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Global Standard Stratotype-Section and Point (GSSP) for the Base of the Jiangshanian Stage (Cambrian: Furongian) at Duibian, Jiangshan, Zhejiang, Southeast China

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*The International Commission on Stratigraphy and the IUGS Executive Committee have recently approved a Global Standard Stratotype-section and Point (GSSP) defining the base of the second stage of the Furongian Series, Cambrian System. This stage is named the Jiangshanian Stage, after Jiangshan City, western Zhejiang Province, China, where the GSSP is located. The GSSP is exposed in a natural outcrop near Duibian Village. It is defined at the base of a limestone (wackestone) layer 108.12 m above the base of the Huayansi Formation in the Duibian B section, coinciding with the first appearance of the cosmopolitan agnostoid trilobite *Agnostotes orientalis* (base of the A. orientalis Zone). The GSSP is at a position of 28° 48.977' N latitude and 118° 36.887' E longitude. Secondary global markers at or near the base of the stage include the first appearance of the cosmopolitan polymerid trilobite *Irvingella angustilimbata*, which coincides with the FAD of the primary marker in the stratotype section, and near the end of a large positive carbon isotopic excursion (SPICE excursion). Faunal turnovers close to the base of the Jiangshanian Stage have been recognized as being at the base of the Iverian Stage in Australia, the Gonggrian Stage in Korea, and the *Agnostotes orientalis*–*Irvingella perfecta* Zone in Siberia, and near the base of the Aksayan Stage in Kazakhstan, the Sunwaptan Stage*

in Laurentia, and the Parabolina brevispina Zone in Baltica.

Introduction

The purpose of this paper is to announce ratification of the Jiangshanian GSSP, the base of which coincides with the FAD of the cosmopolitan agnostoid trilobite *Agnostotes orientalis*. The GSSP for the base of the new stage, the Jiangshanian Stage (Figs. 1, 2, 6), is 108.12 m above the base of the Huayansi Formation in the Duibian B section, near Duibian Village, western Zhejiang, China (or 19.20 m above an arbitrary 0 point in the section) (Figs. 3, 5, 6). The base of the Jiangshanian Stage also coincides with the FAD of the cosmopolitan polymerid trilobite *Irvingella angustilimbata* in the Duibian B section. This point fulfills all of the geological and biostratigraphic requirements for a GSSP (see Remane et al., 1996). The section is easily accessible, and access for research is unrestricted. It is located on public land that has been under permanent protection of the government of Zhejiang Province since 1983, when the Duibian A section was proposed as a candidate for the global Cambrian–Ordovician boundary.

Stratigraphic Rank of the Boundary

The Jiangshanian Stage is the second stage of the Furongian Series (Figs. 1, 2, 7, 8). The base of the stage automatically defines the top of the Paibian Stage, and limits the Paibian to three globally or regionally recognized agnostoid trilobite zones, the *Glyptagnostus reticulatus* Zone, the *Agnostus* (= *Innitagnostus*) *inexpectans* Zone, and the *Tomagnostella orientalis* Zone. The boundary is a standard stage/age GSSP.

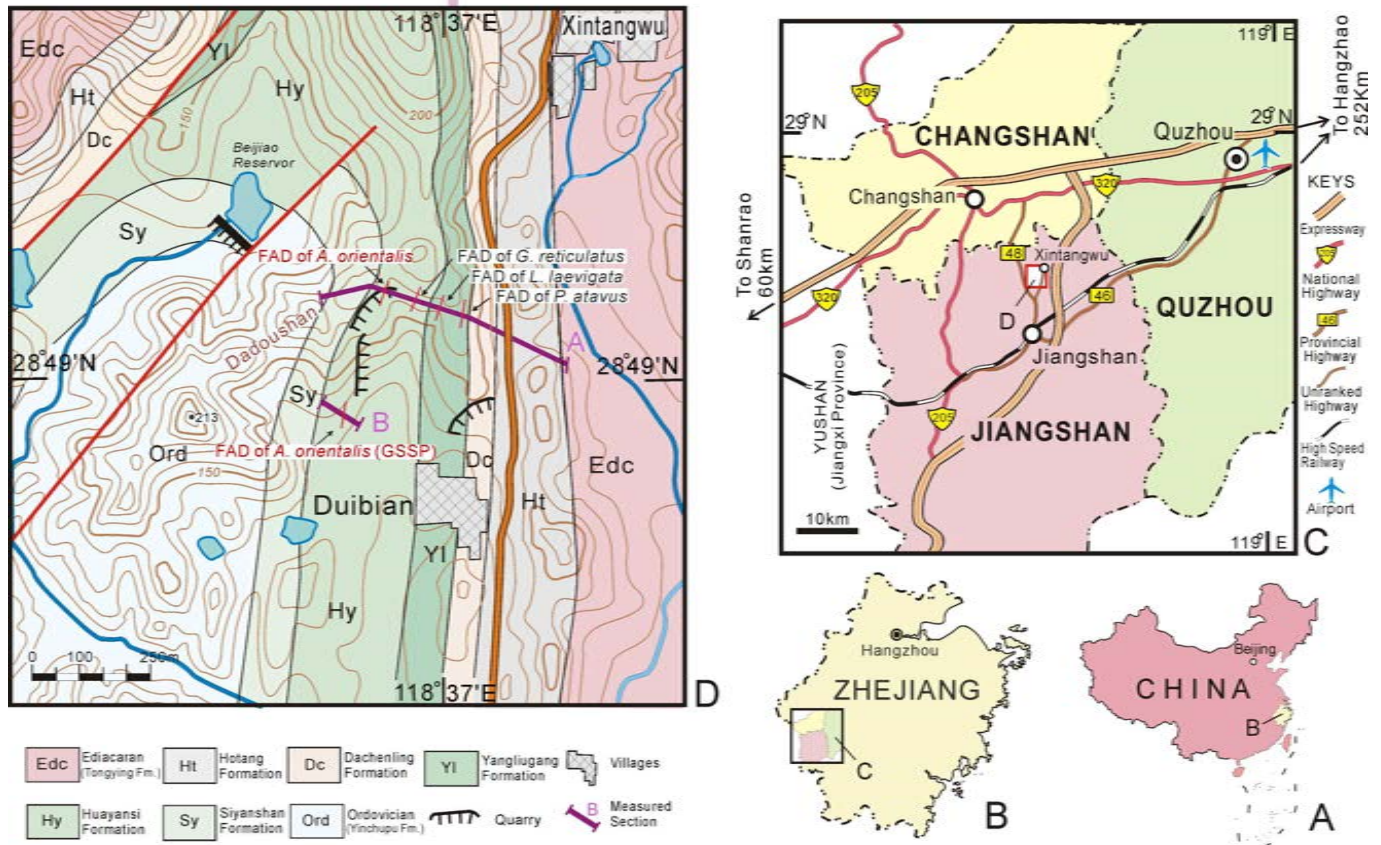


Figure 3. Topographic map of the Duibian area, Jiangshan, Zhejiang, China, showing the position of the Duibian A and B sections. Part D of the figure is from topographic map H50-118-B (Surveying and Mapping Bureau of Zhejiang Province, 1961, scale 1:50000). Position of the Jiangshanian GSSP coincides with the FAD of *Agnostotes orientalis* in the Duibian B section.

and Lin (1989). The Duibian B section, first documented by Peng et al. (2005), is on the same limb of an unnamed syncline with the Duibian A section. It contains the upper part of the Huayansi Formation. The portion of the Duibian B section shown in Fig. 3 is the interval studied in greatest detail. The positions of both the Duibian A and B sections are on topographic map H50-118-B (Surveying and Mapping Bureau of Zhejiang Province, 1961, 1:50000 scale, Fig. 3D). The boundary stratotype for the base of the Jiangshanian Stage is the Duibian B section. The GSSP is exposed in outcrop at a position of 28°48.977'N latitude and 118°36.887'E longitude, and at an elevation of approximately 125 m above sea level.

Geological setting

The Sanshan Region is notable for its well exposed and richly fossiliferous lower Paleozoic strata. A GSSP for the base of the Darriwilian Stage (Ordovician) was erected at Huangnitang, Changshan County, Zhejiang Province (Mitchell et al., 1997), about 18 km northwest of Duibian (Fig. 4). Prior to final selection of the boundary stratotype, both the Duibian A section in Jiangshan and the Xiyanshan (Siyanshan) section in Changshan were among the candidate sections for the global Cambrian–Ordovician boundary (Lu et al., 1983, 1984). The Sanshan Region consists of an extensive series of folded and thrust slices resulting from post-Devonian and post-Permian compressional tectonics that extend through parts of western Zhejiang and eastern Jiangxi provinces (Zhejiang Bureau of Geology and Mineral Resources, 1989; Jiangxi Bureau of Geology

and Mineral Resources, 1984). The Duibian sections are situated on the east limb of a small syncline that constitutes one of the folds on the east limb of a much larger composite syncline ranging through eastern Jiangxi and western Zhejiang provinces (Fig. 4).

