text{Pb}$ and $^{238}\text{U}^{206}\text{Pb}$ dates are used for zircons older and younger than 1000 Ma, respectively, for plotting the zircon age probability histograms.

**Results**

**SIMS zircon U-Pb results**

Zircons from sample 14CJ-2 are 70-120 μm in length and have aspect ratios of 1-3. Most of them are euhedral and subhedral in morphology, with a small portion of rounded grains. Except for a few grains showing no oscillatory zoning, most zircons have oscillatory zoning under CL images. Th/U ratios of the analysed zircons range from 0.22 to 3.92 (mostly within 0.22-2.06). These features indicate that nearly all the analysed zircons are of magmatic origin (Fig. 3). Of the 113 analyses on 113 zircons from this sample, 99 are concordant within uncertainties. The measured $^{238}\text{U}^{206}\text{Pb}$ (< 1000 Ma) and $^{207}\text{Pb}^{206}\text{Pb}$ (> 1000 Ma) dates range from 492 ± 14 Ma to 3083 ± 10 Ma. Apart from the youngest date which is a little discordant (492 ± 14 Ma, discordance = 6.1%), the youngest population includes four dates, namely 515 ± 14 Ma, 518 ± 16 Ma, 524 ± 16 Ma and 528 ± 16 Ma, forming a peak at 520 Ma. Other four older age peaks are present at ca. 605 Ma, ca. 800 Ma, ca. 1025 Ma and ca. 2510 Ma (Fig. 4a).

Zircons from sample 14CJ-3 are similar with those from 14CJ-2. Thirty-nine zircon U-Pb dates out of 43 analyses are concordant within uncertainty. The measured $^{238}\text{U}^{206}\text{Pb}$ (< 1000 Ma) and $^{207}\text{Pb}^{206}\text{Pb}$ (> 1000 Ma) dates range from 499 ± 14 Ma to 2570 ± 18 Ma. They form the main peak at ca. 765 Ma, with a subordinate age peak at
ca. 960 Ma and one “broad” age group between 499 ± 14 Ma and 592 ± 18 Ma (Fig. 4b). The two youngest $^{238}\text{U}-^{206}\text{Pb}$ dates are 499 ± 14 Ma (z37) and 518 ± 16 Ma (z07).

**ID-TIMS zircon U-Pb results**

Five crack-free, inclusion-free, and texture uncomplicated zircons from the youngest populations of the two samples and one grain from sample LM-23-12 in Hofmann *et al.* (2016) were further dated by CA-ID-TIMS U-Pb method. Except for the grain 14CJ-3 z37 with very high Pbc (= 24.9 pg), other five grains yield useful dates. The $^{238}\text{U}-^{206}\text{Pb}$ dates of analysed zircons 14CJ-2 z02, 14CJ-2 z29, 14CJ-2 z66, 14CJ-3 z07, and LM-23-12 z45 are 524.33 ± 0.86/0.87 Ma, 527.79 ± 2.50/2.51 Ma, 584.42 ± 1.23/1.24 Ma, 518.03 ± 0.69/0.71 Ma, and 544.41 ± 4.21/4.21 Ma, respectively (Fig. 3, 5). They corroborate and refine the SIMS dates except for 14CJ-2 z66, whose SIMS date is a little discordant and unreliable (discordance = 6.1%). The youngest zircon 14CJ-3 z07 has low common Pb (Pbc = 0.28 pg), and its U-Pb date is concordant (discordance = -0.7%), indicating that its $^{238}\text{U}-^{206}\text{Pb}$ date, 518.03 ± 0.69/0.71 Ma, is highly reliable (Fig. 5).

