Graptolites from Silurian (Llandovery Series) Sedimentary Deposits Attributed to a Forearc Setting, Co to Formation, Co to Archipelago, Northeast Vietnam

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Graptolites from Silurian (Llandovery Series) sedimentary deposits attributed to a forearc setting, Co To Formation, Co To archipelago, northeast Vietnam

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Abstract. Newly collected graptolites from the Co To Formation, Co To archipelago, NE Vietnam, comprise assemblages indicative of two biostratigraphical levels within the lower Silurian, Llandovery Series, Telychian Stage: the co-occurrence of Spirograptus turriculatus and Torquigraptus proteus suggests an interval most likely within the upper part of the Spirograptus turriculatus Biozone or ‘Monograptus’ crispus Biozone, whilst Oktavites spiralis and Monoclimacis cf. subgeinitzi identify the Oktavites spiralis Biozone. The graptolites provide important biostratigraphical evidence for the age of the upper part of the lower Co To Formation, biostratigraphical ties between the NE Vietnamese succession of the Bac Bo Region and graptolite assemblages of the Long Dai Formation in the Viet-Lao Region of central Vietnam, and include the new species Monograptus hamulus sp. nov. co-occurring with S. turriculatus, which is perhaps an ancestral form to the later Telychian species Monograptus drepanoformis. We also report the first chitinozoans, including Belonechitina, from the Co To Formation.

Key words: biostratigraphy, chitinozoans, graptolites, Llandovery Series, Silurian, Vietnam

Introduction

There is a long tradition of work on the lower Paleozoic geology of Vietnam extending back to the early 20th century (e.g. Mansuy, 1915). Later, graptolites were recognised to be widespread and Nguyen (2002) summarised their distribution in the Ordovician, Silurian and Devonian strata of northern and central Vietnam, identifying (op. cit., fig. 2) some 26 biozonal intervals from the Tremadocian (Lower Ordovician) to the Pragian (Lower Devonian). More recently, Silurian (Telychian) graptolites have been recognised in central Vietnam (Williams et al., 2016) and Ordovician (Tremadocian and Floian) graptolites in NE Vietnam (Rushton et al., 2018).

In this study we describe newly collected graptolites from the Co To Formation of the Co To islands of NE Vietnam (Figure 1) that indicate two biostratigraphical levels within the Telychian Stage of the Llandovery Series (lower Silurian). Study of these graptolites is important for: 1, establishing firm biostratigraphical ages within the Silurian part of the Co To Formation, especially the first record of graptolites of Oktavites spiralis Biozone age; 2, providing a biostratigraphical tie for regional correlation between the lower Paleozoic succession of the Bac Bo Region and graptolite assemblages of the Long Dai Formation in the Viet-Lao Region of central Vietnam; and 3, establishing the geological history of a still poorly known region of northern Vietnam. This paper also presents the first detailed descriptions and illustrations of graptolite assemblages from the Co To Formation, including a new species of Monograptus, and identifies the first chitinozoans from the formation.
Geological setting and previous work

The Co To archipelago lies in Bac Bo Region, the islands being situated off the NE coast of Vietnam, near to the border with China (Figure 1). Collecting in this area by Tran et al. (1972, 1977) identified Silurian graptolites from the Co To Formation. Later, Nguyen (2002) summarised graptolite collections of early Silurian, Rhuddanian (Llandovery) age, through to Gorstian (Ludlow) age in the Co To Formation, identifying several stratigraphically discrete graptolite-bearing intervals, though the graptolites were not figured. Geologically the Bac Bo region is situated north of the Song Ma Suture Zone and was a part of the South China paleocontinent during the early Paleozoic (Cocks and Torsvik, 2013). The Bac Bo Region is subdivided into three ‘zones’, following the terminology summarised in Tong et al. (2013), with the Co To archipelago located within the Quang Ninh Zone which is part of the NE coastal area. The lower Paleozoic stratigraphy of the Quang Ninh Zone comprises the contemporaneous Tan Mai and Co To formations that are both of Ordovician and early Silurian age, and which apparently underlie the Silurian Kien An Formation. The Co To Formation has a total recorded thickness of more than 1000 metres and crops out over 40 islands and islets of the Co To archipelago (Tong et al., 2013). The Co To Formation has a range of lithologies including cross-bedded sandstones, banded claystone, tuffaceous interbeds, and coarse sandstones (Tong et al., 2013). It is thought to have accumulated in an island arc setting (Pham and Nguyen, 1999), with the clastic components suggesting a forearc setting (Nguyen, 2000). By contrast, the Tan Mai Formation may represent a back-arc marine setting situated near an old continental margin (Nguyen, 2000; Tong-Dzuy and Vu Khuc, 2006).