Cambrian strata of South China are assigned to three major depositional environments along a platform-to-basin transect (e.g., Pu and Ye, 1991; Peng and Robison, 2000; Peng and Babcock, 2001). Relatively shallow environments of the Yangtze (South China or Southwest China) Platform were flanked by deeper environments of the Jiangnan Slope Belt, and still deeper environments of the Jiangnan Basin. The GSSP occurs within the Huayansi Formation, which mainly consists of a thick succession of carbonate beds deposited in the outermost part of the Jiangnan Slope Belt, and adjacent to the Jiangnan Basin.

Location of Level and Specific Point

The first thin-bedded, dark gray limestone layer of the Huayansi Formation contains the earliest known specimens of the cosmopolitan agnostoid trilobite *Agnostotes orientalis*. The FAD of *A. orientalis* is 108.12 m above the base of the Huayansi Formation in the Duibian B section. The lowest known *A. orientalis* specimens co-occur with the cosmopolitan polymerid trilobite *Irvingella angustilimbata*.

Specimens of *A. orientalis* at its FAD position in the Duibian B section show the most primitive morphology exhibited in the species. The most notable microevolutionary changes in the species *A. orientalis* occur in the morphology of the frontal sulcus on the

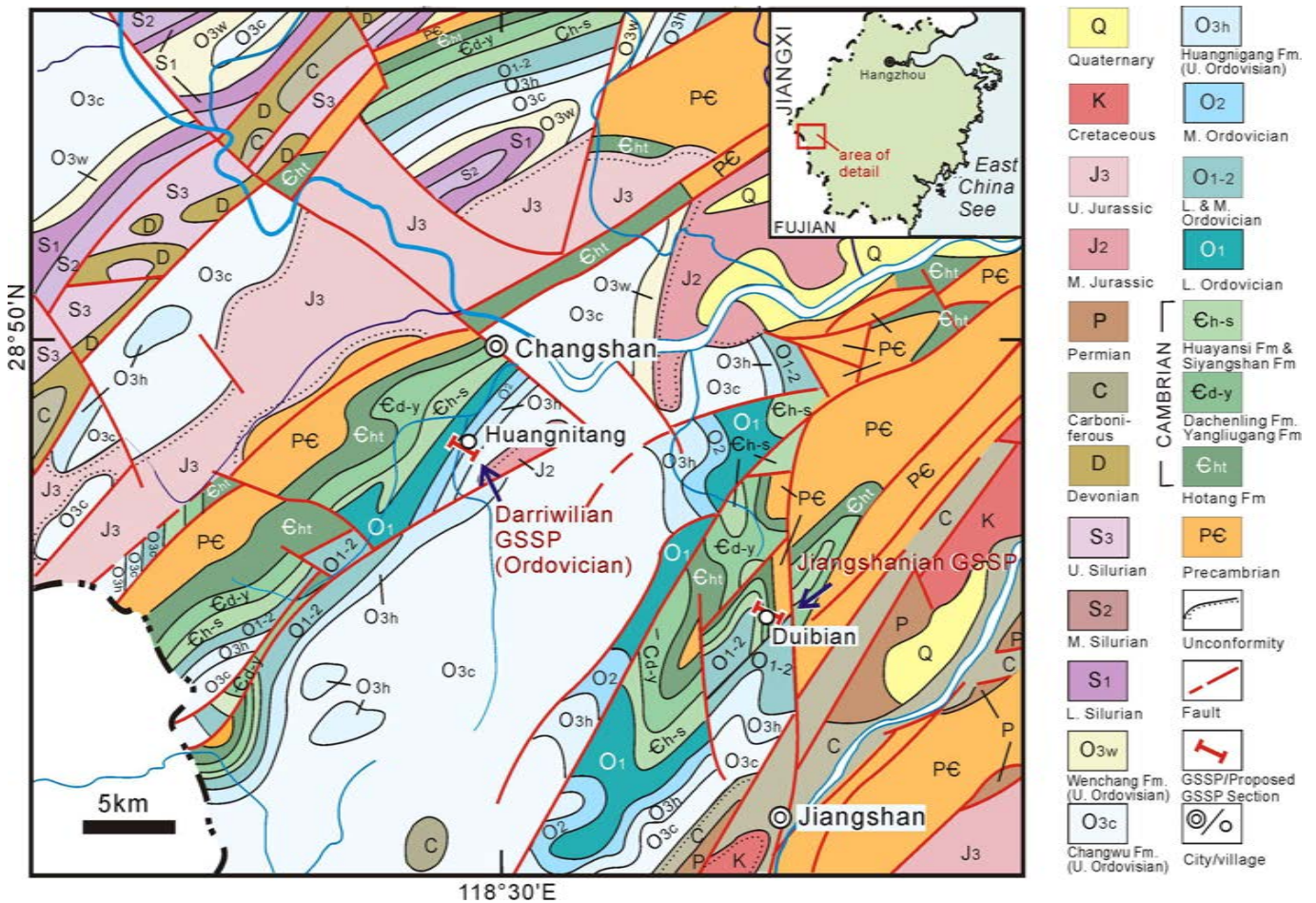


Figure 4. Map of part of western Zhejiang Province, China, showing location of the GSSP of the Jiangshanian Stage (Duibian B section, Duibian, Jiangshan). For reference, the location of the Huangnitang section, the GSSP for the Darriwilian Stage of the Middle Ordovician, is also indicated. Map modified from Zhejiang Bureau of Geology and Mineral Resources (1989).

anterior lobe of the glabella. In the primitive form, the frontal sulcus has a short notch (Fig. 9A, B). In younger and more advanced forms, the frontal sulcus becomes a long furrow that passes sagittally through the anterior lobe (Fig. 9C, D). As this change occurs, the width of the frontal sulcus increases progressively rearward to meet the transglabellar furrow and, as a result, the frontal sulcus separates the anterior lobe into a pair of ovate lobes. These striking morphologic changes can be used to gauge the relative stratigraphic occurrence of individual specimens of *A. orientalis* from any section in the world.

Stratigraphic Completeness

Detailed bed-by-bed correlation of Furongian strata through western Zhejiang, coupled with detailed biostratigraphy (Lu, 1964; Lu and Lin, 1981, 1983, 1989), sedimentology (Lu et al., 1974; Zuo, 2006), sequence stratigraphy (Zuo, 2006), and carbon isotope chemostratigraphy (Zuo, 2006; Figs. 6, 8), clearly demonstrates the stratigraphic continuity of the basal interval of the Jiangshanian Stage in the Duibian sections. Biostratigraphic studies within Zhejiang Province and globally demonstrate that the succession of trilobite species (e.g., Öpik, 1963, 1967; Lu and Lin, 1981, 1983, 1989; Ergaliev, 1980; Peng, 1990, 1992, 2000, 2003; Pratt, 1992; Ergaliev and Ergaliev, 2000, 2008, Geyer and Shergold, 2000; Varlamov et al., 2005; Peng et al., 2009a) and conodont species (e.g., Miller, 1981;

Wang, 1985; Dong et al., 2004; Miller et al., 2006) in the Duibian A and B sections is undisturbed. The Duibian B section lacks synsedimentary and tectonic disturbance at the GSSP boundary interval, although minor bedding-plane slippage, which is expected in an inclined succession of strata, especially when close to the axis of a syncline, occurs along some beds. Bedding plane slip surfaces do not appear to have resulted in any loss or repetition of stratigraphic thickness, and the biostratigraphic succession in the section is unaffected. There is no evidence of faulting resulting in either loss or repetition of section along the present exposure of the formation. Evidence of metamorphism and strong diagenetic alteration is absent.

Thickness and Stratigraphic Extent

In the Duibian B section (Figs. 5, 6), the upper part of the Huayansi Formation consists mainly of a succession of dark, thin-bedded limestones (wackestones) with thin shale interbeds; light-colored ribbon limestones (wackestones or packstones) are present in places. The upper part of the formation has a measured thickness of 50 m. In the Duibian A section, the total thickness of the Huayansi Formation is 141.95 m. Strata below the interval corresponding to the Duibian B section (i.e., the lower and middle Huayansi Formation) have occasional greenish-yellow shale beds less than 0.5 m thick. Another shale sequence occurs in an interval in the *Lotagnostus americanus*



Figure 5. Exposure of the GSSP for the base of the Jiangshanian Stage (coinciding with the FAD of *Agnostotes orientalis*) in the Huayansi Formation, Duibian B section, Jiangshan, Zhejiang, China. Strata underlying the GSSP belong to the Paibian Stage. A, View of Dadoushan Hill with limestone quarries, northwest of Duibian Village, showing the location of Duibian A and Duibian B sections. B, Duibian B section. C, Interval between 19 m and 32 m above the arbitrary 0 m point in Duibian B section (107.4–120.4 m above the base of Huayansi Formation). D, E, Progressively closer views of the Duibian B section showing the FAD of *A. orientalis*, 108.12 m above the base of the Huayansi Formation (19.72 m above the arbitrary 0 m point).