**Discussion**

**Maximum age of the Chengjiang biota**

When interpreting the detrital zircon dates, only U-Pb data within analytical uncertainty of concordia should be used. A percentage date difference discordance filter, such as 10%, is often applied to categorize zircon U-Pb dataset. In this study, all the zircons of the youngest SIMS U-Pb date population pass the 10% discordance filter. However, zircon grain 14CJ-2 z66 with the youngest SIMS U-Pb date (492 ± 14 Ma) of sample 14CJ-2 has a discordance of 6.1% (Fig. 2), and its CA-ID-TIMS U-Pb
date is $584.42 \pm 1.23/1.24$ Ma which is significantly older than its SIMS U-Pb date, indicating that the extremely young SIMS U-Pb date of this grain results from Pb-loss (Fig. 5). Similarly, the grain 14CJ-3 z37 with the youngest SIMS U-Pb date ($499 \pm 14$ Ma) of sample 14CJ-3 has a discordance of 7.5%, and it incorporates high common Pb ($= 24.9$ pg), implying that its young SIMS U-Pb date is probably also caused by Pb-loss (Fig. 5). Consequently, the SIMS U-Pb results of grains 14CJ-2 z66 and 14CJ-3 z37 are not included in the following discussion.

There are several different strategies to constrain the maximum depositional ages of strata containing detrital zircons, such as the youngest single grain age, the youngest graphical age peak controlled by more than one single grain age, the weighted mean age of the youngest two or more grains with overlapping $1\sigma$ uncertainties, and the weighted mean age of youngest three or more grains that overlap in age at $2\sigma$ uncertainties (e.g., Dickinson & Gehrels 2009). Defining the maximum depositional age by the youngest age peak or a weighted mean age yielded from the youngest detrital zircon population has an assumption that those zircons are from a single zircon growth event. This assumption is not true for most sedimentary rocks. In this study, the youngest detrital zircon SIMS U-Pb age peak is ca. 520 Ma, and their weighted mean age is $520.3 \pm 6.7$ Ma ($2\sigma$, $n = 5$, MSWD = 0.5). The normal distribution pattern (Fig. 4) and the acceptable MSWD value of the weighted mean age (Fig. 5) imply that those zircons probably are from a single zircon growth event. However, the three CA-ID-TIMS U-Pb dates of zircons from this group are $524.33 \pm 0.86/0.87$ Ma, $527.79 \pm 2.50/2.51$ Ma, and $518.03 \pm 0.69/0.71$ Ma. They are not overlapping with each other within $2\sigma$ uncertainties (Fig. 5), and the MSWD value of their weighted mean age is extremely high, indicating that they are not from a single zircon growth event. Therefore none of the youngest age peak or the weighted mean
age defined by the youngest SIMS U-Pb population is meaningful and suitable to define the maximum depositional age.

In theory, using the youngest concordant zircon U-Pb date is the best strategy to constrain the maximum depositional age (e.g., Spencer et al. 2016). However, Pb-loss, common Pb incorporation, discordance, and analytical uncertainty would compromise this strategy, especially for the in situ SIMS and LA-ICPMS zircon U-Pb datasets. CA-ID-TIMS zircon U-Pb technique is capable of removing zircon domains that suffered Pb-loss, and yields the most precise and accurate U-Pb dates (e.g., Mattinson 2005). Therefore the youngest concordant CA-ID-TIMS U-Pb date of detrital zircons provides the most robust constraint on the maximum depositional age. However, the time-consuming character of the CA-ID-TIMS zircon U-Pb method makes it impractical to date a large number of detrital zircons to determine the youngest U-Pb date. SIMS U-Pb analysis of zircon is efficient and accurate with an external error of approximately 1%, and its “undamaged” analytical character makes it possible to perform the CA-ID-TIMS U-Pb analysis on the same zircon grain after SIMS U-Pb dating. As a result, integrating SIMS and CA-ID-TIMS zircon U-Pb techniques is the most promising method to constrain the depositional age of strata (e.g., Yang et al. 2017b), especially for those lacking ash bed interlayers.

