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Age of Jurassic basal sauropods in Sichuan, China: A reappraisal of basal sauropod evolution

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ABSTRACT

Sauropoda are the largest terrestrial animals to have ever lived and represent the dominant herbivorous dinosaurs of the Mesozoic Era. The Lower Shaximiao Formation of the Sichuan Basin, Southwest China, hosts abundant Jurassic basal sauropods including the *Shunosaurus-Omeisaurus* Fauna. This formation was previously hypothesized to be Middle Jurassic based on biostratigraphic interpretations, but the exact depositional age is uncertain. Here we report the youngest inductively coupled plasma–mass spectrometry (ICP-MS) detrital zircon U-Pb age of 159 ± 2 Ma for fossil-bearing strata from this formation as the maximum depositional age. This age falls very close to the Oxfordian age interpreted for the *Shunosaurus-Omeisaurus* Fauna and is younger than previously proposed. We suggest that when the widely distributed basal sauropods of the Early-Middle Jurassic were mostly replaced by the phylogenetically more-derived neosauropods in the Late Jurassic in other regions of Laurasia and Gondwana, some more basal members survived and diversified in the Sichuan Basin of southwestern China.

INTRODUCTION

The earliest known sauropods were discovered in Late Triassic units—Norian stage—of Zimbabwe (McIntosh, 1990; Raath, 1972; Yates and Kitching, 2003) and Late Norian or Rhaetian units of Thailand (Buffetaut et al., 2000, 2002) (Fig. 1). Basal sauropods, here we mean sauropods more basal than Neosauropoda, also appeared sporadically in Early to Middle Jurassic localities of China, India, Europe, South America and Africa (e.g., Phillips, 1871; Raath, 1972; Weishampel, 1992; Monbaron et al., 1999; Buffetaut et al., 2000; Allain et al., 2004; Stumpf et al., 2015) (Fig. 1). They became more diversified phylogenetically and flourished in both hemispheres from the Middle Jurassic to the end of the Late Jurassic (Sereno, 1999a), possibly due to the breakup of Pangea (Chatterjee and Zheng, 2002).

In China, Early to Middle Jurassic fossils of basal sauropod only occur in Sichuan and Yunnan provinces (Dong et al., 1983; Dong, 1992). In Sichuan Province of southwest China, basal sauropod fossils unearthed from the Ziliujing Formation (ZLF) and Lower Shaximiao Formation (LSF) in the Sichuan Basin (SCB) are part of the *Zizhongosaurus* and *Shunosaurus-Omeisaurus* faunas (Figs. 2 and 3). These faunas are traditionally assigned Early and Middle Jurassic ages, respectively, based on biostratigraphic correlation of assemblage biozones (Dong et al., 1983; Dong, 1992; Li et al., 1997, 2011; Peng et al., 2005; Ye, 2006; Wang et al., 2008). Even though many studies have been conducted on the basal sauropods from the SCB in the past decades (e.g., Dong, 1992; He et al., 1988, 1998; Li, 1998), few have included geochronologic constraints due to the general lack of igneous bodies within Mesozoic sedimentary rocks. Here we report new detrital zircon U-Pb age determined by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) constraints for four dinosaur-bearing LSF sandstones found on the grounds of the Zigong Dinosaur Museum, Sichuan Province, China. Reliable age determinations for the LSF's fossil bearing beds are critical to understanding evolution and paleobiogeography of sauropods and other Early to Late Jurassic fossil assemblages. Thus, our inductively coupled plasma–mass spectrometry (ICP-MS) U-Pb zircon data provide novel geochronologic constraints on the evolutionary history of early sauropods.

GEOLOGICAL BACKGROUND

The intracratonic SCB is tectonically situated in the northwestern portion of the Yangtze block, surrounded by orogenic belts (Zhang et al., 2004; Liu et al., 2006) (Fig. 2). Numerous studies have described the widely-distributed Mesozoic stratigraphy of this basin (CCMSPSB, 1982; BGMRSP, 1991; Meng et al., 2005). Upper Triassic to Quaternary terrestrial facies reach thicknesses of 2000–6000 m and overlie carbonate-dominated Sinian to Middle Triassic marine facies (BGMRSP, 1991). Upper Triassic and Jurassic SCB sedimentary units consist mostly of typical lacustrine and fluvial facies, which include reddish conglomerates, sandstones and mudstones, referred to as red beds (Wang et al., 2008). Based on lithologic, paleontologic, and sedimentologic characteristics; these sequences are divided into the following formations, in ascending order: the Upper Triassic Xujiahe Formation, the Lower Jurassic Zhenzhuchong Formation and Ziliujing Formation (ZLF), the Middle Jurassic Xintiangou Formation (XTF), Lower Shaximiao Formation (LSF) and Upper Shaximiao Formation (USF), and the Upper Jurassic Suining Formation (SNF) and Penglaizhen Formation (PLF) (BGMRSP, 1991; Wang et al., 2010).