Zone (above the *A. orientalis* Zone). The shales are interpreted to have been deposited under basinal conditions, whereas the limestones represent a deep-water slope environment (Zuo, 2006).

The base of the Jiangshanian Stage occurs in a mostly monofacial succession of dark, fine-grained limestones. The point where *A. orientalis* first appears is in the lower part of an 8 cm thick layer of dark gray, thinly laminated wackestone, overlain by another 8 cm thick layer of thinly laminated, dark gray wackestone (beds with white painted circles on Fig. 5C–E). The basal contact of this bed in the Duibian B section extends laterally about 25 m along the section; it can be also traced northward to the Duibian A section, which is beyond the small bushes growing on the north side of the section.

Provisions for Conservation, Protection, and Accessibility

The exposure containing the GSSP is located on public land that has been under protection of the provincial government of Zhejiang Province since 1983. Because of the geologic importance of the Duibian sections, the sections are not subject to building, landscaping, or other destruction.

Access to the outcrop is essentially unrestricted in all seasons. Travel to Zhejiang is open to persons of all nationalities, and travel for scientific purposes is welcomed. Ordinary vehicles can be driven right to and parked beside the arbitrary 0 point of the Duibian B section. Almost no climbing is needed to examine and work on the stratotype section.

Motivation for Selection of the Boundary Level and of the Stratotype Section

Principal Correlation Event (Marker) at GSSP Level

The agnostoid trilobite *Agnostotes orientalis* (Fig. 9A–G) has a global distribution and its first appearance has been acknowledged as one of the most favorable levels for a GSSP defining the base of a global Cambrian stage (e.g., Geyer and Shergold, 2000; Shergold and Geyer, 2001; Peng and Babcock, 2005b; Babcock et al., 2005; Peng et al., 2006). A position corresponding closely to the first appearance of *A. orientalis* is recognizable in strata of Gondwana, Laurentia, Kazakhstan, and Siberia (e.g., Kobayashi, 1935; Öpik, 1963; Lu, 1964; Lazarenko, 1966; Lu et al., 1965; Lu et al., 1974; Ergaliev, 1980; Lu and Lin, 1983, 1989; Peng, 1990, 1992; Pratt, 1992; Geyer and Shergold, 2000; Zhang, 2000; Pegel, 2000; Choi, 2004; Choi et al., 2004, 2005; Varlamov et al., 2005; Peng and Babcock, 2005b; Peng et al., 2005, 2006, 2009a; Ergaliev and Ergaliev, 2008; Lazarenko et al., 2008a, b; Varlamov and Rozova, 2009), and can be identified with reasonable precision using multiple lines of evidence.

Agnostoid trilobites provide the best and most precise tools for intercontinental correlation in the upper half of the Cambrian System (e.g., Robison, 1984; Peng and Robison, 2000); some intercontinentally distributed polymerids also provide fine stratigraphic resolution. In a number of regions, *A. orientalis* and the polymerid trilobite *Irvingella* co-occur (Lazarenko, 1966; Öpik, 1967; Peng, 1992; Pratt, 1992; Chatterton and Ludvigsen, 1998; Hong and Choi, 2003; Choi et al., 2004, 2005; Varlamov et al., 2005). *Irvingella*

has a wide paleogeographic distribution (Geyer and Shergold, 2000), allowing precise or close correlation into Australia, Baltica, Avalonia, eastern and western Laurentia, Argentina, and probably Antarctica. *A. orientalis*, or co-occurring *Agnostotes* and *Irvingella*, have been used as zonal guide fossils in South China, northeastern and northwestern Siberia, and South Korea. Palmer (1965) and Hong and Choi (2003) recognized a distinct evolutionary series among species of *Irvingella* that can be used to help constrain stratigraphic position.

In South China and Canada, the primitive form of *A. orientalis* makes its first appearance at a level coinciding with the FAD of *Irvingella angustilimbata* (Peng, 1992; Pratt, 1992). This level defines the base of the Jiangshanian Stage in South China and the base of the *Proceratopyge rectispinata* Zone in the Mackenzie Mountains. It lies somewhat below the lower boundary of the Sunwaptan Stage of Laurentian regional usage, which is defined at the base of the *Irvingella major* Zone (Chatterton and Ludvigsen, 1998). Everywhere that *Irvingella major* occurs in strata it is always higher than *I. angustilimbata*. The stratigraphic position and its modified morphology suggest that *I. major* is an advanced species of *Irvingella*, one that was derived from *I. angustilimbata* or a similar relatively primitive species. The first appearance of *A. orientalis* corresponds closely to the base of the Iverian Stage in Australia (Shergold, 1993), the base of the *Pseudagnostus (P.) vastulus-Irvingella tropica* Zone in Kazakhstan (Ergaliev, 1980), and near the base of the “Entsyan horizon” of the Gorbijachinian Stage (Rozova, 1963; Varlamov et al., 2005) or the base of the Mokuteian regional stage (Varlamov and Rozova, 2009) in Siberia. In South Korea, an advanced form of *A. orientalis* was recorded in association with *Irvingella coreanicus* and is succeeded by *I. major*. It succeeds *I. megalops*, which is comparable to *I. angustilimbata* and occurs in the underlying *Eochuangia hana* Zone. This led Hong and Choi (2003) to correlate the base of the *E. hana* Zone, or the base of the Gonggairian Stage of South Korean regional usage, to the GSSP level. Hong and Choi (2003), Choi (2004) and Choi et al. (2004; 2005) also suggested that *Irvingella nuneatonensis* from England (Rushton, 1967, 1983) occurs nearly at the same level as, or slightly above, the Korean *A. orientalis* Zone. In Sweden, *A. orientalis* is not known, but the level corresponding to its first appearance may be at or close to the FAD of *Irvingella suecica*, which is presumed (Terfelt et al., 2008, 2011) to be in the *Parabolina brevispina* Zone (polymerid trilobite zonation) and lowermost *Pseudagnostus cyclopyge* Zone (agnostoid zonation).

Stratigraphically, the first appearance of primitive *Agnostotes orientalis* always succeeds the first appearance of *Tomagnostella orientalis* in South China (Peng, 1992; Choi et al., 2004). Up-section, specimens of *A. orientalis* having the primitive morphology are replaced by ones having more advanced morphologies (Peng, 1992; Peng et al., 2009a; herein). A similar succession, in which primitive *A. orientalis* specimens become replaced by advanced ones, is also observable in the Chopko and Khos-Nelege River sections, Siberia (Varlamov et al., 2005; Lazarenko et al., 2008a, b). Species of *Agnostotes* always succeed the first appearance of the widespread polymerid *Corynexochus plumula*, which is the eponymous guide fossil for the *C. plumula* Zone. The *C. plumula* Zone, in turn, lies above the *Erixanium rectangularis* Zone in stratigraphic successions of Australia and South China (Öpik, 1967; Peng, 1992; Duan, 2003). The first appearances of both *E. rectangularis* and *C. plumula* always succeed the first appearances of the cosmopolitan agnostoid trilobites *Agnostus inexpectans* and *Glyptagnostus reticulatus*. It is desirable