SIMS U-Pb dating results in this study demonstrate that the youngest $^{238}\text{U-}^{206}\text{Pb}$ date peak of detrital zircons from the Maotianshan Shale samples 14CJ-2 and 14CJ-3 is ca. 520 Ma (Fig. 4), which also are confirmed with the results of Hofmann et al. (2016). Six zircons of the youngest SIMS U-Pb group are further dated by CA-ID-TIMS, yielding five useful U-Pb dates. They are not from a single zircon growth event as discussed above. The youngest CA-ID-TIMS $^{238}\text{U-}^{206}\text{Pb}$ date, 518.03 ± 0.69/0.71 Ma, provides the maximum depositional age of the sampling horizon in
the Maotianshan Shale, i.e., the maximum age of the Chengjiang biota. However, it should also be noted that the possibility of underestimating the maximum depositional age cannot be excluded because of possible Pb-loss even the zircon has been chemical abraded. Petrographic and geochemical analyses indicate that the provenance of the Maotianshan Shale was a recycled orogen overall, and it was less mature and included minor elements commonly associated with mafic sources (Hofmann et al. 2016). The characters of sedimentary provenance imply that sediments of the Xiaolantian section were possible to accumulate contemporary volcanic material, so that the sedimentary age of the Maotianshan Shale is likely close to the youngest zircon U-Pb date 518.03 ± 0.69/0.71 Ma determined by CA-ID-TIMS. A $^{207}$Pb-$^{206}$Pb date of 517.0 ± 1.5 Ma on the Antatlasia gutta-pluviae Zone (trilobites) of Morocco (Landing et al. 1998) probably constrains the minimum age of the Chengjiang biota based on the global biostratigraphic correlations (e.g., Peng et al. 2012; Yang et al. 2016b; Zhang et al. 2017). The new geochronological constraint confirms a Cambrian Age 3 depositional age for the Maotianshan Shale in Yunnan Province and is consistent with global chronostratigraphic correlation (Zhu et al. 2006, 2010).

**Geochronological constraint on the major phase of Cambrian explosion**

The Cambrian explosion delineates the unprecedented, unique evolutionary event that nearly all metazoan phyla made their first appearances in the fossil record in a relatively short time span during the Ediacaran-Cambrian transition, leading to the establishment of metazoan-dominated ecosystem accompanied by widespread biomineralization, as well as increases of size and morphological disparity among metazoan phyla (Zhang & Shu 2014). The diversification of coelomates that produced deep and complex burrows marks the first major stage of the Cambrian explosion,
which corresponds to the base of the Cambrian System (Landing et al. 2013). However, molecular clock studies demonstrate that the common ancestor of all metazoans originated prior to ca. 800 Ma with the bilaterians diversified at least 100 Ma before the Cambrian Period (e.g., dos Reis et al. 2015). In the perspective of fossil records, some complex trace fossils such as Treptichnus, Cambrian-type skeletal fossils such as Anabarites and Cambrotubulus, and the oldest triploblastic bilaterian Kimberella start their appearances before the Cambrian Period as well (Jensen et al. 2000; Gehling et al. 2001; Macdonald et al. 2014; Zhu et al. 2017). Both the molecular clock studies and fossil records imply a deep root for the Cambrian explosion of metazoans (Zhu et al. 2017).

The arthropods are the most diverse representatives of the Cambrian biotas younger than 520 Ma such as the Chengjiang biota (e.g., Li et al. 2007; Zhao et al. 2010). The trilobites form a clade in cladistic analyses of the Arthropoda (Wills et al. 1994). Thus, the first trilobite occurrence is a key biotic event in the Cambrian biostratigraphy and marks the most dramatic event in the modernization of ecologic communities in the Cambrian explosion, i.e. the onset of the major phase of the Cambrian explosion (Zhang et al. 2014, 2017). Also, the first appearance of trilobites has long been considered as the primary indicator to define the base of Cambrian Series 2 and Stage 3 (Peng et al. 2012; Zhang et al. 2017 for reviews). However, the first appearances of trilobites are endemic and diachronous on separate paleocontinents (Landing et al. 2013; Zhang et al. 2017). Geochronological constraints on the first appearances of trilobites are scarce. Zircon U-Pb age of 520.93 ± 0.14 Ma from the upper part of the Lie de vin Formation in Morocco (Maloof et al. 2010) provides a maximum geochronological constraint on the first determinable trilobite in this region (Geyer & Landing 2006). The first determinable trilobites in Avalonia including the olenelloid
Callavia broeggeri, which are relatively late among the early trilobites (Landing et al. 2013), are roughly constrained by an zircon U-Pb age of 519.30 ± 0.23 Ma from the Caerfai Bay Shales Formation in Wales (Harvey et al. 2011). Collectively, the occurrence of the first trilobites is possibly bracketed between 520.93 ± 0.14 Ma and 519.30 ± 0.23 Ma.

