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Late Ordovician (Katian) graptolites and shelly fauna from the Phu Ngu Formation, north-east Vietnam

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Abstract. Two new graptolite assemblages are identified from discrete intervals within the Phu Ngu Formation, Na Ri District, Bac Kan Province, north-east Vietnam. The graptolites occur in laminated mud/siltstones thought to be distal turbidite deposits. A low-diversity diplograptid *sensu lato* assemblage occurs in mud-rich layers that are interlaminated with silty and sandy horizons containing the dendroid graptolite *Dictyonema* sp. This level also contains orthoconic nautiloids and conulariids. A few metres stratigraphically above, a second more diverse graptolite assemblage comprises a single *Dicellograptus*, tentatively identified as *D. flexuosus*, together with *Climacograptus dorotheus* and *Orthograptus truncatus pauperatus* in mud and silt laminae that also yield brachiopods, orthoconic nautiloids, conulariids, fragmentary trilobites, and ostracods. The ostracods include the first East Asian occurrence of the typically Baltic genus *Kinnekullea*, and we describe the new species *Kinnekullea gaia*. The graptolites suggest a Late Ordovician Katian age, most probably in the *Dicranograptus clingani* Biozone, this being older than previous biostratigraphical constraints on the Phu Ngu Formation.

Key words: biostratigraphy, graptolites, nautiloids, Ordovician, ostracods, Vietnam

Introduction

The Paleozoic faunas of northern Vietnam have been documented since the time of the French Colonial Survey in the early 20th Century (Mansuy, 1915). Recent efforts have been made to revise and refine aspects of Vietnamese lower Paleozoic biostratigraphy, in particular in the Lower Ordovician strata of north-east Vietnam (Rushton *et al*., 2017), and the Silurian strata of central and north-east (same as title) Vietnam (Williams *et al*., 2016; Saparin *et al*., 2020). Here we describe a new Late Ordovician graptolite and shelly fauna from rocks of the Phu Ngu Formation in the Na Ri District of north-east Vietnam (Figures 1, 2). The fossils include brachiopods, conulariids, graptolites, orthoconic nautiloids, trilobites, and ostracods, and represent an assemblage entirely new to this region. Graptolites are geographically and stratigraphically widespread throughout the Ordovician, Silurian, and Lower Devonian rocks of Vietnam and have been used to help establish a biostratigraphic scheme for the country (Nguyen, 2002; Tong and Vu, 2011; Tong *et al*., 2013). However, much of the existing work is based on specimens that have not been figured, making it difficult to assess the resilience of this biostratigraphic framework. Ostracods are not previously documented from the Ordovician of Vietnam, but elsewhere the group has proven very useful for establishing biogeographical patterns for that period (Schallreuter and Siveter, 1985; Vannier *et al*., 1989; Williams *et al*., 2003a).

We provide taxonomic notes for the various fossil groups identified, and a formal description of a new ostracod species. The new fossil data enable a revision of the stratigraphic range of the Phu Ngu Formation in northern Vietnam, which has generally been considered to belong

