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Late Visean – early Serpukhovian conodont succession at the Naqing (Nashui) section in Guizhou, South China

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Abstract – This study reports the conodont succession across the Visean–Serpukhovian (V/S) boundary interval at the Naqing section, South China. Continuous centimetre-scale sampling of the relatively deep-water section in recent years has provided new data for a more detailed biostratigraphy of conodonts across the Visean–Serpukhovian boundary. Three conodont zones were described in ascending order: the *Gnathodus bilineatus*, *Lochriea nodosa* and *Lochriea ziegleri* zones. The first appearance datum (FAD) of *L. ziegleri* has been moved down to 60.1 m above the base of the Naqing section. The correlation of the conodont succession across the Visean–Serpukhovian boundary in the Naqing section with other sections in Eurasia is discussed.

Keywords: conodont succession, Visean–Serpukhovian boundary, candidate GSSP, Naqing section, South China.

1. Introduction

Pronounced endemism, strong glacial–eustatic control over sedimentation and consequent widespread disconformities hamper the selection of acceptable Global Boundary Stratotype Sections and Points (GSSPs) for the Carboniferous stages, including the Serpukhovian, Moscovian, Kasimovian and Gzhelian stages. The Serpukhovian Stage, proposed by Nikitin (1890), was reintroduced into the Russian stratigraphic scheme in 1974 by the Interdepartmental Stratigraphic Committee of the USSR and has become internationally recognized (Skompski *et al.* 1995; Gibshman, 2001). The type Serpukhovian was deposited in the Moscow Basin and is situated in the Zaborie quarry near the southern margin of the town of Serpukhov, Russia. Unfortunately, the lower boundary of the type Serpukhovian is a basin-wide unconformity that resulted from a latest Visean regression and subaerial exposure followed by a Serpukhovian transgression. Deposition of the type Serpukhovian was strongly influenced by the major glacial–eustatic changes during the late Visean and continued through the Pennsylvanian (Richards & Task Group, 2003). The succession constituting the type Visean was deposited in the Namur–Dinant Basin of Belgium, northern France and southern England. There, the type Visean is represented by a quarry section in Belgium and the contact with the overlying Namurian succession (correlative with the Serpukhovian Stage) is a regional unconformity (Paproth *et al.* 1983). The relatively deeper-water carbonate-slope and basinal sections that may serve as potential candidate sections for GSSP of the Visean–Serpukhovian (V/S) boundary are known from the Cantabrian Mountains (Spain), the South Urals (Russia) and southern Guizhou, South China (Richards & Task Group, 2003; Wang & Qi, 2003; Nemyrovska, 2005; Nikolaeva *et al.* 2005, 2009; Qi & Wang, 2005; Blanco-Ferrera *et al.* 2009).

The Visean–Serpukhovian boundary has yet to be defined by a GSSP, but the first appearance datum (FAD) of conodont *Lochriea ziegleri* Nemirovskaya, Perret-Mirouse & Meischner, 1994 in the evolutionary lineage *Lochriea nodosa* (Bischoff, 1957) – *Lochriea ziegleri* presents an excellent possibility for boundary definition. A group of *Lochriea* species ornamented by numerous nodes and/or ridges appears at, or a short interval below, the Visean–Serpukhovian boundary. Although a globally recognized base of the Serpukhovian Stage is not officially ratified, the International Subcommission on Carboniferous Stratigraphy (SCCS) Task Group to establish a GSSP for the V/S boundary believes the FAD of conodont *Lochriea ziegleri* in the evolutionary lineage from *Lochriea nodosa* to *Lochriea ziegleri* is most suitable for boundary definition. This lineage, along with the associated faunas and strata, is being studied in several areas; the Naqing (Nashui) section in South China and the Verkhnyaya Kardailovka section in the SE Urals of Russia have the best potential as GSSP

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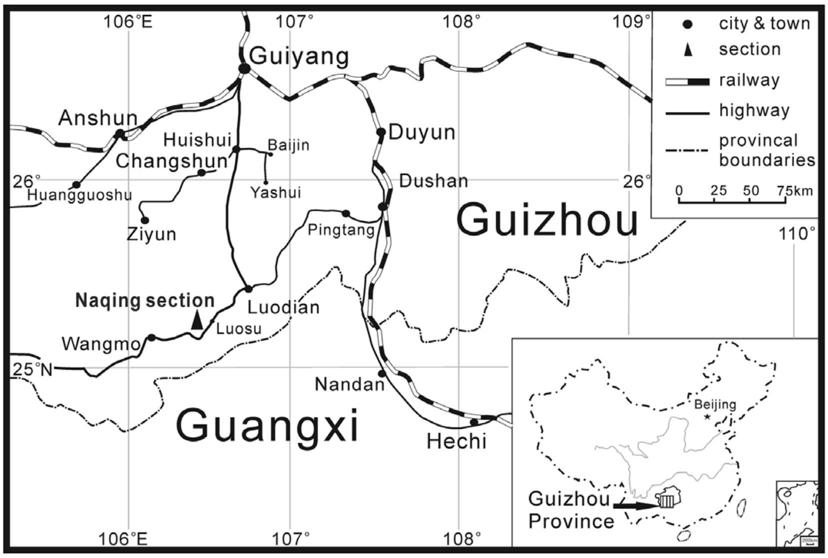

Figure 1. Location map of the Naqing section.

candidates however, and are under intensive study (Richards, 2010).

Carboniferous marine sediments are widely distributed and well developed in South China, where they form continuous sequences of marine carbonates containing conodonts and foraminifers. The Naqing section (formerly called the Nashui section) in Luosu, Luodian, Guizhou Province is the most-studied section across the V/S boundary in South China, as discussed by Wang & Qi (2003), Qi & Wang (2005), Wang & Jin (2005), Qi *et al*. (2007, 2009, 2010*a*, *b*), Wang, Qi & Wang (2008) and Groves (2010). The Naqing section is located at latitude 25° 15′ 03.9″ N and longitude 106° 29′ 06.9″ E, exposed on the side of the Wangmo–Luodian highway (S312) *c*.45 km SW of Luodian, 7 km SW of Luosu countryside and 2 km SW of the village of Naqing, and is easily accessible by car from the capital of Guizhou Province Guiyang (Fig. 1). This section is a relatively deeper-water carbonate-slope facies section that comprises grey thin- to medium-bedded wackestone and packstone beds intercalated with chert beds. The abundant and highly diverse conodont faunas, including 28 species or subspecies representing 6 genera obtained from the Naqing section, provide sufficient support for this section which is being considered as the GSSP for the base of the global Serpukhovian Stage. The purpose of this paper is to report recent results on the conodont succession from the V/S boundary interval of the Naqing section.

2. Geological setting

Geologically, the southern part of Guizhou belongs to the Dian–Qian–Gui Basin developed in the SW part of the South China block. The basic tectonic framework of the Late Palaeozoic of South China was formed during middle–late Silurian time when most of the eastern part of South China was folded during the Caledonian Orogeny. Transgression began again in the Early Devonian and slowly progressed northwards. The rifted basins were filled, the topography was reduced and extensive carbonates were laid down before the Pennsylvanian (Wang & Jin, 2000). The palaeogeographic evolution of the Dian–Qian–Gui Basin was greatly influenced by NE- and NW-trending faults (Wang *et al*. 1994) and, as a result, isolated carbonate platforms are well developed in the basin (Fig. 2). During Mississippian time, lithofacies changed rapidly across the region. Generally, there are four lithofacies groups: (1) the platform margin to slope marked by slump structures and limestone conglomerate; (2) the platform margin with high-energy grainstone and reef limestone; (3) the platform interior marked by low-energy shallow-marine carbonate rocks; and (4) shallow basins characterized by gravity flows and deposits formed in deeper-water environments (Wang *et al*. 1994). The Naqing section belongs to the first lithofacies group. It is one of the best exposed sections in the Guizhou area and contains a carbonate succession that appears to be continuous from the Mississippian to the Late Permian.