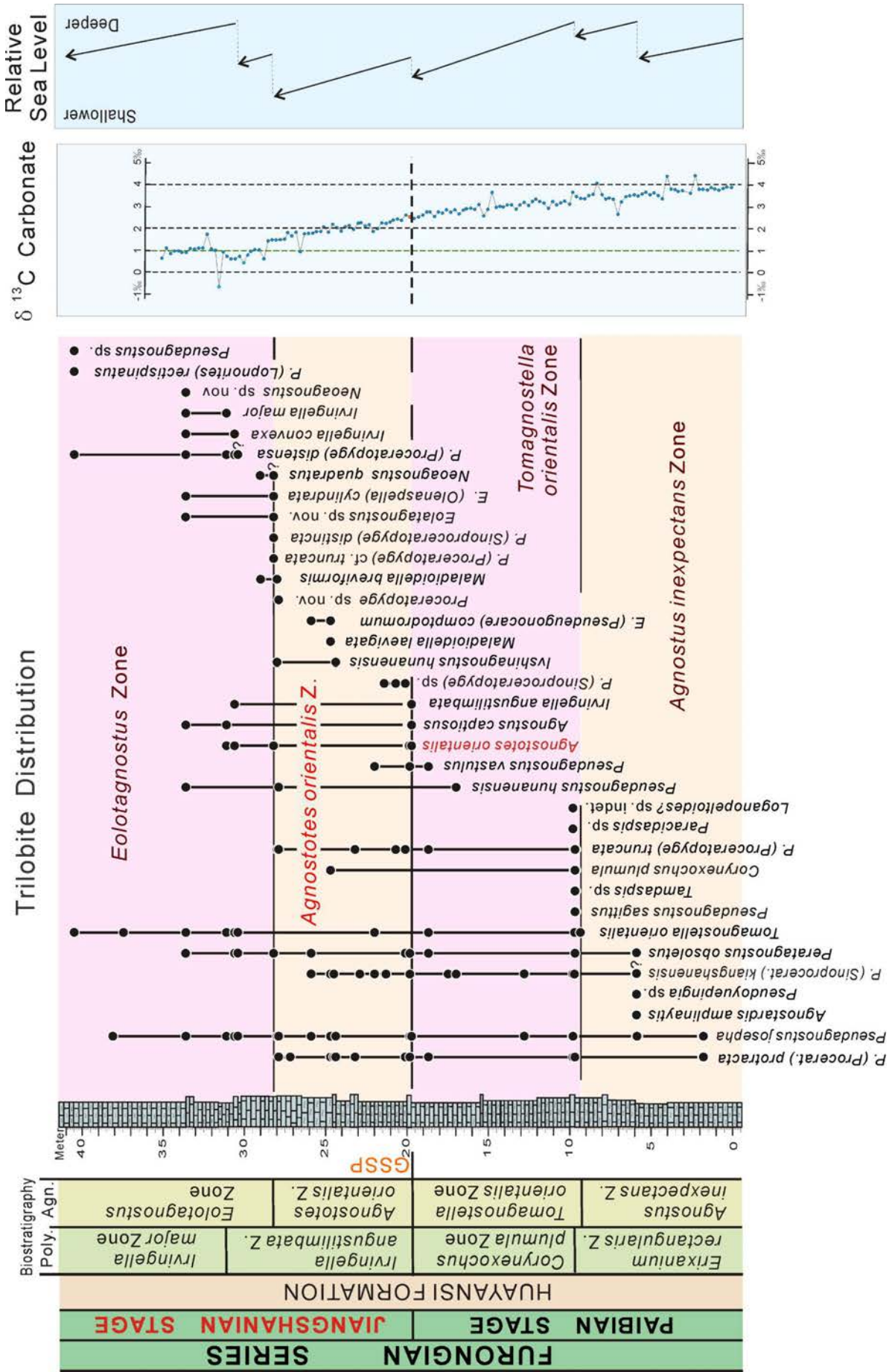


Figure 6. Observed stratigraphic distribution of trilobites in the Huayansi Formation near the base of the *Agnostotes orientalis* Zone, Duibian B section, Jiangshan, Zhejiang, China. The GSSP coincides with the base of the *A. orientalis* Zone in this section. An interpretive sea level history, reflecting small-scale regional or eustatic changes, is added for comparison. Also added for comparison is a curve of $\delta^{13}C_{\text{carbonate}}$ isotopic values, derived from samples collected from the Duibian B section. Agn. = agnostoid trilobite biozones; Poly. = polymerid trilobite biozones.

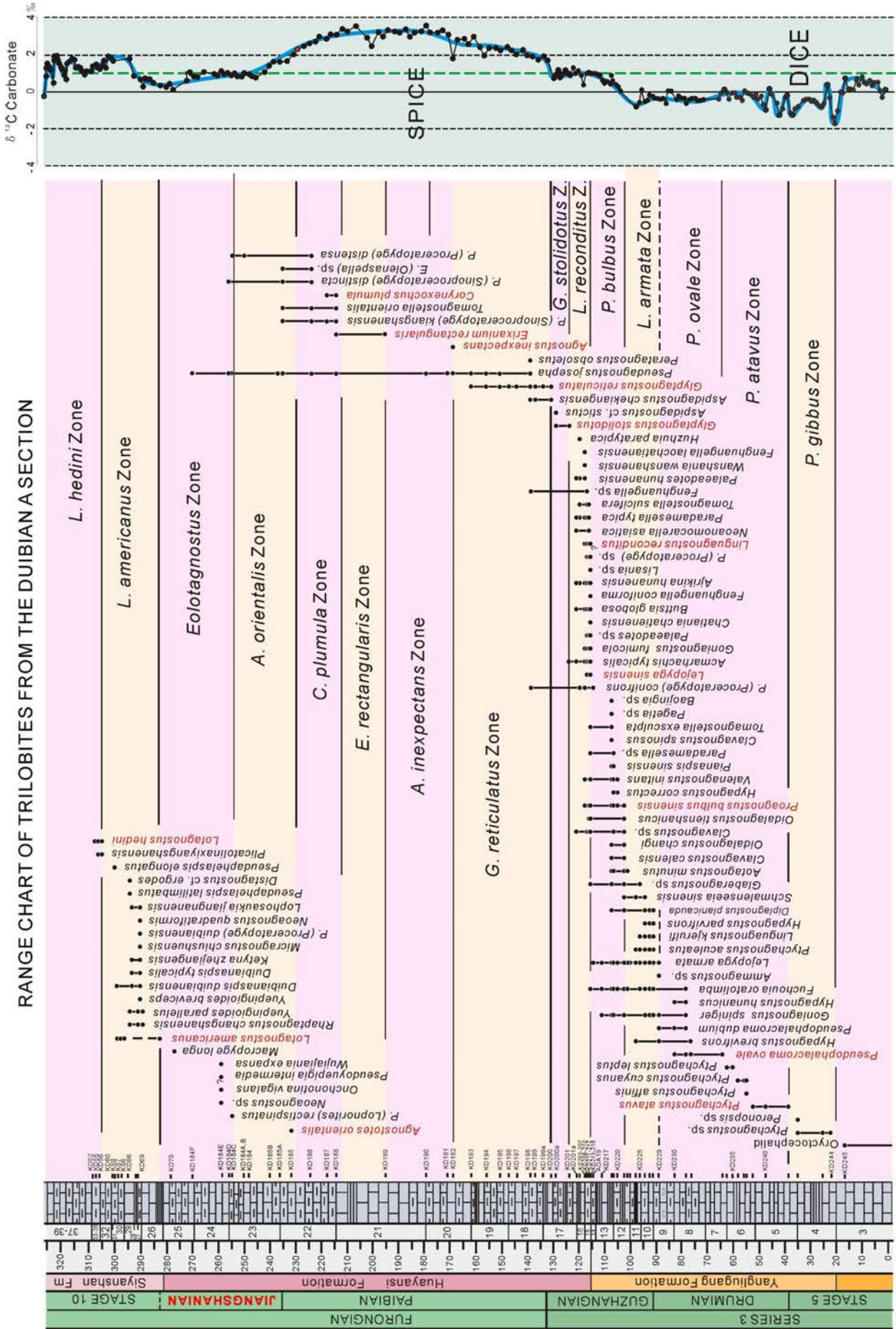


Figure 7. Observed stratigraphic distribution of trilobites in the upper part of the Cambrian of the Duibian A section, north of Duibian Village, Jiangshan, Zhejiang, China, added for comparison with the Duibian B section, which is northwest of the village (modified from Lu and Lin, 1981, 1983, 1989).

to select the position of a GSSP in a section showing a complete succession from the *G. reticulatus* Zone (or the *A. inexpectans* Zone if recognized regionally) through the *A. orientalis* Zone. Selection of the FAD of *A. orientalis* as the primary correlation tool for the base of the Jiangshanian Stage ensures that the boundary will fall within a stratigraphic interval bearing both agnostoid trilobites, many of which are phylogenetically related, and species of the polymerid trilobite *Irvingella*. Together, the narrow stratigraphic range of *A. orientalis* (if both the primitive and advanced forms are present), and the stratigraphic disappearance of both *A. inexpectans* and *G. reticulatus*, allows the boundary to be tightly constrained.