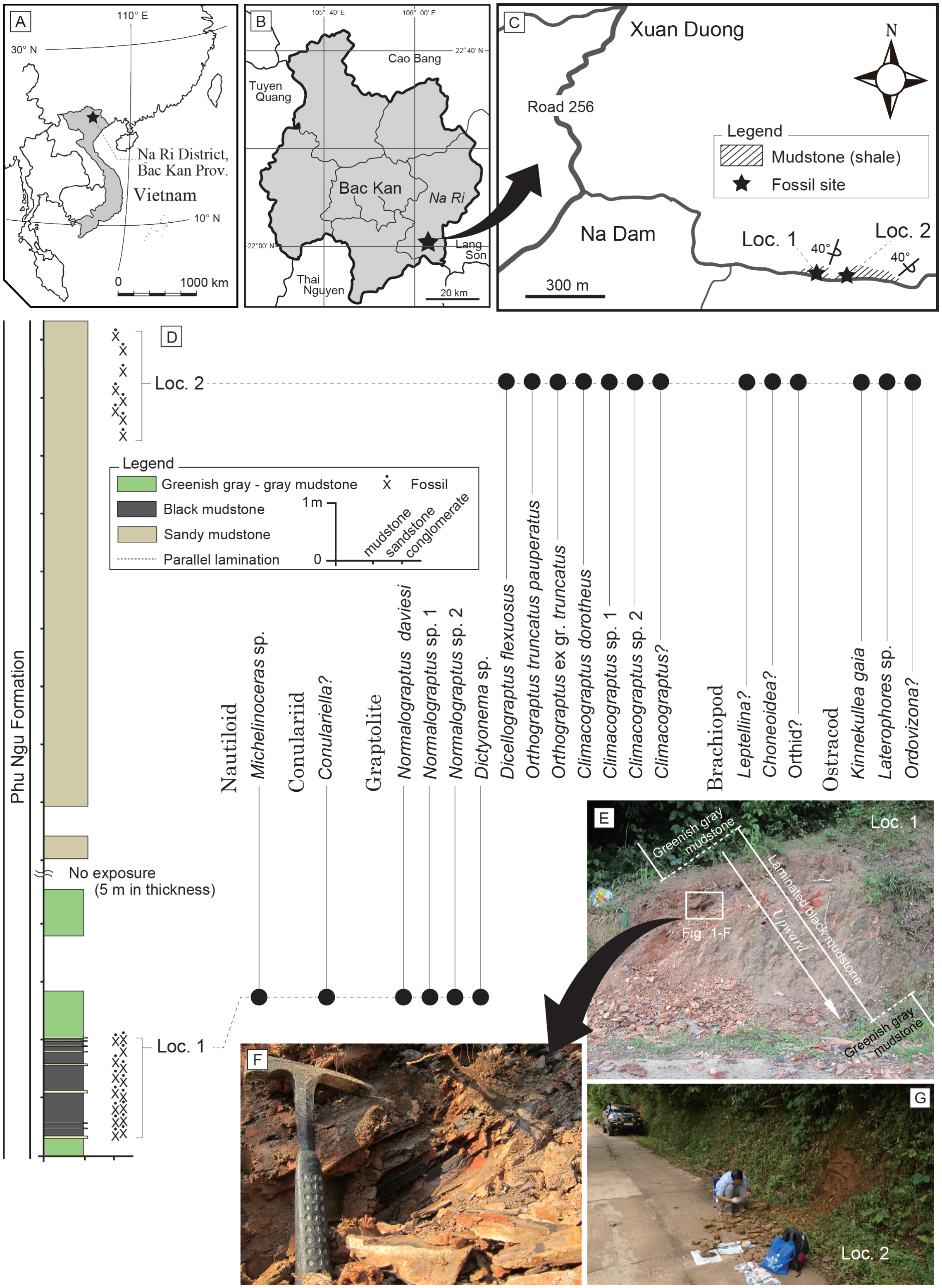

Figure 1. Geographical and geological setting of the Phu Ngu Formation exposures examined in this study. **A–C,** geographic setting of the study area (localities 1 and 2) near Na Dam, Bac Kan Province, northern Vietnam. **D,** stratigraphic log through localities 1 to 2, with notable fossil occurrences at each locality. **E–G,** field photographs from localities 1 and 2 illustrating the exposures.

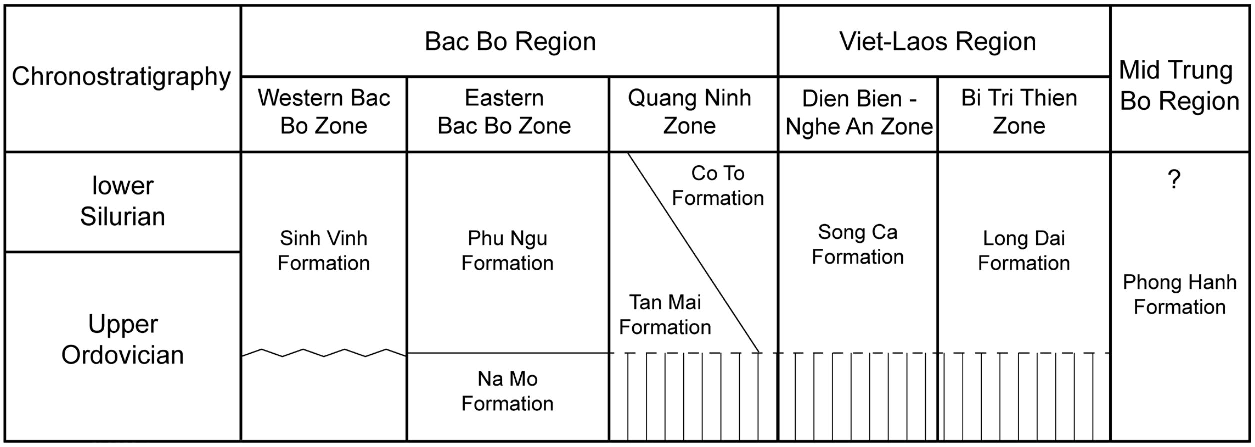

Figure 2. Stratigraphic setting of the Phu Ngu Formation and correlated lithostratigraphical units within the lower Paleozoic succession of Vietnam (adapted after Tong and Vu, 2011, figure 3.2). The informal term ‘lower Silurian’ means strata of pre-Ludlow Series age.