The SCB hosts a range of dinosaur body fossils representing 30 genera and 43 species (Wang et al., 2010) as well as trace fossils—footprints—representing 20 genera and 24 species (Ye et al., 2012). Given this diversity, the SCB is considered a classic locality for Jurassic dinosaurian research. The Middle Jurassic LSF and USF crop

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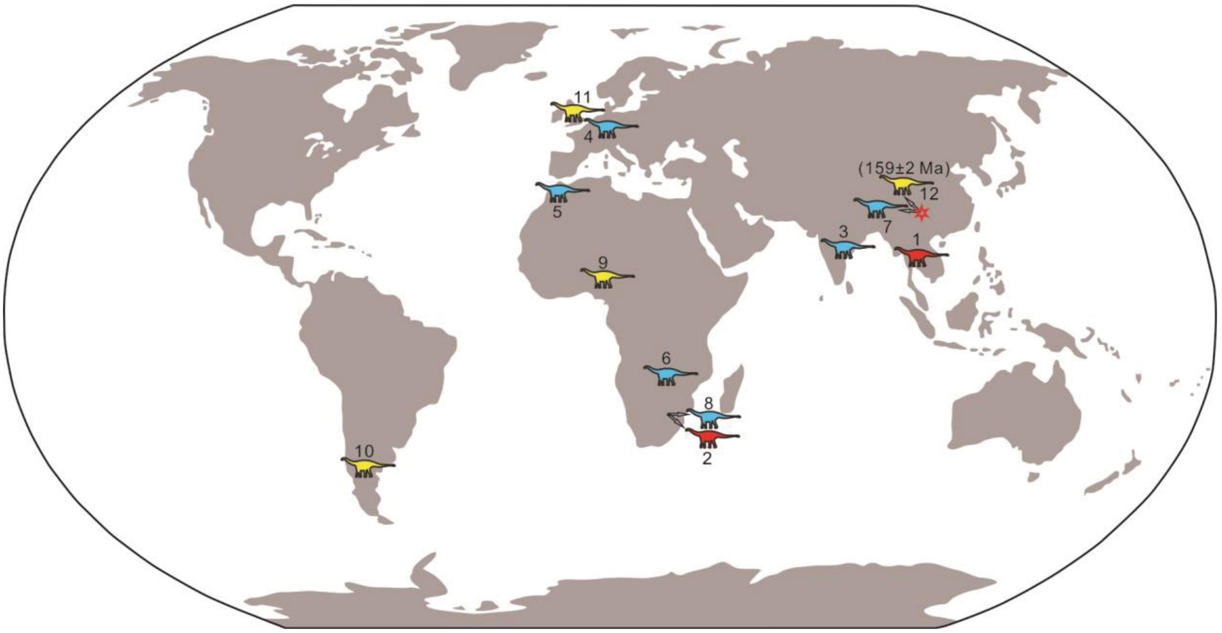

Figure 1. Global distribution of Late Triassic-Middle Jurassic basal sauropods and the sampling location (red star). Late Triassic (red dinosaur markers): 1—*Isanosaurus* from Thailand (Buffetaut et al., 2000) and 2—*Melanorosaurus* (Haughton, 1924) from South Africa. Early Jurassic (blue dinosaur markers): 3—*Barapasaurus* (Jain et al., 1975) from India; 4—*Ohmdenosaurus* (Wild, 1978) and Gravisauria (Stumpf et al., 2015) from Germany; 5—*Tazoudasaurus* from Morocco (Allain et al., 2004); 6—*Vulcanodon* from Zimbabwe (Raath, 1972; Yates and Kitching, 2003); 7—*Zizhongosaurus* (Dong et al., 1983) and *Gongxianosaurus* (He et al., 1998) from China; 8—*Antetonitrus* (Yates and Kitching, 2003) and *Pulanesaura* (McPhee et al., 2015) from South Africa. Middle Jurassic (yellow dinosaur markers): 9—*Jobaria* (Sereno et al., 1999) and *Spinophorosaurus* (Remes et al., 2009) from Niger; 10—*Patagosaurus* (Bonaparte, 1979) from Argentina; 11—*Cetiosaurus* (Phillips, 1871) from England; 12—*Shunosaurus-Omeisaurus* Fauna (Dong et al., 1983; Dong, 1992; Li et al., 1997) from China (dated at 159 ± 2 Ma in this contribution). The world map was downloaded from: www.alternatehistory.com/wiki/lib/exe/detail.php?id=blank_map_directory%3Aworld_gallery_6&media=new_world_map_glow_old_colo.png. We used CorelDRAW (version X7) to create this figure (www.coreldraw.com/en/product/technical-suite/?topNav=en).

out in Zigong City where the main dinosaur-bearing units occur on the grounds of the Zigong Dinosaur Museum. Dinosaur fossils from Zigong City represent the majority of Mesozoic dinosaur specimens in the SCB (Peng et al., 2005; Wang et al., 2008). The LSF yields 10 genera and 12 species of saurischian dinosaurs (Wang et al., 2010), including the basal sauropods *Shunosaurus lii* (Dong et al., 1983; Zhang, 1988; Li, 1998) and *Omeisaurus tianfuensis* (He et al., 1988), which are two of the most iconic fossil taxa of the SCB's *Shunosaurus-Omeisaurus* Fauna.

SAMPLING AND METHODOLOGY

We collected four sandstones from the lower part of the fossil-bearing LSF for geochronological analyses. The LSF outcrop was accessible as part of a large, indoor paleontological exhibit curated by the Zigong. Figure 3 shows lithology of the LSF and sampling localities. Sample ZG-1 was a gray-green, intermediate sandstone from the lowermost LSF (layer no. 1) found in the main hall of the museum. Sample ZG-2 is also a gray-green, intermediate sandstone from the same layer that occurs ~50 cm above sample ZG-1. Sample ZG-3 and ZG-4 are yellow-green, intermediate sandstones from the layer nos. 3 and 7, respectively.