Generic diversity of South China indicates that metazoan diversity received the most significant boost in the middle Cambrian Age 3 due to the exceptional Chengjiang biota (Li et al. 2007), which is consistent with the global biodiversity data (Na & Kiessling 2015). Hosting 228 species in over 18 phyla of animals and displaying the well establishment of the modern style of the complex marine community (Fig. 6; Li et al. 2007; Zhao et al. 2010; Zhang & Shu 2014), the Chengjiang biota provides a unique window to show the major phase of the Cambrian explosion (Fig. 6). The maximum age of the Chengjiang biota is constrained at 518.03 ± 0.69/0.71 Ma, implying that the Cambrian explosion is a protracted evolutionary process (Erwin et al. 2011; Shu et al. 2014; Zhang & Shu 2014) which takes more than 22 million years. The onset of the major phase of Cambrian explosion is marked by the global first appearance of trilobites which is possibly bracketed between 520.93 ± 0.14 Ma and 519.30 ± 0.23 Ma. The major phase of Cambrian explosion represents a rapid episode of metazoan diversification in a relatively short time interval. This phase is followed by a diversity decline in Cambrian Age 4 which extended further through the rest of the Cambrian Period (Li et al. 2007; Na & Kiessling 2015).

Conclusions

We performed integrated SIMS and CA-ID-TIMS U-Pb dating on the detrital zircons from the Maotianshan Shale Member which yields the Chengjiang biota in
South China. The youngest detrital zircon population defines a SIMS U-Pb age peak at ca. 520 Ma. CA-ID-TIMS U-Pb dates of these zircons are scattered with the youngest concordant one at 518.03 ± 0.69/0.71 Ma, providing a maximum age for the Chengjiang biota. The new geochronological constraint on the Chengjiang biota indicates that the Cambrian explosion is a gradual and protracted evolutionary process, along with a rapid episode of metazoan diversification at around 518.03 ± 0.69/0.71 Ma.

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Figure captions

Figure 1. Generalized stratigraphic column of the Xiaolantian section, Chengjiang
County, eastern Yunnan, South China. The biostratigraphy is based on Steiner et al.
(2007) and Yang et al. (2016a), and radiometric ages come from Compston et al.
(2008), Zhu et al. (2009), and Yang et al. (2017a). Ashes beds are marked in red
lines.

Figure 2. Photomicrographs of siltstone sample 14CJ-2 (a) and mudstone sample
14CJ-3 (b).

Figure 3. CL images of zircons analysed by CA-ID-TIMS U-Pb technique. The
ellipses indicate the SIMS U-Pb analytical spots with 30 microns in length for
scale. SIMS zircon $^{238}\text{U}-^{206}\text{Pb}$ dates are presented in black color and CA-ID-TIMS
in red. All the zircon $^{238}\text{U}-^{206}\text{Pb}$ dates are quoted with $2\sigma$ uncertainty. Percentages
in the parentheses represent the discordances defined by the SIMS $^{238}\text{U}-^{206}\text{Pb}$ and
$^{207}\text{Pb}-^{206}\text{Pb}$ dates.

Figure 4. Age distribution patterns of detrital zircons from sample 14CJ-2 and 14CJ-3. $^{207}\text{Pb}-^{206}\text{Pb}$ ages are used for zircons older than 1000 Ma and $^{238}\text{U}-^{206}\text{Pb}$ ages for zircons younger than 1000 Ma. Only concordant or nearly concordant (<10% discordant) data are included.

Figure 5. $^{238}\text{U}-^{206}\text{Pb}$ results of the youngest detrital zircons analysed by SIMS and CA-ID-TIMS. Zircon $^{238}\text{U}-^{206}\text{Pb}$ dates are quoted with 2σ uncertainty in (b).

Figure 6. Cumulative phyla and classes through the late Ediacaran - early Cambrian Period in South China. Diversity data come from Zhang & Shu (2014), and radiometric (or estimated) ages are from Cohen et al. (2013), Yang et al. (2017a), and this study.