This section is represented by the platform margin to slope facies, which are well exposed along the east limb of the Naqing Anticline. Conodont elements are abundant throughout the section, providing precise correlation with the global chronostratigraphic scale. Intercalated gravity flows and coarse-grained bases of turbidite beds throughout the section contain many fusulines and non-fusuline foraminifers, which are the index fossils used for regional stratigraphic correlation. These characteristics make the Naqing section important for stratigraphic correlation between shallow- and deep-water facies, thereby providing an excellent reference for both regional- and global-scale correlations.

3. Sedimentological characteristics

The upper Visean to lower Serpukhovian succession (*c*. 26 m thick) in the Naqing section is generally

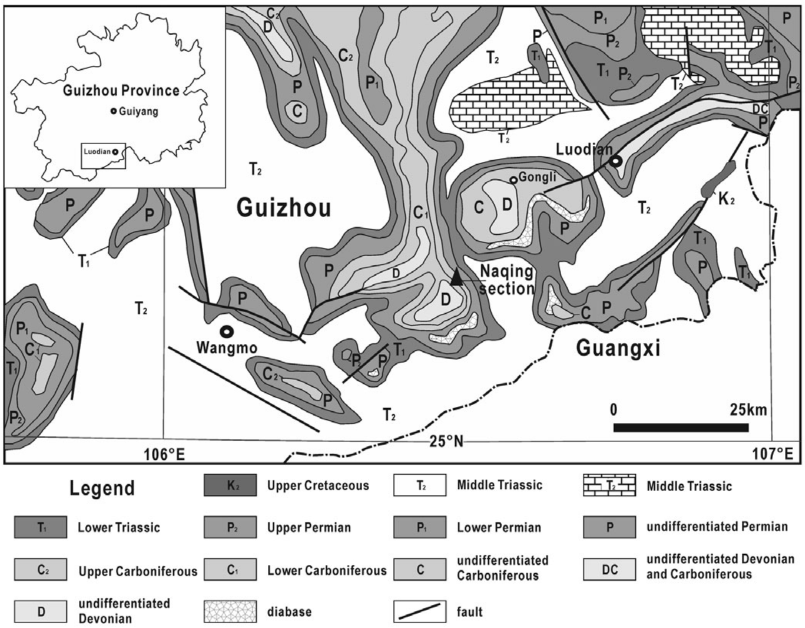

Figure 2. Geological map of the study area.

characterized by thin- to medium-bedded lime mudstone, frequently intercalated with bioclastic wackestone to grainstone and chert layers. A total of 105 rock samples were taken from the studied succession (*c.* 50–71 m): 49 from the upper Visean succession; 1 from the bed that contains the base of the Serpukhovian; and 55 from the lower Serpukhovian succession. Rock samples were cut and polished for slab observation, and more than 150 thin-sections were prepared for detailed petrographic and microfacies analyses. Based on detailed field investigation and measurements and observations of polished slabs and thin-sections in the laboratory, 7 facies were divided from the studied succession including lime mudstone facies (LM), bioclastic wackestone facies (Wb), bioclastic packstone facies (Pb), massive grainstone facies (Gm), crudely laminated grainstone facies (Gcl), normal-graded grainstone facies (Gng) and reverse-graded grainstone facies (Grg). These facies occur throughout the studied succession, both below and above the Visean–Serpukhovian boundary (Fig. 3).

Lime mudstone is mostly homogeneous or slightly bioturbated (ichnofacies index 2), showing mottled texture. Burrows are either vertical, cutting through the lamination, or horizontal. In some cases, lime mudstone is crudely laminated, nodular or conglomeratic. Lime mudstone consists mainly of microcrystalline particles to micrite and a small portion of recognizable fossil fragments such as foraminifers and crinoid. Thin-bedded lime mudstone is sometimes intercalated with thin (a few millimetres to centimetres thick) black shale and grainstone layers. Bioclastic wacke- and packstone is mostly massive, or sometimes horizontal- or cross-laminated, with scattered coarse fossil fragments. Bioclastic grainstone beds are a few centimetres up to 70 cm thick, overlying lime mudstone beds with sharp, irregular lower boundaries. They often show normal grading that is represented by either less or finer grains upwards (i.e. changing from coarse grainstone to wackestone or fine grainstone). Grainstone is composed of abundant fossil fragments (including echinoderm, foraminifer, bryozoans, brachiopod, trilobite, etc.) and irregular micritic lumps. In some cases, a few intraclasts composed of either lime mudstone or grainstone occur in the lower part of the coarse grainstone beds. Grainstone beds locally show load cast structures at the base, overlying lime mudstone bed with sharp contact. Thin beds of bioclastic wackestone to grainstone are partly massive, crudely laminated or cross-laminated. Parallel-laminated grainstone is represented by alternation of dark-grey, micritic and light-grey, sparitic laminae. Elongate fossil fragments are mostly parallel to the lamination. Laminae show either distinct or gradational boundaries. Rare reverse grading is represented by the wackestone or fine grainstone at the base to the intraclasts-bearing coarse grainstone in the upper part. Discontinuous or continuous chert layers are often intercalated within either lime mudstone or grainstone beds. Fossil fragments are clearly recognized in the chert that occurs within grainstone, indicating that most of the chert layers were probably precipitated during diagenesis by replacing carbonate sediment.

The sample (at 60.10–60.22 m) that bears the Visean–Serpukhovian boundary at its basal part is a slightly normal-graded bioclastic medium to fine grainstone, with a discontinuous chert layer (*c.* 5 cm thick) in the middle part separating the lower coarser part and the upper finer part. The grainstone is composed of abundant foraminifers and crinoid stems. Well-preserved