Tong et al. (2013) referred to the lower part of the Co To Formation as representing deep marine sedimentary deposits intercalated with shallow marine deposits, and the upper part of the formation as representing fine-grained, bedded sedimentary deposits of deep marine settings. Graptolites of Silurian age are reported from the silty claystones in the uppermost part of the lower Co To Formation and in the lowermost beds of the upper part of the formation. Tong et al. (2013) considered all of these graptolites to be of early Silurian age. The graptolites and chitinozoans described here are from the upper part of the lower Co To Formation (sensu Tong et al., 2013).
### Table 1. Summary of identified graptolite specimens from Co To and Thanh Lan islands, Co To archipelago, NE Vietnam, their OUMNH repository number, field locality, and biozonal assignment. Locality 4 is represented by four along-strike collections, denoted a–d, and Locality 5 by two collections, denoted a and b.

<table>
<thead>
<tr>
<th>Species name</th>
<th>Figure</th>
<th>Biozone</th>
<th>Locality</th>
<th>OUMNH number</th>
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<td>Monograptus hamulus sp. nov.</td>
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</table>
Materials, methods and repositories

Figured specimens from this paper are curated in the collection of the Oxford University Museum of Natural History, Parks Road, Oxford, United Kingdom (OUMNH CY.31-65, Table 1). They were collected from five localities: two on Co To Island, here termed Locality 1 at Co To town, and Locality 5 at Village 1 on the southern part of the island (Figure 2, inset); and three localities on neighbouring Thanh Lan Island, here termed localities 2 and 3 at Chien Tang, and Locality 4 at B76 Beach on the east coast (Figures 2, 3).

Graptolites from Locality 1 are sourced from laminated mudstones in overturned strata dipping 88° to the south and striking in a NE-SW direction. This locality lies between two houses situated west of a pond with the
coordinates 20°57′42″N, 107°45′33″E (Figure 2A). At localities 2 and 3, graptolite-bearing horizons have been subject to strong tropical weathering on a rock exposure near a road at 20°59′46″N, 107°48′34″E and 20°59′46″N, 107°48′35″E, respectively (Figure 2C). Here strata dip 82° to the south and strike E-W. At Locality 4, the
graptolite layer is a hemipelagic mudstone, located in a sandstone-dominated rock exposure at 21°00′11″N, 107°49′58″E. The strata here dip 16° to the SW with a NW-SE strike (Figure 2D). At locality 5, the graptolite horizon is within mudstone, located on the road intersection with the coordinates 21°58′09″N, 107°46′19″E, and in overturned strata dipping 87° to the south with a NE-SW strike (Figure 2B).

Graptolites are preserved as carbon films or are weathered to iron oxide presumably after pyrite moulds, which in places forms a 3D cast with some periderm remaining. There is no tectonic overprint. The graptolites were examined using light microscopy and were prepared using fine needles. Most of the graptolites have been drawn using a camera lucida attached to a Wild Heerbrugg M8 microscope. Pencil drawings were scanned and digitised. This digitised version of the drawing was used to establish precise measurements for dorsoventral width, two-theca repeat distance (2TRD sensu Howe, 1983), tubarium length (tubarium sensu Maletz, 2014 to replace the older term ‘rhabdosome’), and where preserved, the length of the sicula. Camera lucida drawings, supplemented by photographs together with morphometric data were used to compare with published images of graptolites. Graptolite biozones are established based on the known biostratigraphical ranges of key species, especially biozonal index species.

In addition to the graptolite specimens reported here, a small suite of previously collected graptolites from the ‘Village 1’ locality – essentially our Locality 5 - are curated at the Vietnam National Museum of Nature, Hanoi, Vietnam (CS475GR01, CS475GR06, CS475GR14, CS475GR17, CS475GR25, CS475GR37, CS475GR39, CS475GR52). These graptolites mostly comprise incomplete and indeterminate monograptids.

