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 ± 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}Pb/^{238}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}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}U-^{206}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}U-^{206}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% HNO_3, zircons were transferred to 300 μl Teflon PFA microcapsules, leached in ~5:1 mix of 29M HF + 30% HNO_3 for 12 hours at 180°C (Mattinson 2005). Then the acid solution was removed, and zircons were rinsed again by 30% HNO_3 and 6M HCl before spiking with the mixed EARTHTIME ^{235}U-^{233}U-^{205}Pb tracer (Condon *et al*. 2015). The single zircons were dissolved in ~ 120 μl of 29M HF with a trace amount of 30% HNO_3 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 ^{238}U and ^{235}U 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 ^{238}U-^{206}Pb 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 ^{238}U

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}Pb-^{206}Pb and ^{238}U-^{206}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}U-^{206}Pb (< 1000 Ma) and ^{207}Pb-^{206}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}U-^{206}Pb (< 1000 Ma) and ^{207}Pb-^{206}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}U-^{206}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}U-^{206}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}U-^{206}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 ± 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 ± 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 1σ uncertainties, and the weighted mean age of youngest three or more grains that overlap in age at 2σ 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 ± 6.7 Ma (2σ, 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 ± 0.86/0.87 Ma, 527.79 ± 2.50/2.51 Ma, and 518.03 ± 0.69/0.71 Ma. They are not overlapping with each other within 2σ 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}U-^{206}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}U-^{206}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).

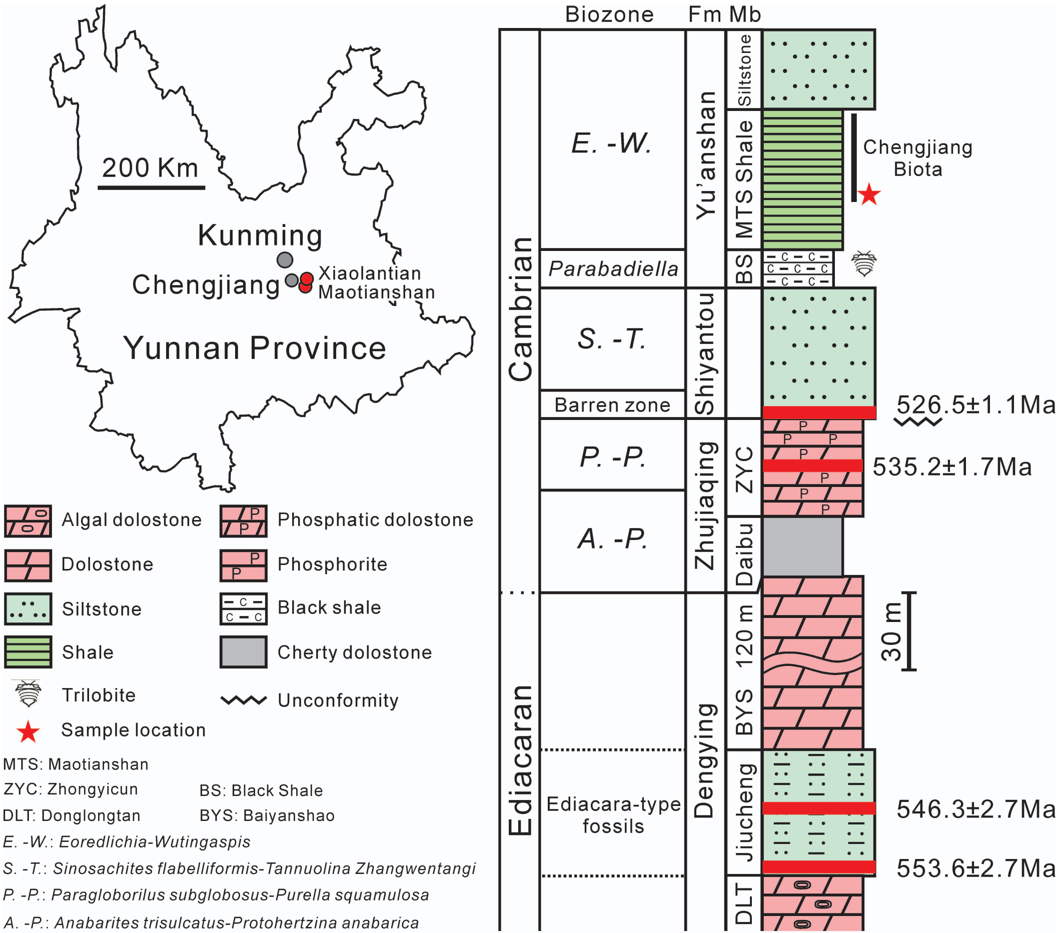
Figure 3. CL images of zircons analysed by CA-ID-TIMS U-Pb technique. The ellipses indicate the SIMS U-Pb analytical spots with 30 microns in length for scale. SIMS zircon ^{238}U-^{206}Pb dates are presented in black color and CA-ID-TIMS in red. All the zircon ^{238}U-^{206}Pb dates are quoted with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