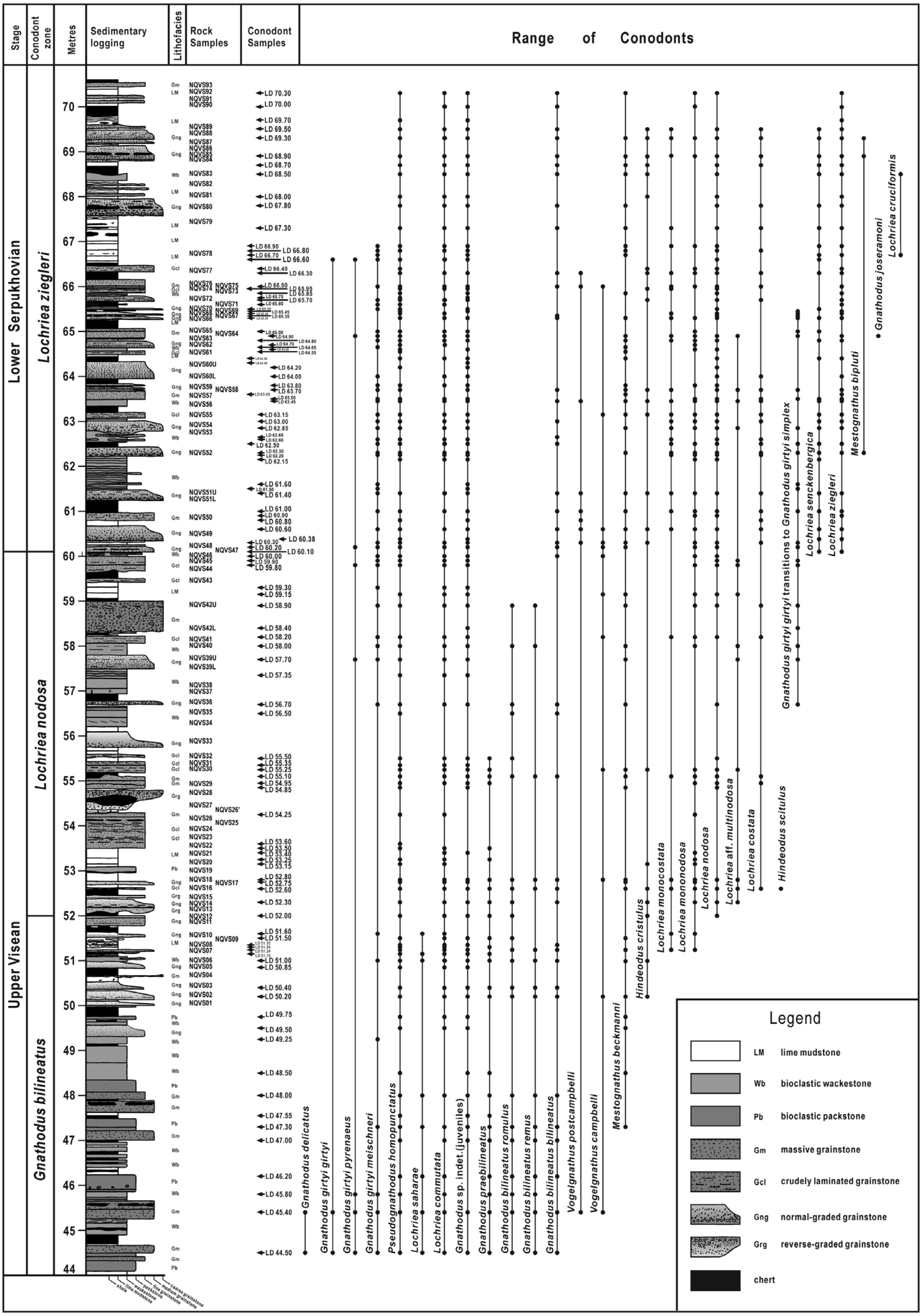

Figure 3. Range chart of conodonts from the V/S boundary interval in the Naqing section.

Lochriea senckenbergica Nemirovskaya, Perret-Mirouse & Meischner, 1994 and *L. ziegleri* were dissolved out from this bed, indicating the base of Serpukhovian. The bed was most likely deposited from turbidity currents that transported shallow-water foraminifers downslope. The conodont fossils were washed into the turbidity currents and deposited together with foraminifers. Such grainstone beds may provide a good correlation between shallow-water foraminifers biostratigraphy and deep-water conodont biostratigraphy (Wang *et al.* 2011), although detailed foraminifer biostratigraphy is also needed.

The carbonates of the studied succession straddling the Visean–Serpkhovian boundary lack typical shallow-water features such as exposure structures or wave-generated deposits and structures. The succession was overall deposited in a relatively deep-water setting, well below fair-weather wave base or even storm wave base. Scarce bioturbation in the lime mudstone beds deposited from the settling of suspended sediment, is indicative of rare fauna activities, most likely below euphotic zone (Burchette & Wright, 1992). The frequently intercalated normal-graded bioclastic wacke- to grainstone is representative of a turbidite sequence (i.e. Bouma sequence) that deposited from turbidity currents on a slope environment (e.g. Nemyrovska *et al.* 2011). Parallel lamination was formed by separation of carbonate grains in the upper-flow transport regime of the turbidity current, whereas cross-lamination resulted from migration of diluted current ripples. Bioclastic wacke- and packstone was most likely formed by distal, dilute turbidity currents. The abundant occurrence of shallow-water foraminifer fossils in the grainstone beds indicates that the turbidity currents were derived from a nearby carbonate platform. Turbidity currents were most likely generated by storms that frequently swept across the shallow platform, or were related to sea-level fluctuations (Wright, 1986).

Distinctive shallow-water carbonate cycles during the Carboniferous ice age are indiscernible in the deep-water slope settings of the studied succession. The worldwide regression event during the Visean–Serpkhovian boundary, reported from the shallow-water carbonate platform (e.g. Veevers & Powell, 1987; Wang *et al.* 2001), is also difficult to recognize in the Naqing section; there is no evidence indicating an upwards shallowing or deepening trend across the boundary. This is most likely caused by the fact that the eustatic signature, if there was any, was most likely obscured by many other geological factors such as siliciclastic input, carbonate production, water depth, topographic relief and tectonic subsidence and uplift (e.g. Miall, 2005; Chen *et al.* 2012).

4. Conodont fauna

A total of 175 samples, each weighing *c.* 3–5 kg, were processed for conodonts from the V/S boundary interval in the Naqing section; 116 samples were productive (Figs 3–6). An estimated 11 000 mostly well-preserved platform conodont elements, including a large number of juveniles, were extracted. Conodont frequency is relatively high with an average of 30 platform elements per kilogram. Some samples exceed 100 platform specimens per kilogram at certain levels, for example: LD45.40, LD47.30, LD48.00, LD52.60, LD52.80, LD60.30, LD60.60, LD61.00, LD61.40, LD62.30, LD62.50, LD62.85, LD63.45, LD63.70, LD64.90, LD66.00, LD66.30, LD68.90, LD69.30 and LD70.30. Platform elements outnumber the ramiform elements, and 28 species or subspecies in 6 genera were identified. Our research focused on the platform elements; only these are classified in this paper.

A relatively abundant conodont assemblage in the V/S boundary interval includes all known conodont genera characteristic of the deep-water late Visean – early Serpukhovian successions of Eurasia. Present are the *Gnathodus bilineatus* and *Gn. girtyi* groups of species and the genera *Lochriea*, *Pseudognathodus* and *Vogelgnathus*, which are all common elsewhere. *Mestognathus beckmanni* Bischoff, 1957 and *M. bipluti* Higgins, 1961, which were interpreted to be shallower-water species, also occur in small numbers near the V/S boundary. It was hypothesized that these two species were transported in from shallower-water settings periodically.

In general, the conodont fauna at Naqing is dominated by the *Gnathodus bilineatus* group, including *Gn. praebilineatus* Belka, 1985, *Gn. bilineatus remus* Meischner & Nemyrovska, 1999, *Gn. bilineatus romulus* Meischner & Nemyrovska, 1999, *Gnathodus bilineatus bilineatus* (Roundy, 1926) and all transitional forms. A great number of juveniles were obtained, most of which could not be identified at the species level. *Gnathodus bilineatus bilineatus* is the most common species of this group.

The next abundant group of conodonts comprises *Lochriea* species. This group includes simple unornamented *Lochriea* species, *Lochriea commutata* (Branson & Mehl, 1941), *L. saharae* Nemyrovska, Perret-Mirouse & Weyant, 2006 and ornamented *Lochriea* species: *L. mononodosa* (Rhodes, Austin & Druce, 1969), *L. monocostata* (Pazukhin & Nemirovskaya, in Kulagina *et al.* 1992), *L. nodosa*, *L. costata* (Pazukhin & Nemirovskaya, in Kulagina *et al.* 1992), *L. ziegleri* and *L. senckenbergica*. *Lochriea commutata* is much more numerous than the other species of *Lochriea* in the Visean, and range up to the end of the Serpukhovian. The strongly ornamented *Lochriea* species make their debut during early Serpukhovian time.