to the Upper Ordovician and lower Silurian (Tong and Vu, 2011; Tong *et al*., 2013), but with an uncertain lower age constraint.

Geological setting and previous work

The northern part of Vietnam was a component of the South China paleocontinent during the early Paleozoic (Tong and Vu, 2011; Torsvik and Cocks, 2013). Within this region the Bac Bo Province can be divided into three geological zones; the northernmost Eastern Bac Bo Zone contains the Na Ri District of the Bac Kan Province. The Eastern Bac Bo Zone is bound to the south and west by the Western Bac Bo Zone (separated by the Song Chay Fault), and to the east by the Quang Ninh Zone (Figures 1, 2; Tong *et al*., 2013). The lower Paleozoic Phu Ngu Formation (Figure 2) crops out regionally in the Eastern Bac Bo Zone and comprises a predominantly siliciclastic succession, approximately 2300 m to 2400 m thick at the type section, with three more argillaceous lower subunits and three sandier upper subunits, which incorporate mafic and felsic volcanic rocks, respectively (Tong and Vu, 2011; Tong *et al*., 2013). The Phu Ngu Formation is thought to have been deposited in a deep marine forearc basin setting on the slope of the Paleotethys Ocean during the Late Ordovician and Silurian (Tong and Vu, 2011; Tong *et al*., 2013).

In the Na Ri District, the Phu Ngu Formation crops out as approximately 250 m of grey and green-grey mudstones, black mudstones and sandy mudstones (Tong *et al*., 2013). However, accurately identifying the stratigraphic positions of localities within the Phu Ngu Formation in the Na Ri District is complicated by dense vegetation which limits exposure, and by the likely presence of faults between exposures. Tong *et al.* (2013) reported several Ordovician and Silurian graptolite taxa from the lower Phu Ngu Formation of the Na Ri District, namely: *Climacograptus* sp., *C.* cf. *scalaris*, *Diplograptus*, *Glyptograptus*, and *Ptilograptus*, but these graptolites were not figured. In addition, Tong and Vu (2011, p. 86) reported but did not figure *Dictyonema* and *Climacograptus* (=*Amplexograptus* according to Riva, 1987) *latus* from the Na Ri District exposures. The genera *Climacograptus*, *Glyptograptus*, and *Monoclimacis* were also reported from the stratotype section of the Phu Ngu Formation (Tong *et al*., 2013). Previously, Nguyen (2002) had reported two distinct assemblages from near Na Dam (sometimes referred to as ‘Nazam’), in the Na Ri District: (1) comprising ‘*Diplograptus bohemicus*’ (likely =*Normalograptus ojsuensis* in South China and hence in Vietnam, following Chen *et al*., 2005), *‘Diplograptus’* (=*Normalograptus*) *ojsuensis*, *Glyptograptus daedatus*, *G. elegantulus*, and *Normalograptus bicaudatus*; and (2) comprising *‘Glyptograptus’* (=*Normalograptus*) *persculptus*, *G. gracilis*, *G. elegantulus*, *N. madernii*, *Dictyonema* cf. *compactum*, and *Thallograptus* sp. None of these graptolites have been figured.

If the identifications are accurate, the strata bearing ‘*Climacograptus*’ (=*Normalograptus*) cf. *scalaris* and *Monoclimacis* are likely to be of early Silurian age (Tong *et al*., 2013). The first assemblage of Nguyen (2002) including *N. ojsuensis* may belong to the *N. extraordinarius-N. ojsuensis* Biozone (see Chen *et al*., 2005), and the second assemblage, including *‘Glyptograptus’* (=*Normalograptus*) *persculptus*, may belong to the *N. persculptus* Biozone. These two assemblages would therefore be early and late Hirnantian (Late Ordovician) in age, respectively (Cooper *et al*., 2012), and these strata of the Phu Ngu Formation would therefore reflect depositional conditions during the icehouse climate of the Hirnantian. Although broadly Late Ordovician to Silurian in age, the precise stratigraphic range of the Phu Ngu Formation remains poorly constrained, as do the ages of individual outcrops of this formation across northern Vietnam (Nguyen, 2002; Tong *et al*., 2013). This hampers a broader understanding of its along-strike lithofacies variation and temporal evolution.