Stratotype Section

The lowest observed occurrence of *A. orientalis*, as recorded by Lu and Lin (1989), in the Duibian A section occurs in the upper part of the Huayansi Formation, 116.6 m (collection AD185) above the base of the formation (Fig. 7). Recent detailed work shows that the faunal elements present at this level are identical with those from collection DB 28.2 (28.2 m above the arbitrary 0 point) in the Duibian B section. The lowest occurrence of *A. orientalis* in the Duibian B section is in collection DB19.72 (19.72 m above the 0 point). This suggests that the FAD of *A. orientalis* should be 108.12 m above the base of the Huayansi Formation in the Duibian A section. Agnostoid trilobite zonation of the Huayansi Formation in the Duibian B section reveals a complete, tectonically undisturbed, marine succession through the upper part of the Paibian Stage (the *A. inexpectans* and *Tomagnostella orientalis* zones) into the GSSP level (coinciding with the base of the *A. orientalis* Zone), through the *Eolotagnostus* Zone of the Jiangshanian Stage. Strata correlated with these zones are also recognized in the Duibian A section and elsewhere in South China.

The stratotype of the Jiangshanian Stage reveals a succession of widespread agnostoid trilobite assemblages. Some of the species present are phylogenetically related pseudagnostid and agnostid species. Successive stratigraphic levels show a succession with the FAD of *Agnostus inexpectans* (ranging upward from 53.55 m above the base of the Huayansi Formation; upper part of the *Glyptagnostus reticulatus* Zone), the FAD of *Tomagnostella orientalis* (98.1 m above the base of the formation), the FAD of *Agnostotes orientalis* (108.12 m, coinciding with the base of the Jiangshanian Stage), the FAD of *Ivshinagnostus hunanensis* (112.84 m), the FAD of *Eolotagnostus* sp. nov., and possibly specimens of the advanced form of *A. orientalis* (116.6 m). Definite advanced specimens of *A. orientalis* occur at 119 m above the base of the Huayansi Formation. For polymerid trilobites, the stratigraphic succession includes assemblages bearing *Erixanium rectangularis*, followed by *Corynexochus plumula*, *Irvingella angustilimbata*, and *Irvingella major*. The FAD of *I. angustilimbata* coincides with the FAD of *Agnostotes orientalis*, and this provides a reliable secondary tool for defining the base of the Jiangshanian Stage. Besides the two guide species of *Irvingella*, a third species of *Irvingella*, *I. convexa*, occurs in succession above *I. angustilimbata* but below *I. major* in the Duibian B section.

The most common polymerid trilobites in the Duibian B section are ceratopygids (*Proceratopyge*, *Tamdaspis*, *Sinoproceratopyge*). Among them is *Proceratopyge* (*Sinoproceratopyge*) *kiangshanensis*, which is commonly used as a guide fossil in South China (Lu and Lin, 1989; Peng, 1992). The general morphology of *Proceratopyge* (*Sinoproceratopyge*) *distincta* suggests that it possibly gave rise to early species of the *Hedinaspis* lineage (e.g., *Hedinaspis*

(=*Asiocephalus*) *sulcatus*, *H. canadensis*), and one of these may in turn have given rise to *Hedinaspis regalis*. In the bed containing the lowest *A. orientalis* in the Duibian B section (108.12 m), the guide species is rare. However, the species is common to abundant in the upper part of the section (119 m and 119.5 m), where it is represented by the advanced forms.

Observed ranges of trilobites across the stratigraphic interval containing the GSSP are summarized in Figure 6. As mentioned above, besides *A. orientalis*, a number of other guide fossils, important for intercontinental or interregional correlation, help to constrain the boundary position.

Conodonts (Figs. 11, 12) are relatively rare in most intervals of the Duibian sections (Lu et al., 1984; herein). In a few layers, however, they occur in abundance and are rather diverse. A conodont association with 10 species has been recorded in the Duibian B section from a short interval about 10 m above the boundary. Components of this association are tentatively assigned to the *Westergaardodina* cf. *calix* – *Prooneotodus rotundatus* Zone of Dong et al. (2004). Samples taken for conodonts close to the GSSP level were unproductive.

Demonstration of Regional and Global Correlation

A position at or closely corresponding to the FAD of *A. orientalis* in the Duibian B section is one of the most easily recognizable horizons on a global scale in the Cambrian (e.g., Geyer and Shergold, 2000; Peng and Babcock, 2005b; Babcock et al., 2005; Fig. 2), in part because the level is marked by the joint first appearances of *A. orientalis* and *I. angustilimbata*. Suitability of the FAD of *A. orientalis* for marking a global stage boundary has been summarized principally by Geyer and Shergold (2000), Peng and Babcock (2005a, b), and Peng et al. (2005, 2006, 2009a). Key correlation tools are described in the following subsections.

Agnostoid trilobite biostratigraphy

As mentioned above, *A. orientalis* has been recognized worldwide and used as a zonal guide fossil independently or jointly with species of either *Irvingella* or *P.* (*Sinoproceratopyge*) in deposits of Gondwana and Siberia (e.g., Lu and Lin, 1981, 1983, 1989; Öpik, 1963, 1967; Ergaliev 1980; Ergaliev and Ergaliev, 2000; Geyer and Shergold, 2000; Shergold and Geyer, 2001; Peng, 1992; Hong and Choi, 2003; Choi, 2004; Choi et al., 2004; 2005; Varlamov et al., 2005; Varlamov and Rozova, 2009). An agnostoid trilobite-based biostratigraphy, one that is distinct from polymerid trilobite-based biostratigraphy, has been proposed for the middle and upper parts of the Furongian Series, based largely on the succession in the Duibian B section. The guide fossils in the two lower zones are also widely distributed. The agnostoid trilobite faunas of the Duibian B section allow a close correlation of the horizon containing the GSSP into Gondwana, Kazakhstan, Laurentia, Siberia, Baltica, and Avalonia.

Polymerid trilobite biostratigraphy

A new polymerid trilobite biostratigraphy that parallels the agnostoid trilobite biostratigraphy is proposed for the middle and upper Furongian in the Duibian sections. Four zones are recognized. In ascending order, they are the *Erixanium rectangularis* Zone, the

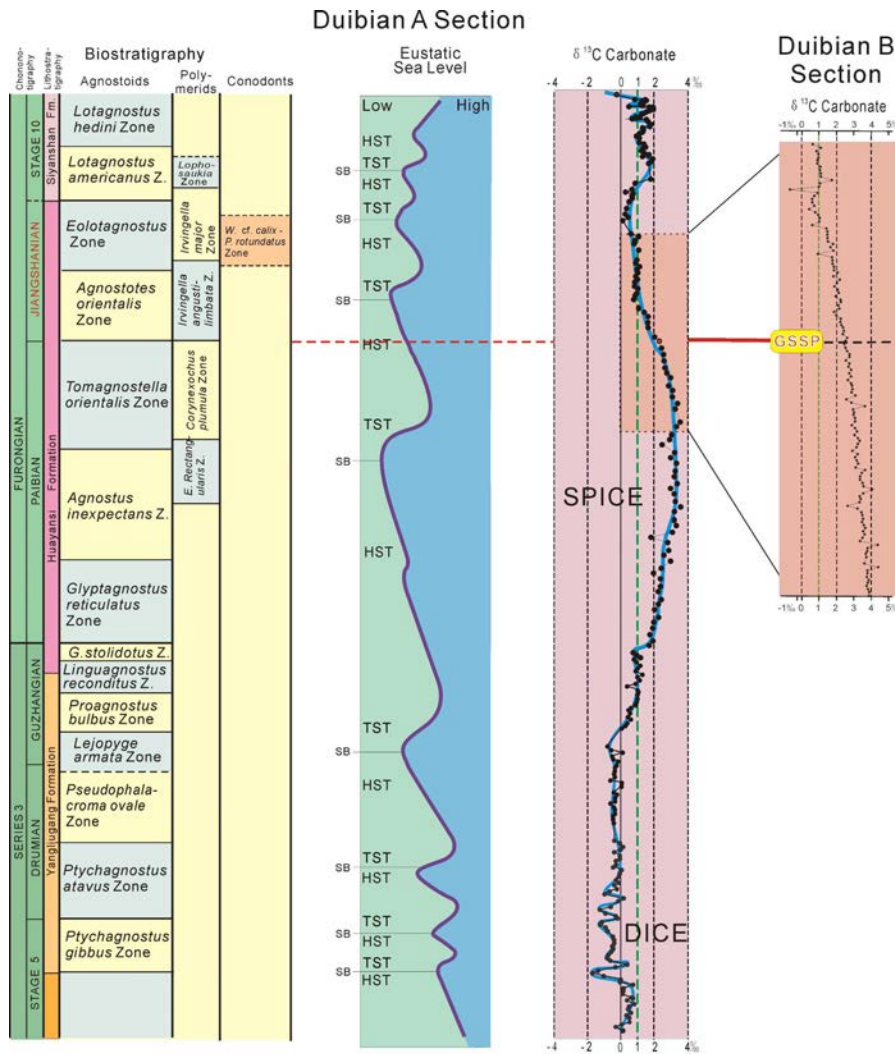


Figure 8. Summary of primary and secondary stratigraphic indicators for the base of the Jiangshanian Stage of the Cambrian System. Major stratigraphic tools used to constrain the GSSP of the stage are the zonation of agnostoid and polymerid trilobites (Lu and Lin, 1981; 1983, 1989; Peng et al., 2006; 2009a), the occurrences of conodonts (Peng et al., 2009a), carbon isotope chemostratigraphy (records from the Duibian A and Duibian B sections from Zuo, 2006), and sequence stratigraphy (Zuo, 2006), all of which have applied in the Duibian B section.