The third abundant group of conodonts contains *Pseudognathodus* species, the most numerous of which is *Ps. homopunctatus* (Ziegler, 1960) which appears in almost each productive sample. Less common is *Ps. mermaidus* (Austin & Husri, 1974). *Ps. symmutatus* (Rhodes, Austin & Druce, 1969) is rare. *Vogelgnathus* species are less common. This group is dominated by *V. campbelli* (Rexroad, 1957) and *V. postcampbelli* (Austin & Husri, 1974). Rather short-lived

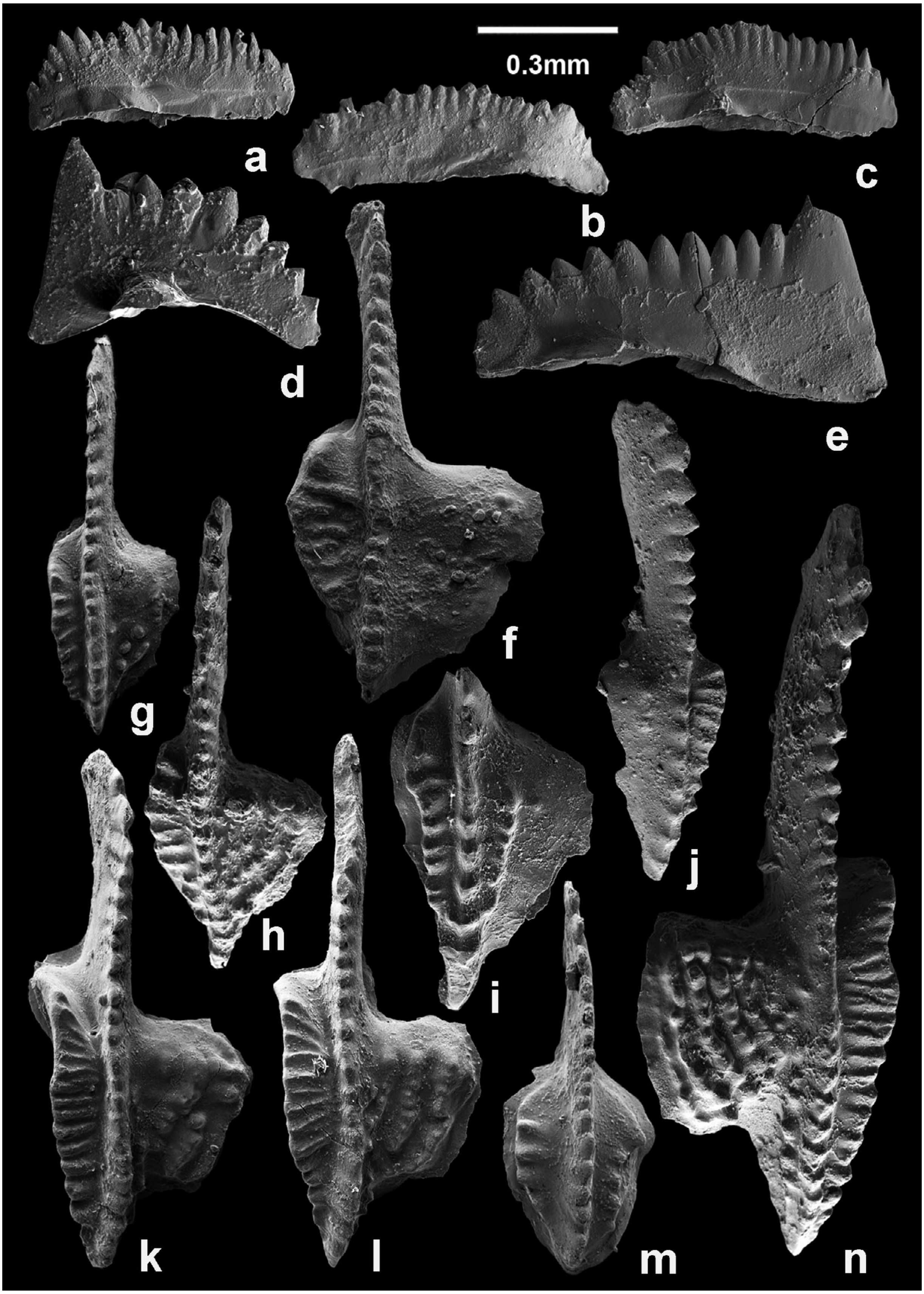

Figure 4. All illustrated specimens (deposited in the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences) are from the Visean–Serpukhovian boundary interval in the Naqing section, Luodian, Guizhou, South China: (a) *Vogelgnathus campbelli* (Rexroad, 1957), lateral view, 60.3 m, Cat. no. 155754; (b) *Vogelgnathus campbelli* (Rexroad, 1957) transitions to *Vogelgnathus postcampbelli* (Austin & Husri, 1974), lateral view, 60.3 m, Cat. no. 155755; (c) *Vogelgnathus postcampbelli* (Austin & Husri, 1974), lateral view, 60.3 m, Cat. no. 155756; (d) *Hindeodus scitulus* (Hinde, 1900), lateral view, 52.6 m, Cat. no. 155757; (e) *Hindeodus cristulus* (Youngquist & Miller, 1949), lateral view, 69.3 m, Cat. no. 155758; (f) *Gnathodus joseramoni* Sanz-Lopez, Blanco-Ferrera

invasions of the *Vogelgnathus*-dominated faunas can be linked to rapid rises in sea level during the periods of maximum flooding of the late Asbian – early Serpukhovian eustatic transgressive-regressive cycles (Ramsbottom, 1973; Ross & Ross, 1988). These invasions of *Vogelgnathus* linked to sea-level rise could represent global events based on the conodont faunas from the Cantabrian Mountains (Boogaard, 1992; Nemyrovska, 2005). Two main invasions of *Vogelgnathus* took place during the time span of the V/S boundary interval in the Naqing section: one during the early *Gn. bilineatus* Zone (sample LD45.4) and another in the earliest Serpukhovian (the earliest *L. ziegleri* Zone, samples LD60.30, LD60.60) shortly above the FAD of *L. ziegleri*. The most abundant *Vogelgnathus* specimens (104 elements) are found in the sample LD60.60.

Least abundant is the *Gnathodus girtyi* group which, besides *Gn. girtyi girtyi* Hass, 1953, includes some transitional forms between *Gn. girtyi girtyi* and *Gn. girtyi simplex* Dunn, 1965, *Gn. girtyi meischneri* (Austin & Husri, 1974) and *Gn. girtyi pyrenaeus* Nemyrovska & Perret-Mirouse in Nemyrovska, 2005 as well as some new forms.

In the Naqing section, the *Gn. bilineatus* lineage starts from its ancestor *Gn. praebilineatus* followed by the first representatives of the *bilineatus* group, *Gn. bilineatus remus* and *Gn. bilineatus romulus*, which gave rise to *Gn. bilineatus bilineatus.* Some forms in the upper part of the section show the features of more advanced *bilineatus*, but they still cannot be assigned to *Gn. bilineatus bollandensis* Higgins & Bouckaert, 1968.

The *Lochriea* lineage, which is regarded as the most important for the Visean–Serpukhovian boundary interval, was proposed as such by a number of conodont workers from other areas (Nemirovskaya, Perret-Mirouse & Meischner, 1994; Skompski *et al.* 1995; Belka & Lehmann, 1998; Nemyrovska, 2005; Somerville, 2008; Nigmadganov *et al.* 2010). The Naqing section is one of the best sections, containing all known species recorded in the interval of the upper Visean – lower Serpukhovian elsewhere. The early Visean species *L. cracoviensis* Belka, 1985 was not found in the Naqing area, as it is the only characteristic of the lower Visean.