Zircon separation and U-Pb dating were conducted at the Department of Earth Sciences, The University of Hong Kong. The four sandstone samples were crushed and sieved by standard methods. Grains having lengths of 60–200 μm were retained and washed with distilled water. Zircons were then separated by magnetic and heavy liquid methods. Euhedral zircon grains were hand-picked under binocular microscope and mounted in epoxy resin. Epoxy mounts were polished to expose grain midsections at approximately two-thirds of their thickness.

Zircon U-Pb data were obtained using a VG PQ Excel ICP-MS equipped with a New Wave Research LUV213 laser-ablation system (LA-ICP-MS). The LA system generates a 213 nm UV light beam with a frequency-quintupled Nd:YAG laser. The analyses were performed with a 30 or 22 μm beam diameter, 6 Hz repetition rate and an energy of 0.6–1.3 mJ per pulse. Other instrumental settings and procedural details used here were described by Xia et al. (2004). The standard zircon 91500 was used as a primary calibration standard and GJ-1 as a secondary reference. Euhedral zircon grains with zoning structures that indicate magmatic origins were selected for dating. We used the Isoplot/Ex 3.0 software package (Ludwig, 2003) for U-Pb age calculation and the Microsoft Excel macro developed by Andersen (2002) for common Pb correction. U-Pb age data with 1σ errors are shown in Supplementary Table DR1[1]

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[1] GSA Data Repository item 2018117, Table DR1, ICP-MS U-Pb isotopic data for zircon grains separated from the dinosaur-bearing sandstones of the Late Jurassic Lower Shaximiao Formation, Sichuan, SW China, is available at http://www.geosociety.org/datarepository/2018 or by request to editing@geosociety.org.

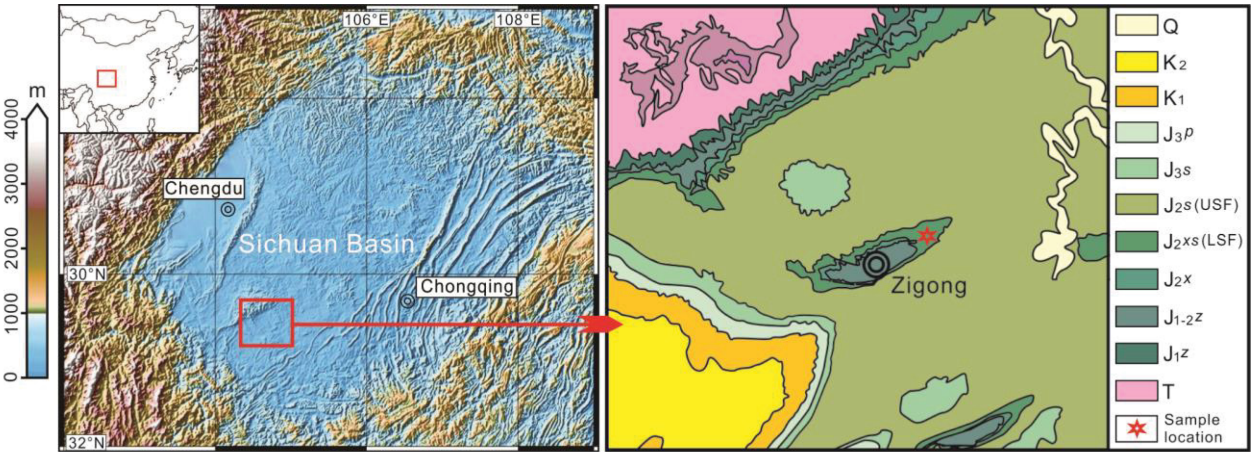

Figure 2. Topographic map of Sichuan Basin and geological map of the sampling locality. T—Triassic sedimentary rocks; J1z—Lower Jurassic Zhenzhuchong Formation; J1-2z—Lower-Middle Jurassic Ziliujing Formation; J2x—Middle Jurassic Xintiangou Formation; J2xs—Middle Jurassic Lower Shaximiao Formation (LSF); J2s—Middle Jurassic Upper Shaximiao Formation (USF); J3s—Upper Jurassic Suining Formation (SNF); J3p—Penglaizhen Formation (PLF); K1—Lower Cretaceous; K2—Upper Cretaceous; and Q—Quaternary sediments. The digital relief map was produced using the Generic Mapping tools software package (GMT-5.3.1) (Wessel et al., 2013). The geological map was drawn by ourselves with the software CorelDRAW (version X7), as mentioned above.

and plotted on concordia diagrams with 1σ uncertainties calculated at the 95% confidence level. Given a 15% discordance range for all the U-Pb ages, we interpret ^{206}Pb/^{238}U ages for zircons younger than 1000 Ma and ^{207}Pb/^{206}Pb ages for older grains.

RESULTS

We analyzed 97, 100, 95, and 96 zircon grains from sandstone samples ZG-1, ZG-2, ZG-3, and ZG-4, respectively, collected on the grounds of the Zigong Dinosaur Museum. Samples came from horizons representing basal-sauropod-bearing units in the LSF. As shown in Supplementary Table DR1 (see footnote 1) and Figure 4, we obtained 76, 99, 81, and 69 concordant ages for each sample. Uncertainties for individual analyses are given at the 1-sigma level, whereas calculated ages are presented at the 2-sigma level.