As part of this study we also subjected a limited suite of rock samples to standard palynological protocols (Vandenbroucke, 2008) at Ghent University (Belgium), to test for the presence of chitinozoan organic-walled microfossils and assess their local potential for biostratigraphy and paleoenvironmental reconstructions (see Vandenbroucke et al., 2010).

Graptolite biostratigraphy

Previous paleontological work on the Co To Formation has identified assemblages of Silurian graptolites referable to the Coronograptus cyphus, Coronograptus gregarius, Stimulograptus halli (or S. sedgwickii?), Spirograptus turriculatus, Strepotagruptus exiguis, and Monograptus vulgaris biozones, and Saetograptus beds, collectively indicating strata of Llandovery, Wenlock and Ludlow age (Nguyen, 2002). However, these graptolites have not been figured and we have been unable to locate them in a museum repository. In this study eleven graptolite taxa have been identified from five localities on Co To and Thanh Lan Islands (Figures 2–4). The graptolites are illustrated in Figures 5–8 and are assigned to two discrete intervals: 1) most likely the upper turriculatus Biozone or ‘Monograptus’ crispus Biozone; and 2) a younger interval indicative of the spiralis Biozone. The report of spiralis Biozone-age graptolites from the Co To archipelago is new.

At Locality 4, Thanh Lan Island, the graptolite assemblages comprise Spirograptus turriculatus (Barrande, 1850), Torquigraptus proteus (Barrande, 1850)? and Monograptus priodon (Brom, 1835). The presence of S. turriculatus together with a Torquigraptus species that is possibly T. proteus (Barrande, 1850), is used to infer the biostratigraphical interval of the upper turriculatus Biozone or succeeding crispus Biozone (Storch, 1994). However, the most abundant species from this interval is Monograptus hamulus sp. nov., recovered from Locality 4 (Figures 2D, 3C, F).

Graptolites assignable to the Oktavites spiralis Biozone are found in the sedimentary succession of both Co To and Thanh Lan islands. On Co To Island the
Figure 5. Graptolites most likely from the upper part of the Spirograptus turriculatus Biozone or succeeding ‘Monograptus’ crispus Biozone, Thanh Lan Island Locality 4. A–E, G–J, Monograptus hamulus sp. nov.; A, enlarged proximal part of B, holotype OUMNH CY.34; C, enlarged proximal part of E, OUMNH CY.36; D, OUMNH CY.35; G, enlarged part of J, OUMNH CY.38; H, enlarged distal part of I, OUMNH CY.37. F, is an indeterminate monograptid (possibly M. hamulus) OUMNH CY.65. K–N, Spirograptus turriculatus (Barrande, 1850); K, OUMNH CY.60; L, OUMNH CY.61; M, OUMNH CY.62; N, OUMNH CY.63. O–Q, Torquigraptus proteus (Barrande, 1850); O, P, OUMNH CY.56; Q, OUMNH CY.59. R–T, Monograptus priodon (Bronn, 1835); R, OUMNH CY.41; S, enlarged proximal end of T, OUMNH CY.42. Scale bar = 1 mm, where ‘1’ applies to: B, D, F, I–K, Q, R, T, and ‘2’ applies to: A, C, G, H, S.
Silurian graptolites from Vietnam

The spiralis Biozone is identified at Locality 1 (Figure 2A), where the graptolites comprise Oktavites? sp. and Oktavites spiralis (Geinitz, 1842). O. spiralis presents its first appearance from the base of the spiralis Biozone in the UK succession, and extends to the lower part of the succeeding lapworthi Biozone (Zalasiewicz et al., 2009). In central Vietnam, assemblages from the Long Dai Formation at Lam Thuy yield abundant O. spiralis, which was assigned to the spiralis Biozone (Williams et al., 2016). At Locality 5, Co To Island, Monograptus parapriodon Bouček, 1931? is recorded. This locality may also be in the spiralis Biozone, as it occurs along strike from Locality 1, though the contained graptolites are not age diagnostic. Graptolites previously collected from Locality 5 are curated at the Vietnam National Museum of Nature, Hanoi (reported as ‘Village 1’). They comprise mostly indeterminate monograptids, but one specimen (CS475GR39) is reported as the long-ranging Retiolites geinitzianus (Barrande, 1850), that is known to occur from the level of the ‘Monograptus’ crispus Biozone.