^{207}Pb-^{206}Pb dates.

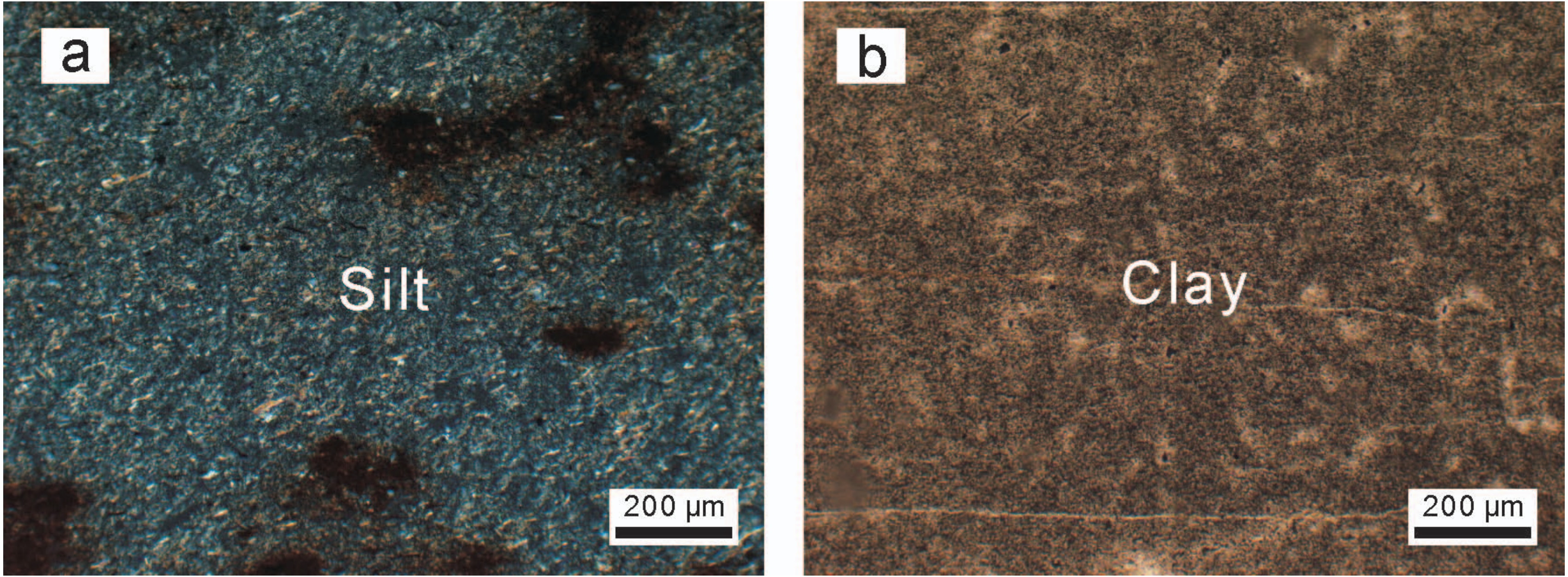
Figure 4. Age distribution patterns of detrital zircons from sample 14CJ-2 and 14CJ-3. ^{207}Pb-^{206}Pb ages are used for zircons older than 1000 Ma and ^{238}U-^{206}Pb ages for zircons younger than 1000 Ma. Only concordant or nearly concordant (<10% discordant) data are included.