Samples ZG-1, ZG-2, and ZG-3 yielded three major age subpopulations including one Jurassic to Permian subpopulation (ca. 300–159 Ma) and two Paleoproterozoic subpopulations (1.9–1.8 Ga and 2.5–2.4 Ga). Only one major Jurassic subpopulation appeared in sample ZG-4 (197–159 Ma). The sample ZG-1 yielded only three sporadic Jurassic ages, the youngest of which was 167 Ma. The sample ZG-2 gave a substantial Early Jurassic subpopulation of 9 ages ranging from 179 to 175 Ma and a minor Late Jurassic subpopulation of 7 ages ranging from 161 to 159 Ma. The sample ZG-3 age distribution included a minor Early Jurassic subpopulation of 8 ages ranging from 188 to 171 Ma.

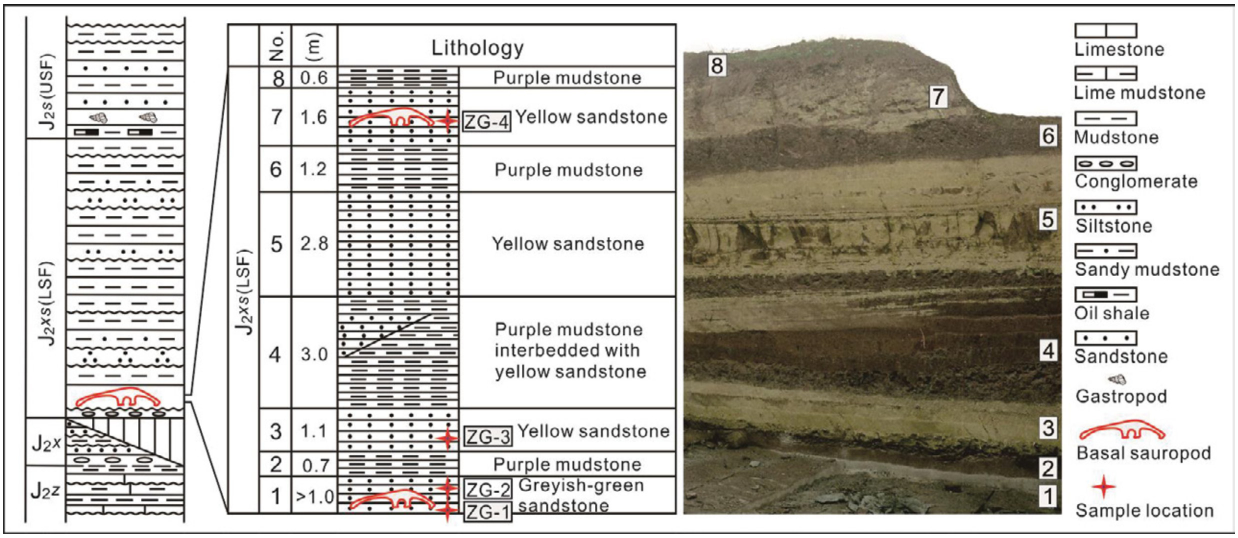

Figure 3. Stratigraphic column showing lithology of the Lower Shaximiao Formation as it occurs on the Zigong Dinosaur Museum grounds and other sample locations. LSF—Lower Shaximiao Formation; USF—Upper Shaximiao Formation.