Figure 6. Graptolites from the Oktavites spiralis Biozone (Telychian, upper Llandovery) Co To Island, Localities 1 and 5. A, Oktavites spiralis (Geinitz, 1842) OUMNH CY.52. B, Oktavites? sp. OUMNH CY.47. C–K, Monograptus parapriodon Bouček, 1931? C and E are part/counterpart of OUMNH CY.43. D is the enlarged proximal part of C while F is the enlarged proximal part of E, both showing interthecal septa. G and I are the part/counterpart of OUMNH CY.44. H is the enlarged distal part of G while J is the enlarged distal part of I, both with interthecal septa. K, OUMNH CY.45, most likely a distal part. Scale bar = 1 mm, where ‘1’ applies to: D, F, H, J, K, and ‘2’ applies to: A–C, E, G, I.
Silurian graptolites from Vietnam

... (Streptograptus sartorius Subzone, questionably from the Monoclimacis galaensis Subzone) to lower Cyrtograptus murchisoni Biozone in the UK (Zalasiewicz et al., 2009).

On Thanh Lan Island, graptolites from localities 2 and 3 identify the spiralis Biozone. At Locality 2 the graptolites comprise Oktavites spiralis, Retiolites sp. and Stomatograptus grandis (Suess, 1851), while from Locality 3 they include Oktavites spiralis, Monograptus priodon, Monoclimacis aff. vomerina (Nicholson) sensu Elles and Wood, 1911 and Monoclimacis cf. subgeinitzi Fu sensu Zalasiewicz et al., 1995. These assemblages suggest the same biostratigraphical level as Locality 1 on Co To Island. The occurrence of Oktavites spiralis likely assigns these localities to the eponymous Biozone. Mcl. subgeinitzi is recorded in Latvia from the middle Monoclimacis crenulata Biozone to the lower part of the spiralis Biozone (Loydell et al., 2003). In Bornholm, Stomatograptus grandis is recorded from the Cyrtograptus lapworthi and Cyrtograptus centrifugus biozones (Bjerreskov, 1975), while in Britain it is recorded from the lower spiralis Biozone (Zalasiewicz et al., 2009).

**Chitinozoan results**

Our preliminary study reports small chitinozoan assemblages from localities 2 (spiralis graptolite Biozone) and 4 (upper turriculatus or crispus Biozone), respectively with 4 and 2 specimens only. All of the specimens are...
poorly preserved, hampering identification beyond the microfossil group, with the exception of a single specimen from locality 2, which is a specimen of the genus Belonechitina (Figure 10). These finds do not allow us to make stratigraphic assessments at this time, but illustrate the presence of these microfossils, which have, when well preserved, a high potential for long-distance biostratigraphic correlations (Vandenbroucke et al., 2019). Additional, careful and selective sampling is required to further test this potential.

Regional stratigraphical considerations

The Silurian succession of Vietnam has been differentiated into zones based on facies and paleoenvironment (Tong et al., 2013). In northern Vietnam, Silurian graptolite-bearing strata occur in the Tan Mai and Co To formations of the Quang Ninh Zone of the Bac Bo Region. In the Viet-Lao Region of central Vietnam graptolites occur in Silurian deposits of the Song Ca Formation in the Dien Bien-Nghe An Zone, and the Long Dai Formation of the Binh Tri Thien Zone (Tong et al., 2013). The biostratigraphical importance of graptolites is widely recognised in Vietnam (Nguyen, 2002; Tong et al., 2013), though much work needs to be undertaken to provide detailed illustrations of these graptolites that can be used to enhance regional biostratigraphical correlation.