It has been suggested that all strongly ornamented *Lochriea* are derived from *L. nodosa* (Nemirovskaya, Perret-Mirouse & Meischner, 1994; Skompski *et al.* 1995). The vertical succession of the strongly ornamented *Lochriea* in Naqing is almost the same as in other areas. However, in Naqing *L. cruciformis* (Clarke, 1960) appears later than in the Rheinisches Schiefergebirge and the Lublin Basin, where *L. cruciformis* appears before *L. ziegleri* and *L. senckenbergica* (Skompski *et al.* 1995). *Lochriea mononodosa* is regarded as an ancestor of *L. nodosa*. That means that its first appearance should be earlier than that of *L. nodosa*, as it is in the Naqing section. However, in the Triollo section (Cantabrian Mountains, Spain; Nemyrovska, 2005) and in the Baily Hill Quarry and Dear Park sections (Ireland; Somerville & Somerville, 1999), *L. mononodosa* was found above the first occurrence of *L. nodosa*. The forms illustrated as *L. mononodosa* from the V/S boundary beds (Skompski *et al.* 1995; Skompski, 1996) show a more advanced sculpture than those that could fit into the lineage *L. commutata* – *L. mononodosa* – *L. nodosa*. These specimens have only one large node or ridge on one side of the platform, but this node is too big for these forms to be regarded as ancestors of *L. nodosa* (Nemyrovska, 2005). The same is found in the Naqing section. On the other hand, *L. mononodosa* is rather rare everywhere so it remains difficult to define its exact first appearance. Additional studies are required to distinguish *L. mononodosa* and *L. monocostata* from the transitional forms between *L. commutata* and *L. mononodosa* and *L. monocostata*. These studies are in progress.

The same problem occurs with *L. cruciformis*. *Lochriea ziegleri* and *L. senckenbergica* are always found in much greater numbers than *L. cruciformis*, which could be why *L. cruciformis* is not found in the same succession of the *Lochriea* species in different areas. The Visean–Serpukhovian boundary is better defined by *L. ziegleri* because it occurs everywhere and in much larger numbers (Nemyrovska, 2005). In the Naqing section, the entry of *L. cruciformis* is 6.6 m above the FAD of *L. ziegleri*; the same situation was noted in the Triollo section, Spain (Nemyrovska, 2005) and in the Yordale beds, England (Varker in Skompski *et al.* 1995). In the Rheinisches Schiefergebirge, Germany and the Lublin Basin, Poland, *L. cruciformis* is found below *L. ziegleri* (Meischner & Skompski in Skompski *et al.* 1995). In the Dnieper–Donets Depression, Ukraine (Nemirovskaya in Skompski *et al.* 1995) and in the Carranques section, Cantabrian Mountains, Spain (Sanz-Lopez *et al.* 2007), *L. cruciformis* is recorded at the same level as *L. ziegleri.*

5. Conodont biostratigraphy

Three conodont zones are distinguished in the V/S boundary interval of the Naqing section: the *Gnathodus bilineatus* and *Lochriea nodosa* zones in the

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& García-López, 2004, oral view, 64.9 m, Cat. no. 155759; (g) *Gnathodus delicatus* Branson & Mehl, 1938, oral view, 51.15 m, Cat. no. 155760; (h) *Gnathodus praebilineatus* Belka, 1985, oral view, 45.4 m, Cat. no. 155761; (i) *Gnathodus girtyi girtyi* Hass, 1953, oral view, 45.4 m, Cat. no. 155762; (j) *Gnathodus girtyi girtyi* Hass, 1953 to *Gnathodus girtyi simplex* Dunn, 1965, oral view, 61.5 m, Cat. no. 155763; (k) *Gnathodus bilineatus romulus* Meischner & Nemyrovska, 1999, oral view, 48.0 m, Cat. no. 155764; (l) *Gnathodus bilineatus remus* Meischner & Nemyrovska, 1999, oral view, 48.0 m, Cat. no. 155765; (m) *Pseudognathodus homopunctatus* (Ziegler, 1960), oral view, 48.0 m, Cat. no. 155766; and (n) *Gnathodus bilineatus bilineatus* (Roundy, 1926), oral view, 45.4 m, Cat. no. 155767.

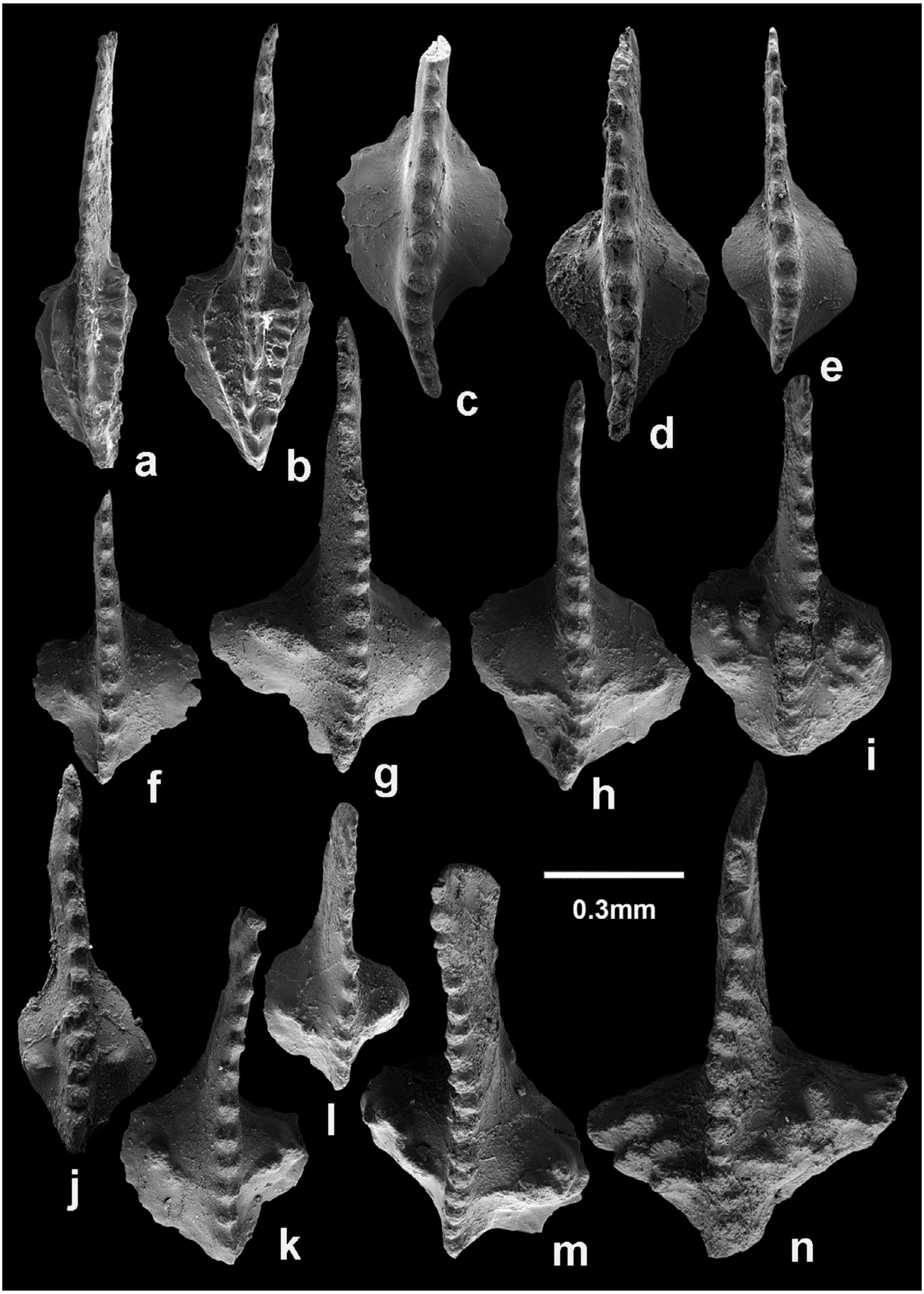

Figure 5. All illustrated specimens (deposited in the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences) are from the Visean–Serpukhovian boundary interval in the Naqing section, Luodian, Guizhou, South China: (a) *Gnathodus girtyi meischneri* (Austin & Husri, 1974), oral view, 45.4 m, Cat. no. 155768; (b) *Gnathodus girtyi pyrenaeus* Nemyrovska & Perret-Mirouse, in Nemyrovska, 2005, oral view, 45.4 m, Cat. no. 155769; (c) *Lochriea saharae* Nemyrovska, Perret-Mirouse & Weyant, 2006, oral view, 47.3 m, Cat. no. 155770; (d) *Lochriea saharae* Nemyrovska, Perret-Mirouse & Weyant, 2006 transitions to *Lochriea commutata* (Branson & Mehl, 1941), oral view, 45.4 m, Cat. no. 155771; (e) *Lochriea commutata* (Branson & Mehl, 1941), oral view, 51.5 m, Cat.