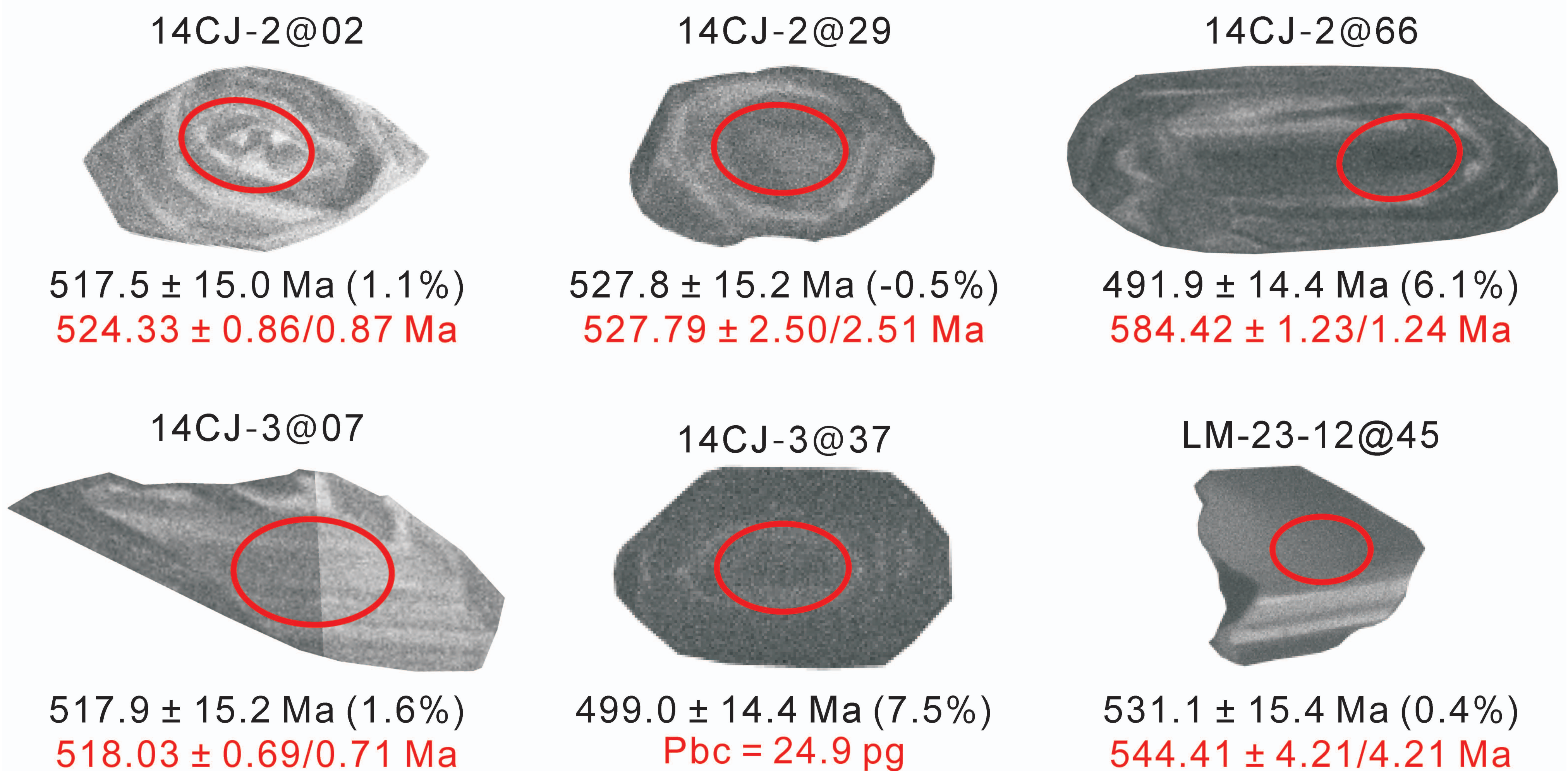
Figure 5. ^{238}U-^{206}Pb results of the youngest detrital zircons analysed by SIMS and CA-ID-TIMS. Zircon ^{238}U-^{206}Pb dates are quoted with 2σ uncertainty in (b).

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.