Graptolites referable to the interval of the turriculatus-exiguus biozones have been reported both from northern and central Vietnam (Nguyen, 2002, fig. 2), albeit without illustrations of the fossils. The interval suggested as the upper turriculatus Biozone or crispus Biozone in the Co To Formation may be approximately equivalent to an interval within the lower part of the exigus Biozone as reported in Vietnam. In the Quang Ninh Zone, Bac Bo region of northern Vietnam, Streptograptus exigus is identified in the Tan Mai Formation where it co-occurs with Monograptus sp. (Nguyen, 2002, loc. 781), and it is also reported from the Co To Formation (op. cit., loc. 762c). In the Viet-Lao region of central Vietnam the exigus Biozone has been identified in the Muong Xen, Long Dai, and Dong Ha areas of the Bin Tri Thien Zone. At Long Dai, identification of the exigus Biozone is based on the eponymous species (Nguyen, 2002, locs. 9217, 9221), and at Dong Ha S. exigus is reported together with Monograptus (op. cit., locs. 8210, 829). At Muong Xen (op. cit., locs. 9924, 9438), the turriculatus-exiguus biozonal interval is based on the identification of S. turriculatus, S. exigus, ‘Monograptus’ cf. crispus (Lapworth, 1876), and Monograptus sp.

This is the first report of graptolites of spiralis Biozone age from the Bac Bo region of northern Vietnam. Graptolites of the spiralis Biozone have previously been reported from the Le Ky and Long Dai areas, Bin Tri...
Thien Zone of central Vietnam (Nguyen, 2002; Tong et al., 2013; Williams et al., 2016). At Le Ky (Nguyen, 2002, locs 8110, 819) the fauna reported is O. spiralis, Retiolites sp., and Monograptus sp. At Long Dai, Nguyen (2002, loc. 9214) reported O. spiralis, Torquigraptus planus (Barrande, 1850), Mcl. crenulata and Monoclimacis griestonisienis (Nicol, 1850), representing a longer biostratigraphical interval than the spiralis Biozone itself if the graptolites are correctly identified. Williams et al. (2016) reported O. spiralis and Oktavites bodentoerensis Loydell, 2003 together with monograptids, pristiograptids and a retiolitid from a spiralis Biozone horizon in the Long Dai Formation at Lam Thuy village.

**Taxonomic notes on the graptolites**

Here we provide information germane to the identification of the graptolites. Monograptus hamulus sp. nov. is given a formal taxonomic description below. For a list of all specimens by localities, and their OUM repository numbers, see Table 1. The graptolites are illustrated in Figures 5–8.

Monoclimacis aff. vomerina (Nicholson) sensu Elles and Wood (1911) possesses a straight tubarium with thecae of typical monoclimacid form (Figure 7I, J, N–P), with gradually increasing doroventral width, being about 0.5 mm at the level of the first theca and reaching 1 mm by theca 15. The 2TRD is 1.91–2.24 mm (measurements based on OUMNH CY.32). The overall dimensions are smaller than the specimens of Mcl. vomerina recorded in Elles and Wood (1911, pl. XLI, figs. 1a–e) while M. vomerina var. gracilis Elles, 1900 is described as having a gracefully recurved proximal portion which is not evident in the Co To material. Measurements for Monoclimacis aff. vomerina from the Co To Formation are similar to Mcl. vomerina recorded in Loydell et al. (2009, fig. 4m) from the Jabalon River, Spain, but the Vietnamese material has overall greater 2TRD, both proximally and distally (Loydell et al., 2009 records 2TRD of 1.2 mm proximally (theca 2–4) and 1.6 mm distally (theca 13–15)). Mcl. aff. vomerina has similar proximal measurements to Mcl. crenulata (Elles and Wood, 1911) figured in Loydell et al. (2003, fig. 7j) from Latvia, but unlike Mcl. crenulata, it does not showhooked thecae proximally.

Monoclimacis cf. subgeinitzi Fu sensu Zalasiewicz et al. (1995) is mostly straight (Figure 7K–M, 8D), but with slight dorsal curvature at the proximal end. Tubarium doroventral width is 1.12 mm at the level of theca 20 with slight dorsal curvature at the proximal end. Tubarium dorsoventral width expands rapidly from 0.81–0.99 mm at the level of the first theca to about 1.36–1.43 mm by theca 5–6, before maintaining a fairly constant width distally.

Three specimens from the spiralis Biozone (Figure 6C–K) referred to as Monograptus parapriodon Bouček, 1931? (see Table 1) have a doroventral width of 1.0–1.22 mm with a distal 2TRD of 2 mm. The doroventral width is much less than the maximum reached by Monograptus priodon: Loydell (1993), for example in his diagnosis of M. priodon, reports specimens reaching 3 mm in width. Specimens of M. parapriodon? show interthecal septa inclined at an angle.