Upper Visean and the *Lochriea ziegleri* Zone in the lower Serpukhovian.

5.a. *Gnathodus bilineatus* Zone

The lower part of the studied interval belongs to the *Gnathodus bilineatus bilineatus* Zone. The characteristic taxa of this zone include *Gn. bilineatus bilineatus* (Fig. 4n), *Gn. bilineatus remus* (Fig. 4l) and *Gn. bilineatus romulus* (Fig. 4k), which represent the earliest subspecies of *Gn. bilineatus* s.l. as well as *Gn. praebilineatus* (Fig. 4h), *Pseudognathodus homopunctatus* (Fig. 4m), *L. saharae* (Fig. 5c, d), *L. commutata* (Fig. 5e), *Gn. girtyi girtyi* (Fig. 4i), *Gn. girtyi meischneri* (Fig. 5a), *Gn. girtyi pyrenaeus* (Fig. 5b), *Vo. campbelli* and *Vo. postcampbelli*. In the uppermost bed of the zone, *L. mononodosa* and *L. monocostata* appear. A large number of juveniles of *Gnathodus* species were recorded in almost every sample. The upper zonal boundary coincides with the entry of *L. nodosa*. This zone covers the interval below 52 m of the section.

5.b. *Lochriea nodosa* Zone

The lower boundary of this zone is defined by the first appearance of *L. nodosa*; its upper boundary coincides with the entry of *L. ziegleri*. This zone includes the interval between 52 m and 60.1 m in the Naqing section. The entry of *L. nodosa* can be traced all over Eurasia and is an important stage in the evolution of *Lochriea* species. The most characteristic species of this zone are *Lochriea nodosa* (Figs 5j, 6a, e), *L. mononodosa* (Fig. 5f), *L. monocostata*, *L. costata*, *L.* aff. *multinodosa* (Wirth, 1967), *L. commutata*, *Gnathodus bilineatus bilineatus* and *Pseudognathodus homopunctatus*. *Gnathodus girtyi girtyi*, *Gn. girtyi meischneri*, *Gn. girtyi pyrenaeus*, *Mestognathus beckmanni* and *Vogelgnathus campbelli* are less common, but still present. The first appearance of *L. costata* is in the lower beds of this zone. With the exception of *L. nodosa* and *L. costata*, all other species extend from the zone below (*Gnathodus bilineatus* Zone).

5.c. *Lochriea ziegleri* Zone

The lower boundary of this zone is defined by the first appearance of *L. ziegleri*, which is now regarded as the best marker for the V/S boundary. This zone spans the interval from 60.1 m upwards in the Naqing section. The following species are characteristic of this zone: *Lochriea ziegleri* (Fig. 5l–n), *L. senckenbergica* (Fig. 6f, g), *L. nodosa* (Figs 5k, 6b), *L. costata* (Fig. 5h), *L. monocostata* (Fig. 5g), *L. mononodosa*, *L. commutata*, *Gnathodus bilineatus bilineatus*, *Mestognathus beckmanni* (Fig. 6i), *Mestognathus bipluti* (Fig. 6j), *Vogelgnathus campbelli* (Fig. 4a, b), *V. postcampbelli* (Fig. 4c) and *Pseudognathodus homopunctatus*. As well as the zonal species, *L. senckenbergica* and *Mestognathus bipluti* made their debut in this zone.

6. Correlation

The majority of conodont species from the Naqing section occur in other areas of Eurasia and North America. In Eurasia, correlations among a number of sections represented by relatively deep-water facies with Naqing are rather straightforward (S. I. Park, unpub. Ph.D. thesis, Philips University of Marburg, 1983; Nemirovskaya, Perret-Mirouse & Meischner, 1994; Skompski *et al.* 1995; Nemyrovska, 2005; Belka & Lehmann, 1998; Sanz-Lopez *et al.* 2007; Somerville, 2008; Nigmadganov *et al.* 2010; Pazukhin *et al.* 2010). Even in shallower-water sections there are a large number of species in common (Groessens, 1975; Higgins, 1975; Nemirovskaya, 1985; Varker & Sevastopulo, 1985; Skompski *et al.* 1995; Kabanov *et al.* 2013). However, Late Mississippian conodont faunas of North America differ greatly; they are mostly represented by shallow-water taxa and ornamented *Lochriea* species are almost absent (Lane & Straka, 1974). Recently a couple of specimens assigned to early *L. ziegleri* were found in North America from the Barnett Formation, central Texas.

Preliminary correlations of conodont zones in the V/S boundary interval of the Naqing section with those in other areas are listed in Table 1. Abundant and taxonomically diverse conodont faunas in the Naqing section enable the correlation of the Tatangian (upper Visean) and lower Duwuan (lower Serpukhovian) (Zhang, 2000) to the coeval deposits of other areas. Two levels are most reliable for correlation by conodonts within the studied interval: the entry of *Gn. bilineatus* s.l. at the base of the Tatangian and the first occurrence of strongly ornamented *Lochriea*, particularly *L. ziegleri*, at the base of the Duwuan in South China (Y. P. Qi, unpubl. Ph.D. thesis, Graduate University of Chinese Academy of Sciences, 2008). The first level is outwith the scope of the present paper but the second level is discussed below.

The *Gnathodus bilineatus* Zone can be correlated to the middle part of the Genicera (or Alba) Formation (*G. bilineatus* Zone) in the Cantabrian Mountains (Sanz-Lopez, Blanko-Ferrera & García-López, 2004;

no. 155772; (f) *Lochriea mononodosa* (Rhodes, Austin & Druce, 1969), oral view, 59.15 m, Cat. no. 155773; (g) *Lochriea monocostata* (Pazukhin & Nemirovskaya, 1992 in Kulagina *et al.* 1992), oral view, 65.3 m, Cat. no. 155774; (h) *Lochriea costata* (Pazukhin & Nemirovskaya, 1992 in Kulagina *et al.* 1992), oral view, 60.3 m, Cat. no. 155775; (i) *Lochriea* aff. *multinodosa* (Wirth, 1967), oral view, 63.7 m, Cat. no. 155776; (j) *Lochriea nodosa* (Bischoff, 1957), oral view, 54.85 m, Cat. no. 155777; (k) *Lochriea nodosa* (Bischoff, 1957) transitions to *Lochriea ziegleri* Nemirovskaya, Perret-Mirouse & Meischner, 1994, oral view, 62.6 m, Cat. no. 155778; and (l–n) *Lochriea ziegleri* Nemirovskaya, Perret-Mirouse & Meischner, 1994, Cat. nos 155779–155781, oral views: (l) 60.9 m; (m) 62.5 m; and (n) 68.9 m.