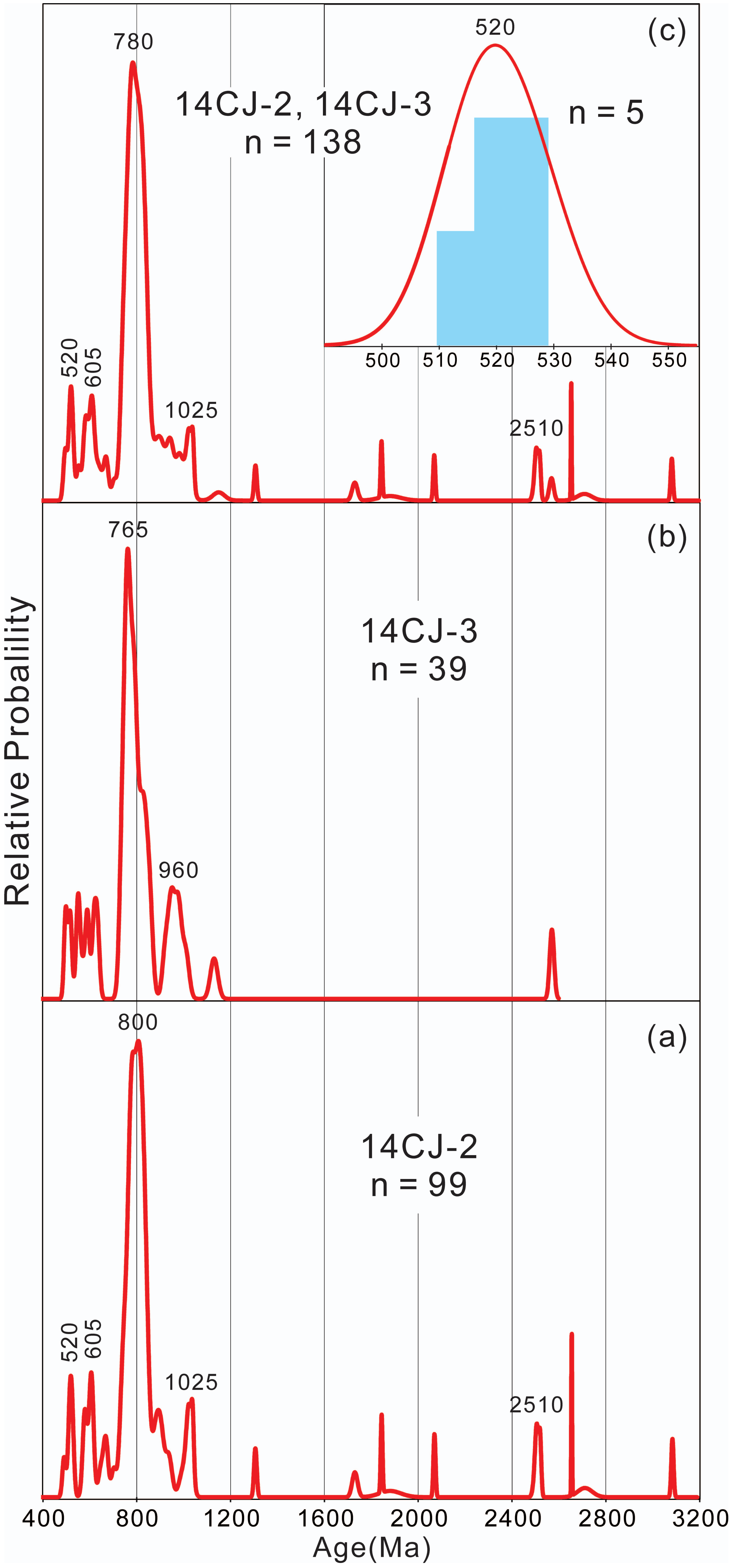


200 Km
Kunming
Chengjiang
Xiaolantian
Maotianshan
Yunnan Province
Biozone
Fm Mb
Cambrian
Ediacaran
E. -W.
Parabadiella
S. -T.
Barren zone
P. -P.
A. -P.
Ediacara-type fossils
Yu'anshan
Shiyantou
Zhujiaqing
Dengying
Siltstone
MTS Shale
BS
ZYC
Daibu
120 m
BYS
Jiucheng
DLT
Chengjiang Biota
526.5±1.1Ma
535.2±1.7Ma
546.3±2.7Ma
553.6±2.7Ma
30 m
Algal dolostone
Phosphatic dolostone
Dolostone
Phosphorite
Siltstone
Black shale
Shale
Cherty dolostone
Trilobite
Unconformity
Sample location
MTS: Maotianshan
ZYC: Zhongyicun
BS: Black Shale
DLT: Donglongtan
BYS: Baiyanshao
E. -W.: Eoredlichia-Wutingaspis
S. -T.: Sinosachites flabelliformis-Tannuolina Zhangwentangi
P. -P.: Paragloborilus subglobosus-Purella squamulosa
A. -P.: Anabarites trisulcatus-Protohertzina anabarica