Specimens of Oktavites show an arched or spiral tubarium with typical oktavitid subtriangular thecal morphology. Tubaria are relatively robust, with planar coiling and generally 2–3 whorls. Maximum doroventral width is 2.19 mm. Some of the well preserved thecae show a characteristic laterally expanded aperture. One specimen of Oktavites spiralis (Geinitz, 1842) shown in Figure 7D shows a higher rate of expansion after the second whorl, while other specimens of O. spiralis (Table 1) show a more constant rate of expansion for each whorl (Figures 6A, 7A–C, 8C). One specimen appears tectonically distorted and is referred to as Oktavites? sp. (Figure 6B).

Two specimens tentatively referred to as Retioliites sp. (see Table 1) possess a straight tubarium with skeletal meshwork and a zig-zag structure on the reverse side of the tubarium formed by mid-dorsal lists of the thecal framework (Bates et al., 2005). Thecae are parallel-sided along their entire length, inclined to the axis about 50°–
60°, and possess thecal lips in some parts (Figures 7G, H, 8A). The distal dorsoventral width of this *Retiolites* reaches a maximum of 7.8 mm. 2TRD is ca. 2.5 mm in the middle part of the tubarium as preserved. The measurements of dorsoventral width are greater than for *Retiolites geinitzianus* (Barrande, 1850), which reaches a maximum dorsoventral width of 6.0 mm distally (see Loydell et al., 1997). A single specimen from ‘Village 1’ in the collections of the Vietnam National Museum of Nature (CS475GR39) has been referred to *Retiolites geinitzianus* (Barrande, 1850).

A single specimen (OUMNH CY.55) referred to *Stomatograptus grandis* (Suess, 1851) has a distinctive median row of large pores in the reticulum (Figures 7E, F, 8B). These median pores are considered to be the most useful features to distinguish stomatograptids from retiolitids (see Lenz and Melchin, 1987). The dorsoventral width of this specimen at the level of the first theca is 2.2 mm and this increases to a maximum of about 5.0 mm distally. Tubarium length is 6.0 cm as preserved. Spacing of pores is 3 pores in 5 mm. The specimen conforms with the morphology and dimensions of *Stomatograptus grandis* given by Bjerreskov (1975, p. 39, pl. 5, fig. 1, specimen MMH 13511). It is larger than the similar Chinese stomatograptid species *Stomatograptus shiqianensis* Mu et al., 1974 and *Stomatograptus sinensis* Wang, 1965.

Four specimens are tentatively referred to as *Torquigraptus proteus* (Barrande, 1850)? (Table 1). These possess a coiled tubarium with a loose helical spiral (Figure 5O–Q), which differs from the more tightly coiled *Oktavites*. None of the specimens have the proximal end preserved. The metathecal hook twists halfway along its length, causing the thecal aperture to face the other side of the tubarium. Tubarium dorsoventral width develops from 0.4 mm to 1.9 mm, while 2TRD is around 1.6–2.0 mm. The helical spiral is most similar to that of *Torquigraptus proteus* reported in Loydell (1993, text-fig 21, 6).

*Spirograptus turriculatus* (Barrande, 1850) (five specimens, Table 1) possesses a trochospiral tubarium and hooked thecae with an almost triangular shape and long spines, directed to the obverse side of the tubarium (Figure 5K–N). The thecae are mostly poorly preserved. Proximally the tubarium dorsoventral width may be as low as 0.3 mm (not counting the spines), but the average width is around 0.4–0.6 mm. Distally an average of 0.7–1.2 mm is more common. The 2TRD is variable, up to a maximum of 1.6 mm distally. The dorsoventral width of the Vietnamese specimens distinguishes them from the narrower *Spirograptus guerichi* Loydell, Storch and Melchin, 1993. Other species, such as *Spirograptus andrewsi* (Sherwin, 1974), have a very low trochospire, while *Spirograptus minimus* Obut and Morozova in Obut et al. (1988) only attains a maximum distal width of 0.7 mm (Loydell, 1993).

**Systematic paleontology**

Suborder Monograptina Lapworth, 1880
Family Monograptidae Lapworth, 1873

Genus *Monograptus* Geinitz, 1852 *sensu stricto*

**Type species.**—Subsequent designation; Bassler, 1915, p. 822; *Lomatoceras priodon* Bronn, 1835, p. 56, pl. 1, fig. 13; from the Silurian of Germany.