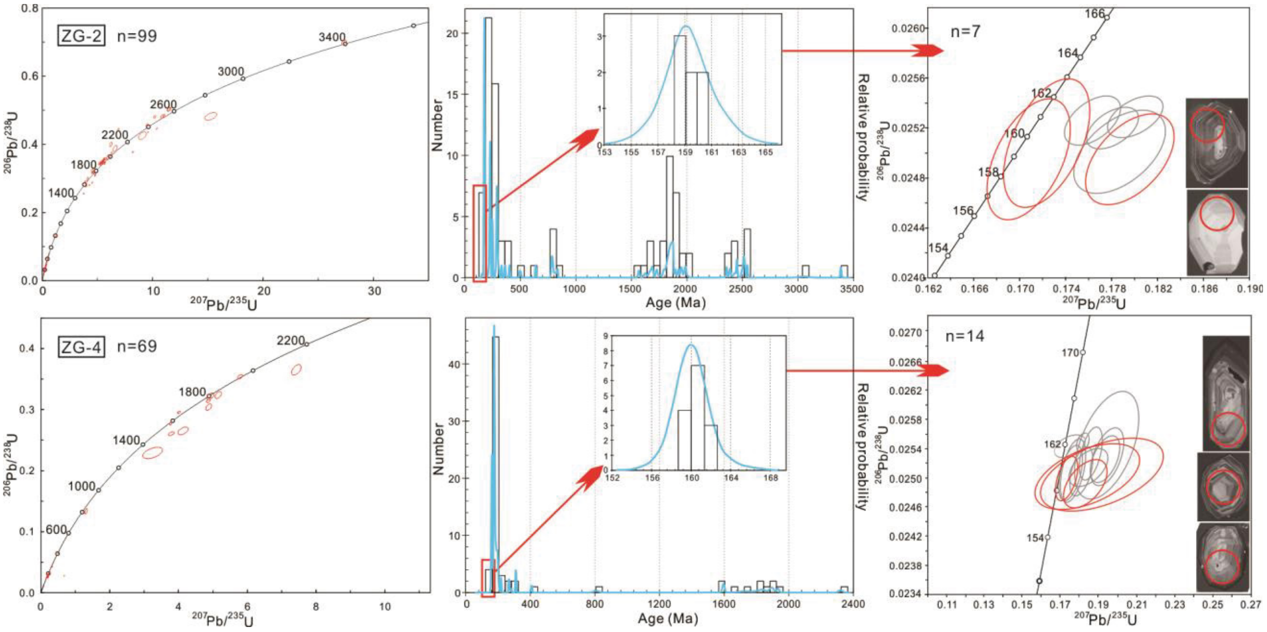

Figure 4. Concordia and probability density diagrams for detrital zircon U-Pb ages and cathodoluminescence images for representative zircon grains analyzed by this study (right). Maximum depositional age was interpreted from concordant ages indicated by red circles in the concordia diagrams. These ages are the single youngest ages in the youngest age population (as shown by the gray circles).

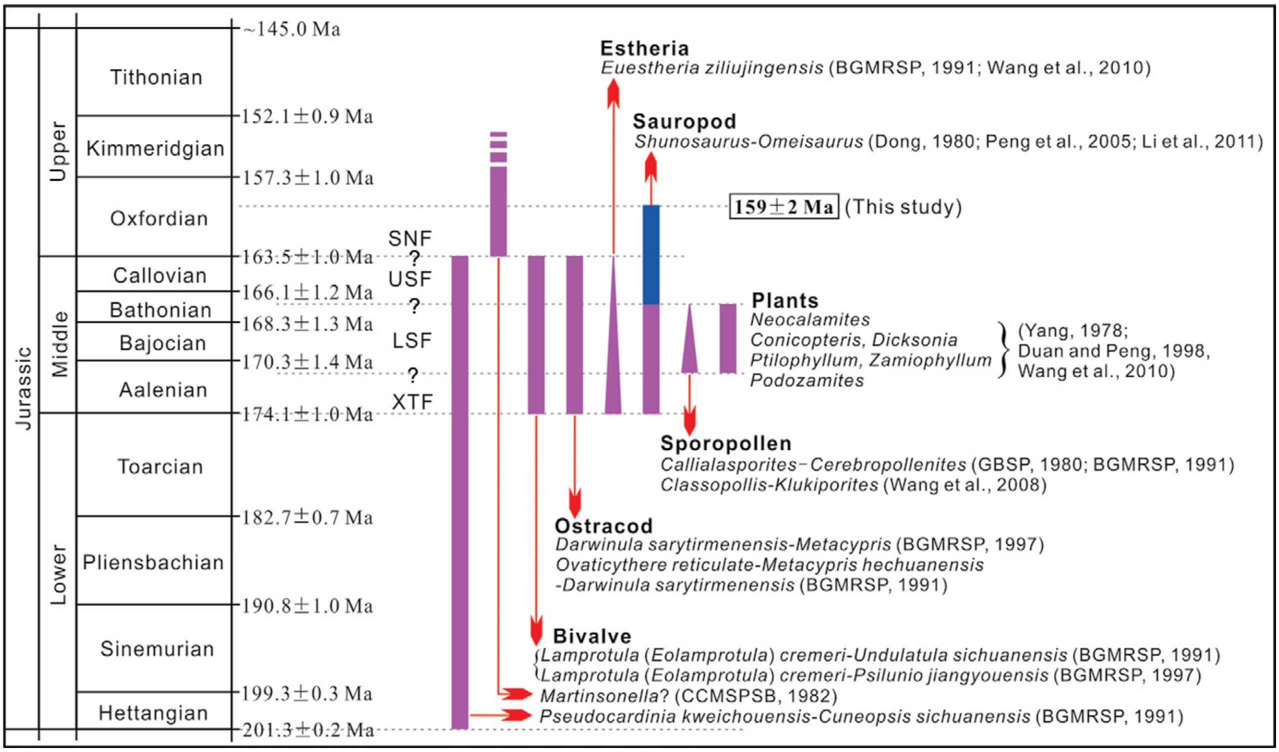

Figure 5. Biostratigraphic range of fossils known from Jurassic sedimentary rocks of the Sichuan Basin, marked with biostratigraphic constraints (purple bars) from previous research. Blue bar represents the extended time interval for the *Shunosaurus-Omeisaurus* Fauna constrained by the zircon U-Pb ages in this contribution. Dashed purple bar indicates that the minimum age of the bivalve *Martinsonella*? (CCMSPSB, 1982) is unknown. Triangles show the decrease on abundance of sporopollen and estheria species assemblages. LSF—Lower Shaximiao Formation; SNF—Suining Formation; USF—Upper Shaximiao Formation, XTF—Xintiangou Formation.