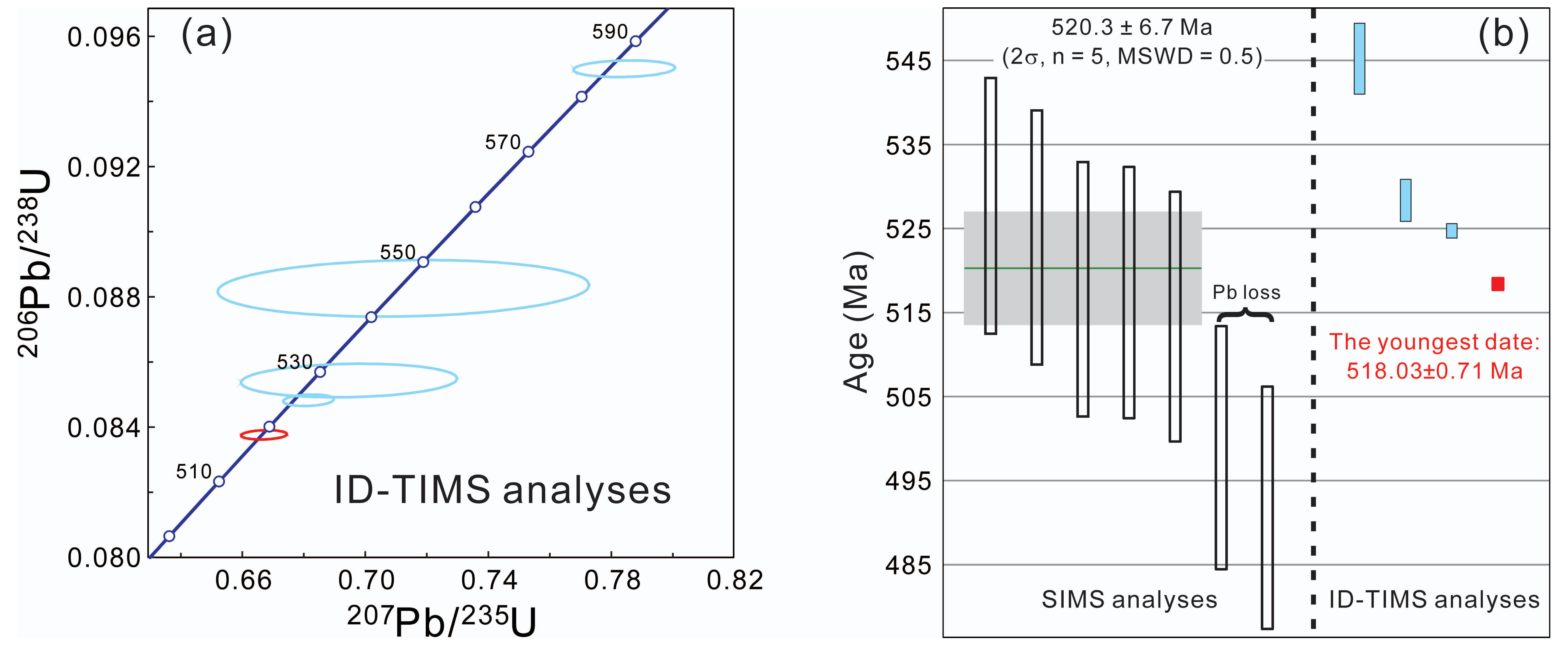

a
Silt
200 μm
b
Clay
200 μm



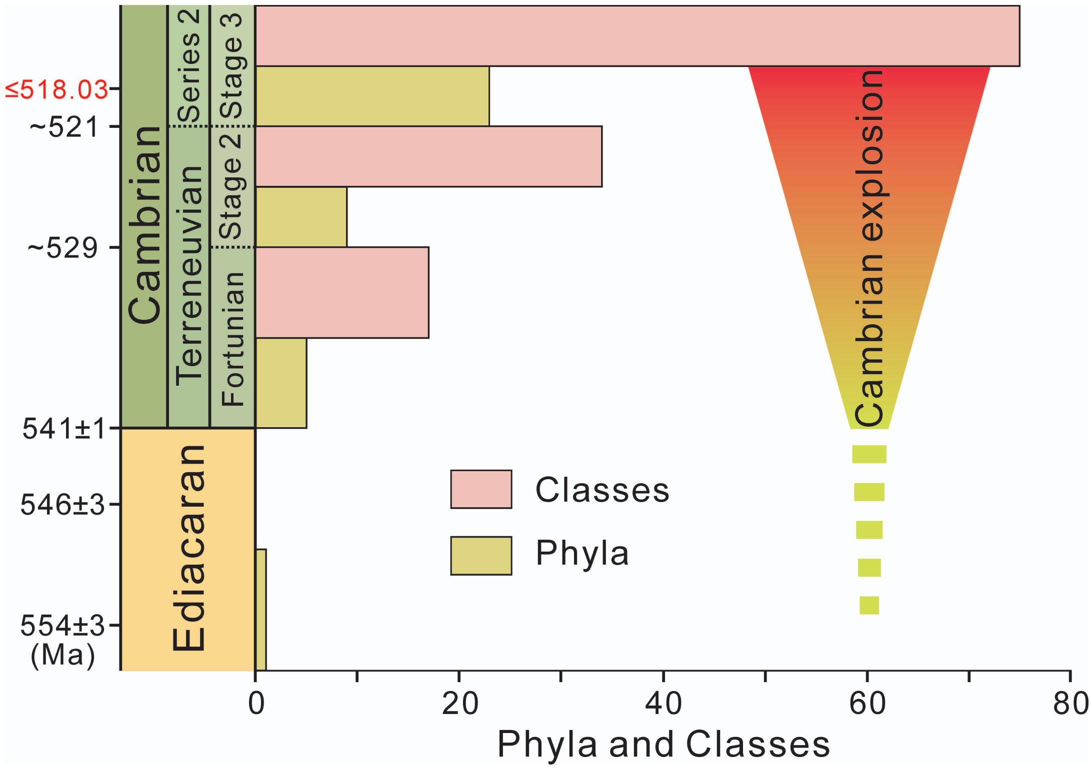
14CJ-2@02
517.5 ± 15.0 Ma (1.1%)
524.33 ± 0.86/0.87 Ma
14CJ-2@29
527.8 ± 15.2 Ma (-0.5%)
527.79 ± 2.50/2.51 Ma
14CJ-2@66
491.9 ± 14.4 Ma (6.1%)
584.42 ± 1.23/1.24 Ma
14CJ-3@07
517.9 ± 15.2 Ma (1.6%)
518.03 ± 0.69/0.71 Ma
14CJ-3@37
499.0 ± 14.4 Ma (7.5%)
Pbc = 24.9 pg
LM-23-12@45
531.1 ± 15.4 Ma (0.4%)
544.41 ± 4.21/4.21 Ma



(c)
780
14CJ-2, 14CJ-3
n = 138
520
n = 5
500
510
520
530
540
550
520
605
1025
2510
(b)
765
14CJ-3
n = 39
960
Relative Probability
(a)
800
14CJ-2
n = 99
520
605
1025
2510
400
800
1200
1600
2000
2400
2800
3200
Age(Ma)



(a)
590
570
550
530
510
ID-TIMS analyses
0.096
0.092
0.088
0.084
0.080
0.66
0.70
0.74
0.78
0.82
206Pb/238U
207Pb/235U
(b)
520.3 ± 6.7 Ma
(2σ, n = 5, MSWD = 0.5)
545
535
525
515
505
495
485
Age (Ma)
Pb loss
The youngest date:
518.03±0.71 Ma
SIMS analyses
ID-TIMS analyses


≤518.03
~521
~529
541±1
546±3
554±3
(Ma)
Cambrian
Series 2
Terreneuvian
Stage 3
Stage 2
Fortunian
Ediacaran
Cambrian explosion
Classes
Phyla
0
20
40
60
80
Phyla and Classes