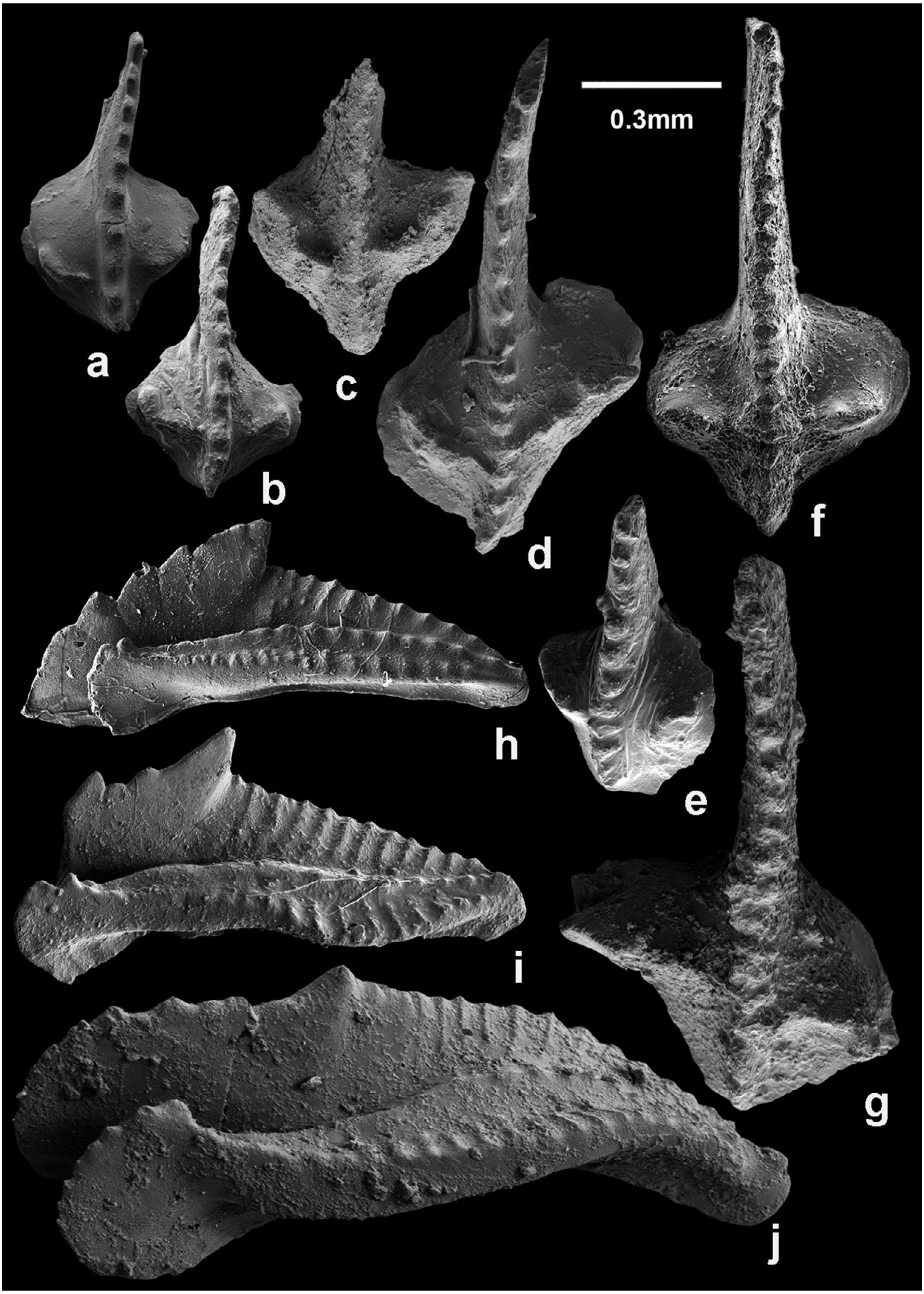

Figure 6. All illustrated specimens (deposited in the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences) are from the Visean–Serpukhovian boundary interval in the Naqing section, Luodian, Guizhou, South China: (a) *Lochriea nodosa* (Bischoff, 1957) transitions to *Lochriea ziegleri* Nemirovskaya, Perret-Mirouse & Meischner, 1994, oral views, 52.6 m, Cat. no. 155782; (b) *Lochriea ziegleri* Nemirovskaya, Perret-Mirouse & Meischner, 1994 transitions to *Lochriea cruciformis* (Clarke, 1960), oral views, 70.3 m, Cat. no. 155783; (c, d) Lochriea cruciformis (Clarke, 1960), oral views: (c) 66.7 m, Cat. no. 155784 and (d) 68.5 m, Cat. no. 155785; (e) *Lochriea nodosa* (Bischoff, 1957) transitions to *Lochriea senckenbergica* Nemirovskaya, Perret-Mirouse

Nemyrovska, 2005), to the uppermost part of the lower Visean – lower part of the upper Visean of the Rheinisches Schiefergebirge (Meischner & Nemyrovska, 1999), to the late Asbian and early Brigantian of western Europe (England, Ireland and Belgium; Higgins, 1975, 1985; Somerville, 2008), to the Alexinian and Mikhailovian horizons (characterized by the *G. bilineatus bilineatus* Zone) of the Russian Platform (Barskov *et al.* 1984; Makhlina *et al.* 1993) and to the *Gn. bilineatus bilineatus* and *L. mononodosa* Zone of South Urals (Pazukhin *et al.* 2010). The *Gn. bilineatus bilineatus* Zone can be compared to the Alexinian and lower Mikhailovian horizons of the Moscow Basin (Alekseev *et al.* 2004) and it can be correlated to the lower Talassian of the Paltau section, Uzbekistan (Nigmadganov *et al.* 2010), to the Donetzian and Mezhevskian of the Donets Basin (O. M. Lipnyagov, unpub. Candidate Dissertation in Geology and Mineralogy, Kiev, 1979) and to the lower Chesterian (characterized by the *G. bilineatus* Zone) of North America (Lane & Straka, 1974; Lane, Sandberg & Ziegler, 1980; Krumhardt, Harris & Watts, 1996; Lane & Brenckle, 2001).

The *Lochriea nodosa* Zone, the latest Visean zone, is widely recognized in Eurasia both in shallow and deep-water biofacies (Skompski *et al.* 1995; Nemyrovska, 2005; Pazukhin *et al.* 2010). This zone at Naqing can be correlated with the same zone in the upper beds of the Alba (equivalent to the Genicera) Formation of the Cantabrian Mountains (Adrichem-Boogaert, 1967; Menéndez-Alvaréz, 1978; Higgins & Wagner-Gentis, 1982; S. I. Park, unpub. Ph.D. thesis, Philips University of Marburg, 1983; Belka & Lehmann, 1998; Sanz-Lopez, Blanko-Ferrera & García-López, 2004; Nemyrovska, 2005) and in the uppermost Visean, the upper Mikhailovian and Venevian horizons of the Moscow Basins (Alekseev *et al.* 2004), to the upper part of the Mezhevskian Horizon of the Donets Basin and Dnieper–Donets Depression (O. M. Lipnyagov, unpub. Candidate Dissertation in Geology and Mineralogy, Kiev, 1979; Nemirovskaya, 1983, 1985) and Middle Tienshan (Nigmadganov *et al.* 2010), *L. nodosa* Zone of Germany (Meischner, 1970) and Ireland (Somerville & Somerville, 1999) and can be roughly correlated with the upper part of the *Gnathodus bilineatus* Zone in North America (Lane & Straka, 1974; Lane & Brenckle, 2001). This zone is also recognized in the uppermost Visean of the Pyrénées (Boersma, 1973; Buchroithner, 1979; Perret, 1993; Sanz-López, 2002), in Belgium (Groessens, 1975) and Poland (Skompski, 1996).