The sample ZG-4 included a major Late Jurassic (162–159 Ma) subpopulation of 14 ages and a major Early Jurassic (197–171 Ma) subpopulation composed of 33 ages. Given that the youngest detrital zircon ages from samples ZG-1 and ZG-3 were sporadic and much older than those found in the other two samples, and given the consistency of the youngest subpopulations found in samples ZG-2 and ZG-4, the age distributions from samples ZG-1 and ZG-3 cannot precisely constrain the age of the fossil-bearing LSF. All Jurassic to Permian zircon grains show relatively high Th/U ratios (>0.3) and oscillatory zoning patterns, indicative of igneous origins. As shown in Supplementary Table DR1 (see footnote 1), a few Proterozoic grains gave Th/U lower than 0.1, indicative of metamorphic alteration. Ages falling within 10% of concordance were plotted on concordia, cumulative probability and probability density diagrams (Fig. 4). We interpret the youngest single analyses of 159 ± 2 Ma from both of the samples ZG-2 and ZG-4 as the maximum depositional age for the LSF.

DISCUSSION

Depositional Age of the LSF

The SCB does not appear to have experienced significant magmatic activity making datable material scarce in the LSF (Zhang, 1988). Geochronologic data have not been reported for the LSF and the lack of chronostratigraphic constraints limits paleoclimatic and paleoecological correlations for the SCB. Chronostratigraphic assignments of fossil assemblages from the SCB's red beds are primarily based on their lateral correlations (BGMRSP, 1997). However, some of the fossils, such as the sporopollen, are unevenly distributed and poorly preserved (Wang et al., 2008), so that depositional ages remain uncertain (CCMSPSB, 1982). The unique intracontinental setting of the SCB and its paleogeographic isolation in the Mesozoic makes lateral correlation of its fossil assemblages difficult. The Jurassic LSF mainly consists of fluvial and lacustrine interbedded sandstones and mudstones that host abundant fossil animals (summarized in Fig. 5) including bivalves belonging to the *Lamprotula* (*Eolamprotula*) *cremeri-Undulatula sichuanensis* assemblage (BGMRSP, 1991) or the *Lamprotula* (*Eolamprotula*) *cremeri-Psilunio jiangyouensis* freshwater assemblage (BGMRSP, 1997), estheria belonging to the *Euestheria ziliujingensis* assemblage (BGMRSP, 1991), ostracods belonging to *Darwinula sarytirmenensis-Metacypris* (BGMRSP, 1997) or *Ovaticythere reticulate-Metacypris hechuanensis-Darwinula sarytirmenensis* assemblages (BGMRSP, 1991) and sporopollen belonging to *Callialaaporites-Cerebropollenites* (GBSP, 1980; BGMRSP, 1991) or *Classopollis-Klukiporites* assemblages (Wang et al., 2008). Additionally, four species of plant fossils occur in the LSF (Yang, 1978) (Fig. 5). Several plant species from this formation, such as *Coniopteris* (Yang, 1978; Duan and Peng, 1998), have flourished on a global scale since the Middle Jurassic (Harris, 1961). The LSF also hosts well-known vertebrate assemblages, the *Shunosaurus-Omeisaurus* Fauna (Dong et al., 1983; Dong, 1992; Ye, 2006; Wang et al., 2008; Li et al., 2011). Among other formations in the SCB, the LSF is exemplary for its dinosaur fossils, which include 10 genera and 12 species of basal saurischian dinosaurs (Wang et al., 2010).

Lower to Upper Jurassic fossil assemblages, especially the plant and invertebrate fossils, show temporal variation in inheritance and continuity but also some noteworthy similarities. For instance, the most recent studies on sporopollen (Wang et al., 2008) and estheria assemblages (BGMRSP, 1991) show matching species composition between the LSF and USF, but a decrease in the abundance of each species in younger units. Other fossil assemblages exhibit significant differences, for example, bivalve fossils are distinctly different in the LSF, USF and SNF (CCMSPSB, 1982) (Fig. 5). Bivalve assemblages in the XTF, LSF and USF contain *Eolamprotula*, which is regarded as a middle to late Middle Jurassic index fossil in South China (CCMSPSB, 1982; Gu, 1982). Correlations between *Eolamprotula* and other invertebrate fossils also indicate a Middle Jurassic age for the LSF (Wang et al., 2010).

Our ICP-MS results showed detrital zircon age subpopulations in two of the LSF's dinosaur-bearing sandstones (ZG-2 and ZG-4). The youngest subpopulation consisted of 7 analyses ranging from 161 to 159 Ma (ZG-2) and 14 analyses ranging from 162 to 159 Ma, (ZG-4) (Fig. 4). Zircon grains that gave these ages exhibited euhedral morphologies, oscillatory zoning patterns and high Th/U ratios (0.4–1.7 for ZG-2 and 0.4–0.5 for ZG-4) indicating igneous origins. Consistent variation in observed length/width ratios and color/contrast of zircon grains from each sample suggests crystallization from different igneous bodies. We thus interpret the youngest single grain age of 159 ± 2 Ma (2 Ma as the analytic error, also the same age as detected in both samples) as the maximum depositional age for the LSF. Outdated version of the geologic time scale (Harland et al., 1990) placed the absolute age boundary between the Middle and Late Jurassic at 157 Ma. However, this boundary has been updated to 163.5 ± 1.0 Ma most recently (Ogg et al., 2016). We thus interpret a Late Jurassic and specifically Oxfordian depositional age for the LSF.