Corynexochus plumula Zone, the *Irvingella angustilimbata* Zone, and the *Irvingella major* Zone (Figs. 6, 8). The base of the *A. orientalis* Zone coincides with the base of the *I. angustilimbata* Zone. *I. angustilimbata* has been recognized in the upper part of the *Elvinia* Zone in Laurentia (Pratt, 1992), the *Irvingella tropica* [= *I. angustilimbata*] Zone in Australia (Öpik, 1963; Geyer and Shergold, 2000), the *Agnostotes clavata* [= *A. orientalis*]–*Irvingella angustilimbata* Zone in Siberia (Varlamov and Rozova, 2009), and the *Pseudagnostus* (*P.*) *vastulus*–*Irvingella tropica* [= *I. angustilimbata*] Assemblage-zone in Kazakhstan (Ergaliev and Ergaliev, 2008). Similar preglabellar field-bearing species of *Irvingella*, assigned to *I. megalops*, have been recognized at the base of the *Eochuangia hana* Zone in South Korea (Hong and Choi, 2003).

Conodont biostratigraphy

The interval from 29.12 m to 31.5 m above the 0 point (i.e., 117.52

m to 119.9 m above the base of the Huayansi Formation), here assigned to the lowermost part of the *Eolotagnostus* trilobite zone, yield a conodont fauna with 10 species including, among others, *Coelocerosodus bicostatus*, *Prooneotodus gallatini*, and *Prooneotodus rotundatus*. These taxa, even though they range higher, possibly indicate the *Westergaardodina* cf. *calix* – *Prooneotodus rotundatus* Zone established by Dong et al. (2004) for South China. This zone is characterized by the abundance of *Prooneotodus* and is broadly equivalent to the *W. aff. fossa*–*P. rotundatus* Zone established by An (1987) for North China. Other taxa present in the Duibian B section are either long ranging or left in open nomenclature due to poor preservation. Some specimens could be early representatives of *Proconodontus*, but this assignment requires further investigation.

Chemostratigraphy

The FAD of *A. orientalis* occurs within the upper part of the SPICE excursion, near the end of a long, monotonic decline of the $\delta^{13}\text{C}$ excursion (Figs. 6–8). The underlying Paibian Stage is characterized by a long positive shift with a maximum value of 4.2 ‰ being reached in the middle of the *Erinxaniaum rectangularis* Zone (Figs. 6, 7). The peak interval occurs in the upper part of the *E. rectangularis* Zone and lower part of the *Corynexochus plumula* Zone, where positive $\delta^{13}\text{C}$ values vary between 3 and 4 ‰.

The FAD of *A. orientalis* occurs just below the peak of a long monotonic shift in $^{87}\text{Sr}/^{86}\text{Sr}$ toward the maximum value (0.7082) reached in the Cambrian (Peng et al., 2012), although Sr isotope values have not been recorded from the Duibian B section. The peak value closely coincides with the sharp return to near-0 values of $\delta^{13}\text{C}$ at the end of the SPICE

excursion and the extinction associated with the Pterocephalid Biome in Laurentia.

Sequence stratigraphy

Work in the Duibian sections shows that the base of the *A. orientalis* Zone is associated with the late part of a long regressive event whose inception is recorded in the lower part of the *A. inexpectans* Zone (Figs. 6, 8). Overall, the Yangliugang, Huayansi, and Siyangshan formations in the Duibian A section are inferred to have been deposited during eight third-order cycles (Zuo, 2006), which together form a second-order cycle. Superimposed on these long-term cycles are a series of smaller scale transgressive-regressive cycles. A comparable sequence stratigraphy with eight third-order cycles within a larger second-order cycle has been recognized from a basically equivalent stratigraphic interval in Guizhou Province, China (Mei et al., 2007). In the Duibian B section, the FAD of *A. orientalis*