The *Lochriea ziegleri* Zone is the earliest Serpukhovian conodont zone, and is easily distinguished in Eurasia as the zonal index is strongly ornamented and easy to identify. Its lower boundary represents the most reliable correlative level in Eurasia and coincides with the V/S boundary. This zone in the Naqing section can be directly correlated with the same zone in the Cantabrian Mountains of Northern Spain (Nemyrovska, 2005), the *L. cruciformis* Zone of Northern Spain (Sanz-Lopez *et al.* 2007), the *L. ziegleri* Zone in Moscow Basin and the South Urals of Russia (Alekseev *et al.* 2004; Pazukhin *et al.* 2010), the Donets Basin of Ukraine (Skompski *et al.* 1995; Nemyrovska, 1999), Germany, England, the French Pyrénées and Poland, (Nemirovskaya, Perret-Mirouse & Meischner, 1994; Skompski *et al.* 1995) and Uzbekistan (Nigmadganov *et al.* 2010). It can also be roughly correlated with the uppermost part of the *G. bilineatus* Zone and the lower part of the *Cavusgnathus naviculus* (Hinde, 1900) Zone in North America (Lane & Straka, 1974; Lane & Brenckle, 2001). Moreover, because specimens of *L. ziegleri* were identified from the Barnett Formation, central Texas, the correlation between Eurasia and North America might be easier than before. However, other strongly ornamented *Lochriea* such as *L. senckenbergica* and *L. cruciformis* have not yet been found in North America.

The appearance of conodont species *Lochriea ziegleri* within the lineage *Lochriea nodosa* – *L. ziegleri* is being discussed as the most promising marker for the Visean–Serpukhovian boundary by the majority of conodontologists. Some conodont workers prefer to use another ornamented species of *Lochriea* – *L. cruciformis* (see the correlation described in Table 1).

7. Conclusion

Both *L. ziegleri* and *L. cruciformis* fall close to the Visean–Serpukhovian boundary (Skompski *et al.* 1995; Nikolaeva *et al.* 2002, 2009; Nemyrovska, 2005; Qi & Wang, 2005) in contrast to *L. ziegleri*, which is much more widespread around Eurasia. The abundance of conodonts discovered in the Naqing section has confirmed the potential of *L. ziegleri* as the best marker for the definition of the Visean–Serpukhovian boundary.

In the Naqing section the first *Lochriea ziegleri* and *L. senckenbergica* occur in the same sample, but the lineage of *Lochriea nodosa* – *L. ziegleri* with many transitions between seems to be quite reliable (taxonomic studies are in progress). The *L. costata* – *L. cruciformis* lineage cannot yet be demonstrated by data from the Naqing section (even with very close sampling), as insufficient specimens were obtained. The first appearance of *Lochriea* aff. *multinodosa*, another strongly ornamented species, is close to the base of the *Lochriea nodosa* Zone in the Naqing section.

& Meischner, 1994, oral view, 52.6 m, Cat. no. 155786; (f, g) *Lochriea senckenbergica* Nemirovskaya, Perret-Mirouse & Meischner, 1994, oral views: (f) 64.8 m, Cat. No. 155787 and (g) 62.3 m, Cat. no. 155788; (h) *Mestognathus beckmanni* Bischoff, 1957, lateral view, 51.24 m, Cat. no. 155789; (i) *Mestognathus beckmanni* Bischoff, 1957, transitions to *Mestognathus bipluti* Higgins, 1961, lateral view, 61.0 m, Cat. no. 155790; and (j) *Mestognathus bipluti* Higgins, 1961, lateral view, 68.9 m, Cat. no. 155791.

Table 1. Preliminary correlations of conodont zones in the V/S boundary interval of the Naqing section with those in other areas.

South China (this paper)	Cantabrian Mountains NW Spain (Palencia, Triollo section) (Nemyrovska, 2005)	Cantabrian Mountains NW Spain Leon, Esla area (Belka & Lehmann, 1998)	Cantabrian Mountains NW Spain (Asturias, Carranques section) (Sanz-Lopez *et al.*, 2007)	Rheinischews Schiefergebirge, Schaelk quarry, Germany (Meischner, in Skompski *et al.*, 1995)	Middle Tien-shan Uzbekistan (Nigmadganov *et al.*, 2010)	Urals Russia (Pazukhin *et al.*, 2010)	Moscow Basin Russia (Alekseev *et al.*, 2004; Kabanov *et al.*, 2013)	Ljublin Basin Poland (Skompski, 1996)	Dnieper-Donts Depression, Donets Basin (O. M. Lipnyagov, unpub. Candidate Dissertation in Geology and Mineralogy, Kiev, 1979; Nemirovskaya, 1983)	
L. ziegleri	*L. ziegleri*	*L. cruciformis*	*L. ziegleri*	*L. ziegleri*	*L. cruciformis*	*L. ziegleri*	*L. ziegleri*	*L. cruciformis*	*L. ziegleri*	
L. nodosa	*L. nodosa*		*L. nodosa*		*L. nodosa*	*L. nodosa*	*L. nodosa*	*L. nodosa*	*L. nodosa*	*L. commutata-Gn. bil. bil.*
						L. mononodosa				
Gn. bil. bil.	*Gn. bil. bil.*		*Gn. bil. bil.*		*Gn. bil. bil.*	*Gn. bil. bil.*	*Gn. bil. bil.*			

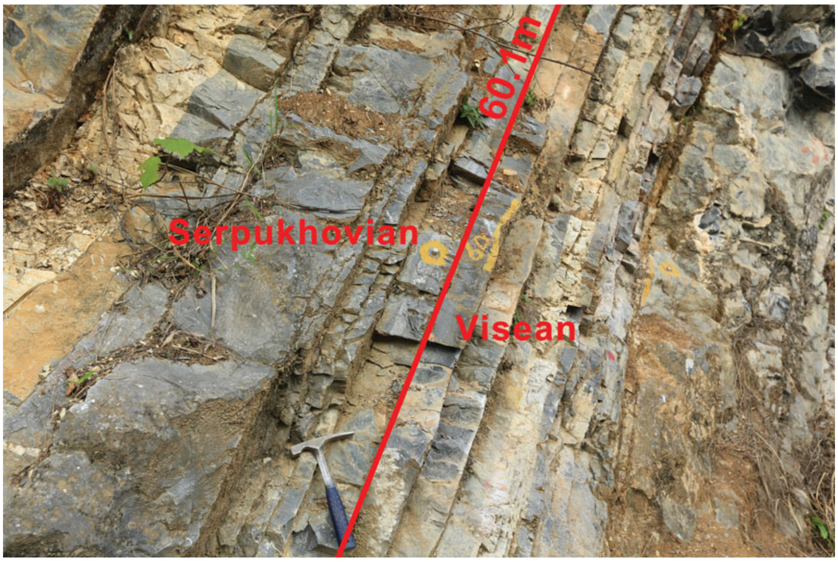

Figure 7. (Colour online) Visean and Serpukhovian boundary level in the Naqing section.

The lineage of *Lochriea nodosa* – *L. ziegleri* or *L. senckenbergica* therefore has the greatest potential to be used for defining the Visean–Serpukhovian boundary. In addition, The entry of strongly ornamented *L. ziegleri* is widespread in Eurasia as well as in North America. Furthermore, this species could be easily recognized and more numerous than any other strongly ornamented *Lochriea* species. The FAD of *Lochriea ziegleri* is therefore the best marker for the base of the Serpukhovian or Duwuan of China.

The previously reported FAD of *L. ziegleri* in the Naqing section has been found lower at 60.6 m (Y. P. Qi, unpub. Ph.D. thesis, Graduate University of Chinese Academy of Sciences, 2008; Qi *et al.* 2009), down to 60.38 m (Qi *et al.* 2010*b*) and now down to 60.1 m (Qi *et al.* 2010*a*) (Fig. 7) above the base of the section, according to continuous centimetre-scale sampling in May 2008 and October and November 2009.

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