Lateral correlation of the LSF's *Euestheria* fossils with those found in the Lanqi Formation in western Liaoning, China, supports our Oxfordian age interpretation. *Euestheria ziliujingensis* found in the LSF occur widely throughout China, appearing in the Haifanggou and Lanqi formations of western Liaoning and in the Jiulongshan and Tiaojishan formations of northern Hebei (Wang, 1998; Chen and Hudson, 1991). The Lanqi for example has yielded tuff samples from its uppermost units recently dated by high-precision $^{40}Ar/^{39}Ar$ methods at 160.7 ± 0.4 Ma and 158.7 ± 0.4 Ma (Chang et al., 2009). An andesite dated from the Lanqi's lowermost unit gave $^{40}Ar/^{39}Ar$ ages of 160.7 ± 0.4 Ma and 158.7 ± 0.4 Ma (Chang et al., 2014). Age constraints for the lowermost (165 Ma) and uppermost (156–153 Ma) units in Tiaojishan Formation of western Liaoning and northern Hebei provinces (Zhang et al., 2008) also support a Late Jurassic age interpretation for the correlative LSF.

Age of Basal Sauropods in the SCB

The *Shunosaurus* Fauna (Dong et al., 1983) or *Shunosaurus-Omeisaurus* Fauna (Li et al., 1997) were previously interpreted as representative Middle Jurassic basal sauropods (Dong et al., 1983; Dong, 1992; Zhang, 1988; Li, 1998; Sereno, 1999b; Buffetaut et al., 2000; Chatterjee and Zheng, 2002). The *Chuanjiesaurus* Fauna also occurs in the lower Middle Jurassic Chuanjie Formation of Yunnan Province, south of Sichuan Province. *Chuanjiesaurus* is proposed to be chronostratigraphically comparable to *Omeisaurus*, based on morphological similarities in the postcranial skeletons (e.g., cervicals, caudals, the shoulder girdle, and the hindlimbs) (Fang et al., 2008). Li et al. (2011) argued that the *Chuanjiesaurus* is more derived than *Shunosaurus* and *Omeisaurus*, while the *Chuanjiesaurus* Fauna is different from the *Shunosaurus-Omeisaurus* Fauna in its fossil composition, and therefore may correspond instead to the *Mamenchisaurus* Fauna, which is suggested Middle to Late Jurassic in age (Li and Cai, 1997; Ye, 2008). This lack of chronostratigraphic constraints on basal sauropods limits lateral correlation and interpretation of their Middle Jurassic geographic range. Even though invertebrate fossil assemblages generally indicate a Middle Jurassic age for the LSF and USF, *Shunosaurus-Omeisaurus* and *Mamenchisaurus* faunas appear distinct from each other in these two formations and may represent faunas at different evolutionary stages (Li et al., 2011). Dinosaurs from the *Shunosaurus-Omeisaurus* Fauna show more phylogenetically derived characteristics than those observed in the *Zizhongosaurus* Fauna from the underlying ZLF (Wang et al., 2010). The *Shunosaurus-Omeisaurus* Fauna however shows more plesiomorphic characteristics than those observed in the *Mamenchisaurus* Fauna (McPhee et al., 2017). Previous studies therefore assigned the *Shunosaurus-Omeisaurus* Fauna a Middle Jurassic age (Dong et al., 1983; Dong, 1992; Li and Cai, 1997; Li et al., 2011). Jurassic sauropod dinosaurs in the SCB in fact appear to show a high diversity associated with both temporal differentiation and strong provincialism, possibly indicating rapid radiation during this time (Li et al., 2011). Li et al. (1997) also interpreted a middle to late Middle Jurassic age for the LSF and USF from invertebrate fossils and from a 178–165 Ma age measured by electron spin resonance (ESR) dating of samples from the Shaximiao Formation in western areas of the SCB (Gou et al., 2000). Thermal stability constraints, however, place the upper age limit of ESR dating at around 1–2 Ma (Grün, 1989). ESR therefore does not give reliable age estimates for rocks formed before the Cenozoic (Laurent et al., 1998; Zhao et al., 2006).

The detrital zircon U-Pb ages from the LSF's dinosaur-bearing beds indicate a maximum depositional age of 159 ± 2 Ma for the *Shunosaurus-Omeisaurus* Fauna, younger than the previous estimate of Middle Jurassic for the fauna (e.g., Dong et al., 1983; Dong, 1992; Zhang, 1988; Buffetaut et al., 2000; Sereno, 1999b; Chatterjee and Zheng, 2002; Upchurch et al., 2004). *Omeisaurus tianfuensis* however is generally assigned a Late Jurassic age (McIntosh, 1990).