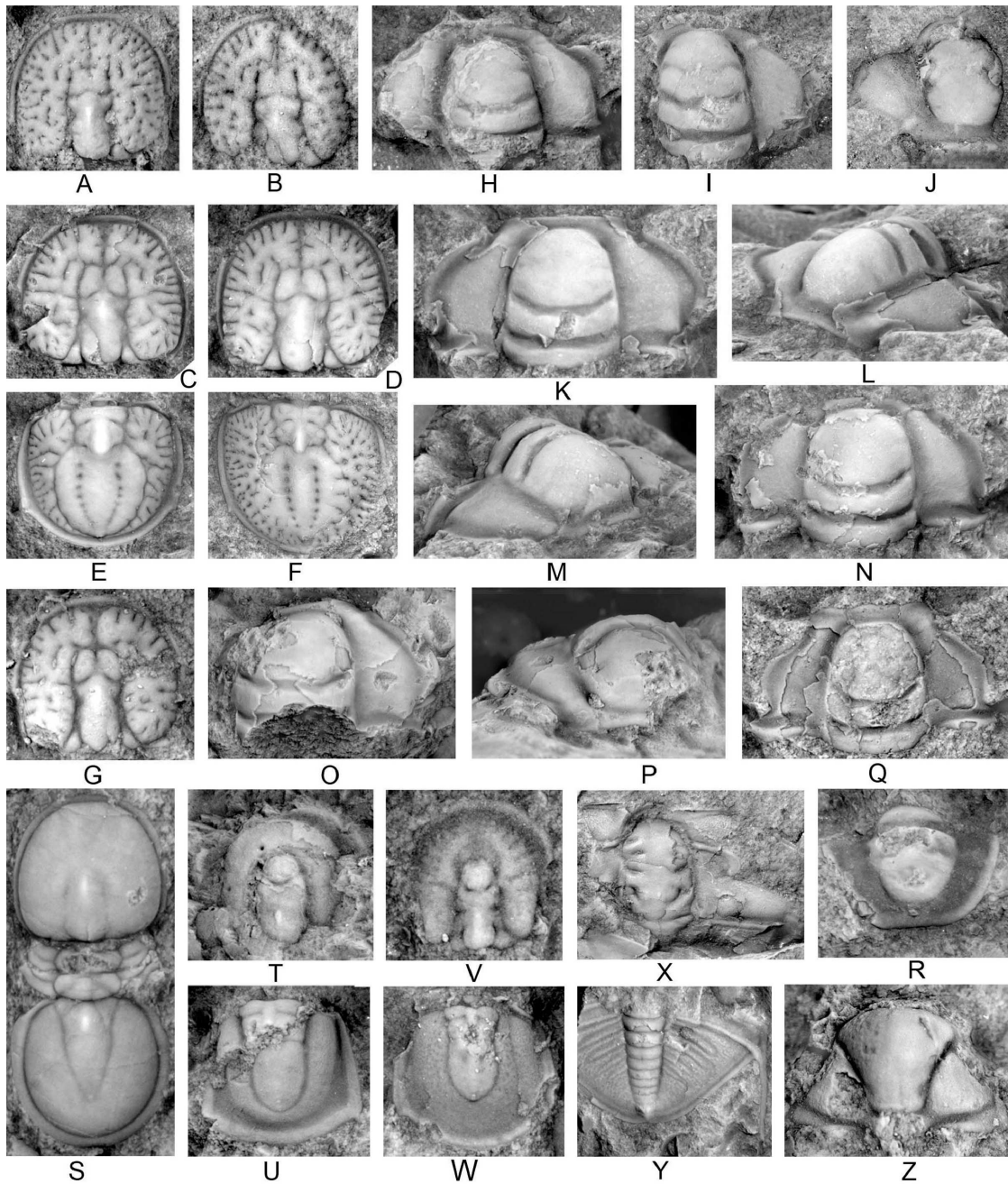


Figure 9. Key trilobite species used for recognition of the base of the Jiangshanian Stage. Numbers with the prefix DB (for Duibian section) indicate collecting horizons in meters above the arbitrary 0 m point. Unless stated otherwise, all are dorsal views. A–G, *Agnostotes orientalis* (Kobayashi, 1935), a series of primitive and derived forms. A, B, two cephala, DB19.72, 108.12 m above the base of Huayansi Formation, $\times 6$, $\times 7.5$; note that the frontal sulcus has a short notch; C–F, two cephala (C, D) and two pygidia (E, F), DB30.6, 119 m above the base of Huayansi Formation; note that the frontal sulcus on the cephalon extends rearward into the transglabellar furrow and divides the anterior lobe of the glabella into a pair of ovate lobes, $\times 5.4$, $\times 6$, $\times 5$, $\times 4.6$; G, cephalon, DB31.1, 119.5 m above the base of Huayansi Formation, $\times 9$; note that the frontal sulcus in this cephalon deeper than in other illustrated specimens; H–R, a series of primitive and derived species of *Irvingella*. H–J, *Irvingella angustilimbata* (Kobayashi, 1938). H, cranidium, I, J, cranidium (J, anterior view, latex cast), DB19.72, 108.12 m above the base of Huayansi Formation, $\times 7$, $\times 4.5$, $\times 4.5$; K–N, *Irvingella convexa* (Kobayashi, 1935). K, L and M, N, two cranidia (L and N in anterolateral views), DB30.6, 119 m above the base of Huayansi Formation, $\times 5.7$, $\times 5.7$, $\times 4$, $\times 4$; O–R, *Irvingella major* Ulrich and Resser in Walcott, 1924. O, P, cranidium (P in anterior view), R, pygidium, DB31.1, 119.5 m above the base of Huayansi Formation, $\times 4.2$, $\times 4.2$, $\times 10$; Q, cranidium, DB33.6, 122 m above the base of Huayansi Formation, $\times 4.5$; S, *Tomagnostella orientalis* (Lazarenko, 1966), exoskeleton, DB31.1, 119.5 m above the base of Huayansi Formation, $\times 9$; T, U, *Ivshinagnostus hunanensis* Peng, 1992, cephalon (latex cast), pygidium, DB28, 116.4 m above the base of Huayansi Formation, $\times 9$, $\times 9.5$; V, W, *Eolotagnostus* sp. nov., cephalon, pygidium, DB33.6, 122 m above the base of Huayansi Formation, $\times 14$, $\times 8$; X, Y, *Proceratopyge* (*Sinoproceratopyge*) *distincta* Lu and Lin, 1989, cranidium, pygidium, DB33.6, 122 m above the base of Huayansi Formation, $\times 7$, $\times 6$; Z, *Corynexochus plumula* Öpik, 1963, cranidium, DB9.7, 98.1 m above the base of Huayansi Formation, $\times 12$.

| Zhejiang, South China (this study) | | | Hunan, South China Dong et al., 2004 | North and Northeast China An, 1982; Wang, 1985 | Great Basin, USA Miller, 1981 Miller et al., 2006 |
|--|--------------|--|---|--|---|
| Series | Stage | Formation | Formation | Formation | Formation |
| Conodont Zone and Subzone | | Formation | Formation | Conodont Zone and Subzone | |
| FURONGIAN | JIANGSHANIAN | Siyanshan | Shenjiawan | Fengshan | Notch Peak |
| | | Huayansi | Huaqiao | Chanshan | |
| Conodont Zone and Subzone | | Conodont Zone | Conodont Zone | Conodont Zone and Subzone | |
| W. cf. calix - Prooneotodus rotundatus | | Proconodontus | Proconodontus | Proconodontus muelleri | |
| | | Proconodontus tenuiserratus | Proconodontus tenuiserratus | Proconodontus posterocestatus | |
| | | Westergaardodina cf. calix - Prooneotodus rotundatus | Westergaardodina aff. fossa - P. rotundatus | Proconodontus tenuiserratus | |
| | | Westergaardodina lui - W. ani | Muellerodus? erectus | No zonation established | |

Figure 10. Tentative biostratigraphic correlation of the *Westergaardodina cf. calix* - *Prooneotodus rotundatus* conodont Zone in the Duibian B section with other areas.

is associated with the onset of a small-scale transgressive event (Zuo, 2006, fig. 4). The regression with which the FAD of *A. orientalis* is associated is interpreted to be of eustatic scale.

Other Regional Reference Section

Apart from the Duibian A section, western Zhejiang, there is another well-exposed section in South China, which yields the primitive morphotype of *A. orientalis*. The section is located near Shenjiawan in the Cili-Taoyuan area, Hunan Province, China. It exposes limestone deposits of the upper part of the Huaqiao Formation, which were formerly referred to the lower part of the Bitiao Formation by Peng (1992). The first observed occurrence of *A. orientalis* in the section is about 42 m above the base of the *Corynexochus plumula*-

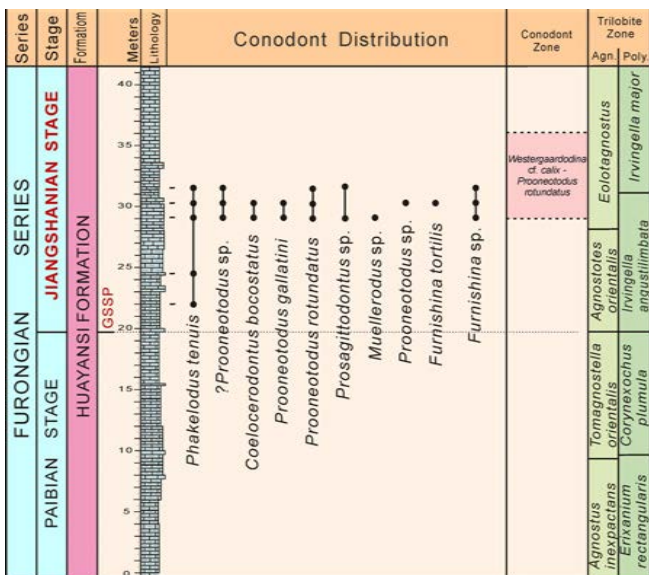


Figure 11. Observed stratigraphic distribution of conodonts in the Huayansi Formation near the base of the *Agnostotes orientalis* Zone, Duibian B section, Jiangshan, Zhejiang, China. Agn.= agnostoid trilobite biostratigraphic zonation; Poly.= polymerid trilobite biostratigraphic zonation.

Proceratopyge (*Sinoproceratopyge*) *kiangshanensis* Zone (Peng, 1992). Down-section the Huaqiao Formation contains a few carbonate debris beds in the *Glyptagnostus reticulatus* Zone suggesting that the Huaqiao Formation near Shenjiawan represents a somewhat less deep slope environment than does the Huayansi Formation of the Duibian sections.

Extraregional Reference Sections

Two extraregional sections were considered by the ISCS as potential stratotype sections for the GSSP of the Jiangshanian Stage. Both are well exposed, well documented, have an inferred complete succession of strata through the base of the *A.*

orientalis Zone, and meet all of the major requirements for a GSSP. In both cases, though, accessibility is less easy than in the case of the Duibian section. Nevertheless, the Cambrian Subcommittee considers both extraregional sections to be important for correlation purposes both regionally and globally.

The first extraregional section occurs along the Kyrshabakty River, about 28 km northeast of Zhanatas, Malyi Karatau Range, Kazakhstan (Ergaliev, 1980; Ergaliev and Ergaliev, 2000, 2008). The base of the section is located at 43°32'02" N, 69°51'28" E and an elevation of 527 m. It is located in a protected area, the Aksai State Natural Reserve, but accessible for study. The Malyi Karatau Range represents a northwestern extension of the Tien Shan Mountains. The Kyrshabakty section was long considered a major reference section for stratigraphic subdivisions of the historic Middle and Upper Cambrian of the former USSR, and later for Kazakhstan (Ergaliev and Ergaliev, 2000; Ergaliev et al., 2009).

In the Kyrshabakty section, Cambrian strata ranging from the upper part of the Paibian Stage through the Jiangshanian Stage are assigned to the Bestogai Formation, a succession dominated by medium gray to dark gray, thin to medium bedded limestones (lime mudstones); some limestone turbidites with packstone texture are present. The first appearance of *A. orientalis* is 61.2 m above the base of Unit 8 in the Bestogai Formation (and 259 m above the base of the measured section). *A. orientalis* is rare at this locality. The first appearance of *A. orientalis* in this section is 2.0 m above the first appearance of the polymerid trilobite *Irvingella angustilimbata* (commonly cited at this locality under the name of a junior synonym, *I. tropica*).