*Monograptus hamulus* sp. nov., Saparin, Zalasiewicz, Rushton and Williams

Figures 5A–E, G–J, 8F, 9

**Holotype.**—Designated here, a complete tubarium, Figure 5A, B; OUMNH CY.34; from the Co To Formation; Locality 4, Thanh Lan Island, Co To archipelago, most likely to be the upper *turriculatus* Biozone or *crispus* Biozone (Telychian, Llandovery).

**Material.**—Two well preserved specimens (including the holotype), four moderately preserved specimens that still show the overall tubarium shape, and ca. 12 specimens that are poorly preserved mostly as fragments. From Locality 4, Thanh Lan Island, Co To Islands (see Figures 2, 3, and Table 1).

**Diagnosis.**—Strongly ventrally curved tubarium, dorsoventral width up to 0.6 mm distally. Thecae are conspicuous open hooks, with short “wings” projecting from on or near the thecal aperture. Prothecae show distal expansion throughout the tubarium. Curvature of the tubarium is more than 90° and commences at the level of the 2nd–3rd thecae.

**Description.**—The tubarium is ventrally curved with dorsoventral width ranging from 0.24–0.38 mm in the proximal part to 0.57–0.62 mm in the distal part. 2TRD is 1.08 mm at the level of theca 3, 1.37 mm at theca 7, and 1.66 mm at theca 10. Thecae show conspicuous open hooks, with short “wings” projecting from on or near the thecal aperture. Thecal overlap is visible. The sicula appears to be shorter than 1 mm long but is too poorly preserved from available material to be measured precisely. Prothecae expand distally throughout the tubarium and possess a slight bulge on the expanding part (Figure 5C). Tubarium curvature begins at the 2nd–3rd thecae and overall is more than 90°.

**Remarks.**—One of the distinctive features along with the curved tubarium, is the expanding prothecae compared to other similarly curved graptolites that mostly possess parallel prothecae. The thecae face proximally instead of being enrolled like those of streptograptids, but with short “wings” (or a distal lobe?) projecting from near the aperture. The hooked shape and what appears like centrally placed nozzles on the metathecae are reminiscent of.
Silurian graptolites from Vietnam

‘Monograptus’ crispus Lapworth, 1876 but that species differs significantly with its much shorter, slender tubarium, parallel prothecae and tightly enrolled metathecae (Loydell and Maletz, 2004). *M. hamulus* appears closely related to *Monograptus drepanoformis* Toghill and Strachan, 1970 which shows similar thecal morphology. However, *M. drepanoformis* is more tightly curved and is shorter (Figure 9). The proximal part of the tubarium prior to curvature is also much longer in *M. drepanoformis*, and curvature commences at the level of the 3rd–4th thecae. *M. drepanoformis* is from a younger (Telychian) griestoniensis/lower crenulata Biozone horizon and it is possible that *M. hamulus* is an ancestral form.

Conclusions

This is the first detailed analysis of Telychian (Silurian) graptolites from the Co To Formation of the Co To archipelago, NE Vietnam, including illustration of the biozonal index species *Spirograptus turriculatus* and *Oktavites spiralis*, and permits identification of biostratigraphical intervals that are assignable to: 1) probably the upper *turriculatus* Biozone or *crispus* Biozone; and 2) the *spiralis* Biozone, Llandovery Series, Telychian Stage. *Monograptus hamulus* sp. nov., from the older of the two biostratigraphical intervals reported here, forms a new element of the East Asian Silurian graptolite fauna. Illustration of the graptolites, and their placement within the upper part of the lower Co To Formation (sensu Tong et al., 2013), affords greater stratigraphical reliability in correlating the NE Vietnamese lower Silurian succession of the Bac Bo Region with the graptolite assemblages of the *turriculatus-exiguus* Biozone, and *spiralis* Biozone as identified in the Long Dai Formation of the Viet-Lao Region, central Vietnam. The report of chitinozoans from two of the investigated localities suggest that with further study, these microfossils could potentially be used for regional and wider correlations.

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Author contributions

MAS, MW, JZ, AR and TK undertook the graptolite identifications. TK, HDD, HTT, HBN and MTN initiated the project and collected the graptolites. TRAV undertook the chitinozoan analyses. All authors contributed to and wrote the manuscript.