Radiation and Migration of Sauropods Prior to the Late Jurassic

The basal sauropodomorphs, including the "prosauropods" and Early Jurassic sauropods, also have a presence in western China (e.g., *Yunnanosaurus*, *Lufengosaurus*, *Gongxiansaurus*), yet phylogenetic positions of these western Chinese taxa are embedded with other coeval taxa from a global distribution (Brusatte et al., 2010; McPhee et al., 2017). The probable earliest reported sauropod, *Isanosaurus attavipachi*, was discovered from Late Triassic units in Thailand indicating that sauropods originated as early as Middle Triassic from a small region of Southeast Asia, part of Pangea, (Buffetaut et al., 2000) as predicted by Wilson and Sereno (1998). Basal sauropods dispersed to other parts of Laurasia and Gondwana in the Early Jurassic. Evidence of this expansion includes *Melanorosaurus* from the Late Triassic of South Africa (Haughton, 1924), *Antetonitrus* (Yates and Kitching, 2003) and *Pulanesaura* (McPhee et al., 2015) from the Early Jurassic of South Africa, *Barapasaurus* from the Early Jurassic of India (Jain et al., 1975), *Vulcanodon* from the Early Jurassic of Zimbabwe (Raath, 1972), *Tazoudasaurus* from the Early Jurassic of Morocco (Allain et al., 2004), *Zizhongosaurus* (Dong et al., 1983) and *Gongxianosaurus* (He et al., 1998) from the Early Jurassic of China, *Jobaria* (Sereno et al., 1999) and *Spinophorosaurus* (Remes et al., 2009) from the Middle Jurassic of Niger, *Patagosaurus* from the Middle Jurassic of Argentina (Bonaparte, 1979), *Cetiosaurus* from the Middle Jurassic of England (Phillips, 1871) and *Ohmdenosaurus* from the Early Jurassic of Germany (Wild, 1978) (Fig. 1). Osteological descriptions of these basal sauropods are generally based on fragmentary and incomplete skeletons precluding accurate phylogenetic analyses and taxonomic assignments. Uncertainties persist regarding phylogenetic relationships among sauropods (Gillette, 2003; Apaldetti et al., 2011). Regardless of these ongoing debates, Middle and Late Jurassic sauropods clearly thrived throughout Laurasia and Gondwana (McIntosh, 1990; Upchurch, 1998; Wilson and Sereno, 1998; Gillette, 2003; Upchurch et al., 2004). Sauropods however did not appear in North America until the Late Jurassic (Gillette, 1996a, 1996b), and all reported sauropod fossils from North America belong to the clade Neosauropoda. Except for Antarctica, which hosts only a putative sauropod (Smith and Pol, 2007), all the other major land masses hosted clear examples of Late Jurassic and Cretaceous sauropods. Along with the SCB, Tibet hosts an additional Asian example of the *Shunosaurus-Omeisaurus* Fauna (He et al., 1988).

Rich et al. (1999) described the resemblance between the neosauropod *Tehuelchesaurus* from the late Middle Jurassic/Late Jurassic of Argentina (Rich et al., 1999; Cúneo et al., 2013; Rauhut et al., 2015) and the Late Jurassic *Omeisaurus* from the SCB. Those workers suggested that South American and Chinese sauropods were not isolated but rather enjoyed a continuous and broad geographic range in the Middle to Late Jurassic. However, Russell (1993) and Li et al. (2011) proposed a paleogeographic isolation in the Late Jurassic SCB based on the unique morphologies in *Mamenchisaurus* (e.g., the elongated cervical vertebrae, though an elongated neck is also found in *Omeisaurus*) as well as the differences in the dinosaurian assemblage of the *Mamenchisaurus* Fauna from the contemporary world. The chronostratigraphic constraints on fossil beds described here support this latter hypothesis. Although phylogenetically more primitive, the *Shunosaurus-Omeisaurus* Fauna is younger than the neosauropod *Tehuelchesaurus*. Given that all non-Chinese basal sauropods appear in units older than Late Jurassic, basal sauropods from the SCB such as *Shunosaurus, Omeisaurus* and even *Mamenchisaurus* may represent isolated faunas. While other basal sauropods went extinct, basal sauropods from the SCB survived into the Late Jurassic, existing simultaneously with neosauropods in other parts of Laurasia and Gondwana, as the neosauropods became the dominant sauropod clade beginning in the Late Jurassic. Sauropods appear to have greatly expanded their geographic range from the late Middle Jurassic to early Late Jurassic, a time frame during which they appeared on all continents except Antarctica (Gillette, 2003). Comprehensive geochronologic and palaeobiogeographic studies on early sauropods can further constrain their evolutionary history following the breakup of Pangea. The new and reappraised age interpretations for the LSF and associated *Shunosaurus-Omeisaurus* Fauna presented here reveals the spatial complexity of early sauropod evolution.

CONCLUSIONS

Our new and robust detrital zircon U-Pb geochronology by ICP-MS provide the maximum depositional age for the lower Lower Shaximiao Formation, where the famous *Shunosaurus-Omeisaurus* Fauna was established. One hundred and ninety-six detrital zircon grains from two out of four sandstones collected from the dinosaur-bearing Lower Shaximiao Formation yielded 7 and 14 concordant analyses with ages ranging between 162–159 Ma, respectively. Combining with the zircon age data and the geobiological age of the invertebrate fossil assemblages, we interpret the single youngest analyses, 159 ± 2 Ma, as the maximum depositional age of the Lower Shaximiao Formation and the age of the *Shunosaurus-Omeisaurus* Fauna. According to the latest version of the geologic time scale, given the ICP-MS age provided here, the Lower Shaximiao Formation and the *Shunosaurus-Omeisaurus* Fauna should be assigned to the Oxfordian stage of the Late Jurassic, rather than the Middle Jurassic as previously proposed. Since the *Shunosaurus-Omeisaurus* Fauna was geographically isolated, our new and reappraised age interpretations for the LSF may lead to insights on the geographic expansion of the Middle–Late Jurassic sauropods in terms of temporal distribution and diversity through Laurasia and Gondwana.

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