Cambrian Series 3 and Furongian strata exposed in the Kyrshabakty section were deposited on a prograding margin of an isolated carbonate platform called the Aisha-Bibi Seamount (Cook et al., 1991). Detailed bed-by-bed correlation, coupled with detailed biostratigraphy, suggest that the Zhumabai and overlying Bestogai formations record a complete, essentially continuous stratigraphic succession. The FAD of *A. orientalis* is in a bed within the Bestogai Formation, immediately overlying a carbonate turbidite that extends over part of the outcrop. However, the turbidite pinches out approximately 50 m away from the line of the measured section, and the *A. orientalis*-bearing bed can be traced laterally from the line of

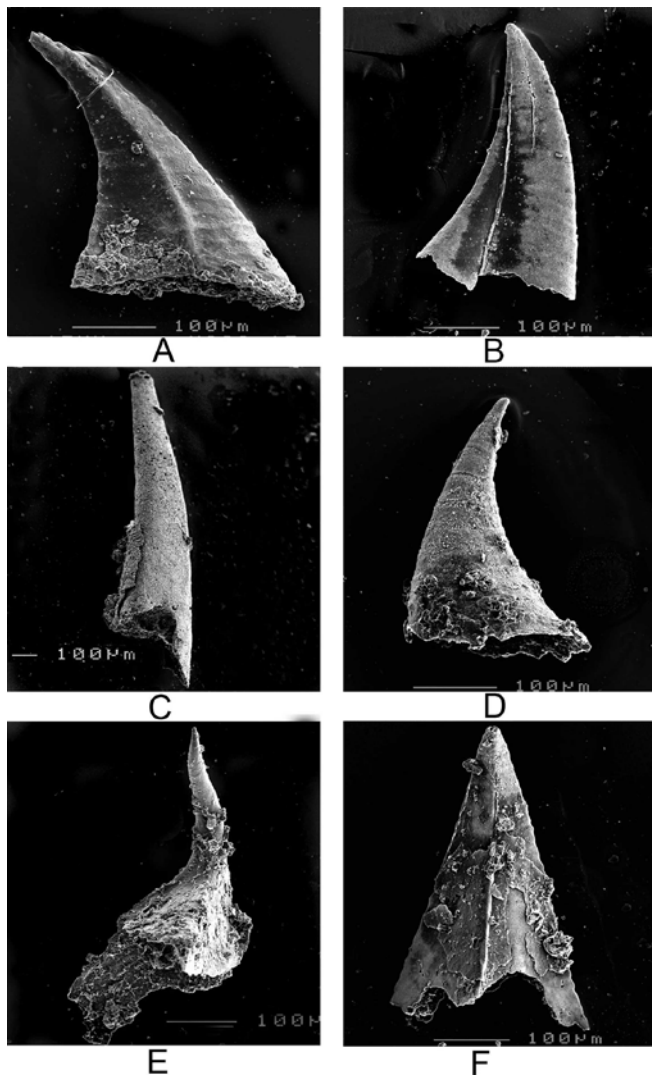


Figure 12. Conodonts used for constraining the base of the Jiangshanian Stage. **A.** *Coelocerodontus bicostatus* van Wamel, 1974; sample DBC30.3, 118.7 m above the base of Huayansi Formation, lateral view, $\times 120$. **B.** *Coelocerodontus bicostatus* van Wamel, 1974; sample DBC30.3, 118.7 m above the base of Huayansi Formation, lateral view, $\times 110$. **C.** ?*Prooneotodus* sp.; sample DBC29.12, 117.52 m above the base of Huayansi Formation, posterolateral view, $\times 36$. **D.** *Prooneotodus gallatini* (Müller, 1959); sample DBC30.3, 118.7 m above the base of Huayansi Formation, lateral view, $\times 120$. **E.** *Furnishina tortilis* (Müller, 1959); sample DBC30.3, 118.7 m above the base of Huayansi Formation, posterolateral view, $\times 90$. **F.** *Prosagittodontus* sp.; sample DBC31.5, 119.9 m above the base of Huayansi Formation, posterior view, $\times 110$.

the measured section. The order of trilobite occurrences is consistent with an unbroken stratigraphic succession.

The second extraregional section occurs along the Khos-Nelege River, Siberia, near where it joins the Neleger River. The Neleger River is a tributary to the much larger Lena River. The section is located about 25 km northeast of the village of Chekurovka and 60 km southwest of the town of Tiksi, in the Kharaulakh Mountains (southern part of the Tuora-Sis Ridge), North Verkhoyanie, western part of the Republic of Sakha (Yakutia), Russia (Lazarenko et al., 2008a, b). The base of the Jiangshanian Stage is located 500 m

upstream from the junction of the Khos-Nelege River with the Neleger River, at a position of $71^{\circ}14'36''$ N, $127^{\circ}31'35''$ E. The section is exposed in the western limb of the Chekurovian anticline of the Verkhoyansk folded area, northeastern part of the Siberian Platform. This area, at the mouth of the Khos-Nelege River, is located in the Lena Delta Research Reservation, part of the Ust'-Lenskij State Natural Reserve. The land is public, under permanent protection of the government of the Republic of Sakha (Yakutia), and accessible for research. Access to the site is limited by weather conditions in the Arctic, with July and August being the optimal times for field research.

In the Khos-Nelege River section, Cambrian strata ranging from the Drumian Stage through the Jiangshanian Stage are assigned to the Ogon'or Formation, a succession dominated by rhythmic, thin-to thick-bedded, dark gray carbonates (wackestones to packstones), carbonate shales and silty limestones, intercalated with bioturbated limestones and shales. The FAD of *A. orientalis* is 213.3 m above the base of the Ogon'or Formation (and 3.3 m below the top of bed 32). The first appearance of *A. orientalis* in this section occurs close to the first appearances of two species of the polymerid trilobite *Irvingella*, *I. megalops* and *I. major*. *I. megalops* first appears 210.5 m above the base of the Ogon'or Formation, and *I. major* first appears 219.6 m above the base of the formation. Thus, the first appearance of *A. orientalis* is 2.8 m above the first appearance of *I. megalops*, and 6.3 m below the first appearance of *I. major*.

Cambrian strata of eastern Siberia were deposited within the vast Yudoma-Olenek Basin, which opened to the east (Lazarenko et al., 1990; Sukhov, 1997). The Khos-Nelege River section exposes a northern sublongitudinal slope of this basin. One shelf margin of the basin, a carbonate platform edge, is exposed 20 to 30 km to the north in the Bulkur anticline. Detailed bed-by-bed correlation, coupled with detailed biostratigraphy, suggests that the Ogon'or Formation records a complete, essentially continuous stratigraphic succession. The order of trilobite occurrences is consistent with an unbroken stratigraphic succession.

Best Estimate of Age for the Base of the Jiangshanian Stage

Shergold (1995) estimated an age of ~ 500 Ma for the traditional Middle-Upper Cambrian boundary, and that position is close to the base of the *Linguagnostus reconditus* Zone of South China (Peng and Robison, 2000; Ahlberg, 2003; Ahlberg et al., 2004). This boundary is two agnostoid zones lower than the conterminant base of the Furongian Series and Paibian Stage. Peng and Robison (2000) suggested that the average duration for a single agnostoid zone is about 1 m.y. If so, the base of the Furongian Series is likely to have an age of ~ 498 Ma.

The closest rather reliable U-Pb zircon age, 488.71 ± 2.78 Ma (Davidek et al., 1998; Peng et al., 2009a), comes from within the Furongian Series. This radioisotopic age derives from a crystal-rich volcanoclastic sandstone in the *Peltura scarabaeoides* Zone (Dolgellau Formation) at Ogof-ddû, near Criccieth, North Wales. This age constrains the top of the *Lotagnostus americanus* Zone of South China and elsewhere to a great extent because the last occurrence of *L. americanus* [= *Lotagnostus trisectus* Salter] in Sweden is within the lower *P. scarabaeoides* Zone as used historically (Westergård, 1922; Ahlberg and Ahlgren, 1996). In Sweden, this position is now referred (Terfelt et al., 2008, 2011) to the top of the *Lotagnostus americanus*

Zone (agnostoid zonation) and the *Ctenopyge linnarssoni* Zone (polymerid trilobite zonation). The interval of the *L. reconditus* Zone through the *Lotagnostus americanus* Zone should have had a duration of 8 to 11 million years because about 8 biostratigraphic zones are recognized in China (Peng, 1990, 1992; Shergold and Cooper, 2004) and 11 zones are recognized for the comparable interval in Australia (Shergold and Cooper, 2004); the average duration of each zone is assumed to be 1 million years or less. This yields a best age estimate of 494 Ma, or slightly older, for the base of the *A. orientalis* Zone (i.e., the base of the Jiangshanian Stage), which is three zones above the base of the *Glyptagnostus reticulatus* Zone. Because we have only one reliable isotopic age date within the Furongian Series, estimation of age of the base of the Jiangshanian Stage is made with less confidence than the estimate for the base of the Guzhangian Stage. The Guzhangian age was based on multiple numerical age dating sources (summarized in Peng et al., 2009b).

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