The fossil specimens examined in this study were collected from two roadside localities, separated by approximately 100 m, in the Na Ri District near the village of Na Dam (Figure 1), close to the 'Nazam' Section 25 of Nguyen (2002). At both localities, strata dip at approximately 40° to the east. Locality 1 comprises black mudstones interlaminated with lighter-coloured siltier and fine sand-rich layers, sandwiched between greenish-grey to grey mudstones (Figure 1). This locality yields graptolites, orthoconic nautiloids, and conulariids. Locality 2 (see Figure 1) is stratigraphically above Locality 1 and comprises beige-coloured sandy mudstones that yield graptolites, ostracods, orthoconic nautiloids, conulariids, brachiopods and trilobites. A 5 m stratigraphical interval with no exposure separates the two localities (Figure 1).

Materials, methods, and repositories

Figured specimens from this paper are curated in the collection of the Vietnam National Museum of Nature, Hanoi (Table 1). Graptolites from Locality 1 (Figure 3) are preserved as flattened specimens with a slight tectonic overprint discernible. Graptolite specimens from Locality 2 (Figure 4) are preserved either as flattened remains preserving the periderm, or three-dimensionally by iron hydroxide, likely after pyrite. There is no tectonic overprint on the specimens from Locality 2. The shelly fauna is preserved as moulds, the original shell material having decomposed.

Graptolites and other fossil specimens were examined using reflected light microscopy and, where necessary, were developed using a fine mounted needle. All specimens were photographed using a Canon EOS 5D DSLR camera which was mounted to a Leitz Aristophot apparatus with Leica 12 mm Summar lens for high magnification photography. Graptolite illustrations were drawn in pencil using a camera lucida attached to a Wild Heerbrugg M8 binocular microscope; the pencil drawings were traced in ink and digitised. Photographs and camera lucida drawings were used to make precise measurements of and identify the graptolite specimens. Graptolite biozones are established based on the known biostratigraphical ranges of key species, especially biozonal index species.

Ostracods are preserved as moulds on rock slabs, so silicone casts were made using 'Silcoset 101'. Due to the heavily weathered rock surface and high porosity, the specimens were first consolidated using a solution of 1% 'Paraloid B72' in acetone. To further prevent the silicone from adhering to the specimen 'Ambersil HD' silicone release agent was applied to the consolidated surface prior to applying the Silcoset with a syringe. Positive internal moulds on the surface of slabs could not be directly imaged with SEM due to the high porosity preventing the use of gold coating. Therefore, epoxy replicas of these specimens were made from the silicone casts, using a black epoxy resin placed in a pressure chamber at 2 bar overnight to reduce bubbles. The resulting silicone and epoxy casts were gold-coated and stereo-images taken using a Hitachi S-3600N environmental scanning electron microscope in the University of Leicester, School of Geography, Geology and the Environment.

Graptolite biostratigraphy

Previous work on the Phu Ngu Formation has identified graptolites of the *Normalograptus extraordinarius-N. ojsuensis* and *N. persculptus* biozones (latest Ordovician), as well as the definitively Silurian genus *Monoclimacis* (Nguyen, 2002; Tong and Vu, 2011; Tong *et al*., 2013). The graptolite-bearing section examined here is close to Section 25 of Nguyen (2002) who identified two different graptolite assemblages in the Phu Ngu Formation in Na Ri, both of Hirnantian (latest Ordovician) age. We also recovered two different graptolite faunas from the Phu Ngu Formation exposures in Na Ri, a stratigraphically lower fauna from the black mudstones of Locality 1 (Figures 1, 3), and an upper, more diverse, fauna from the sandy mudstones of Locality 2 (Figures 1, 4).

Normalograptids dominate the low-diversity assemblage of Locality 1 (Figure 3). The majority of these are identified as *Normalograptus* (formerly *Glyptograptus*) *daviesi* (Williams, 1982), though other *Normalograptus* species are present. Graptolites of the dendroid (acanthograptid) *Dictyonema* are also found at Locality 1, though they are exclusive to the silty and sandy laminae and therefore likely belong to an allochthonous fauna only brought deeper into the basin during events of rapid deposition (Figures 5, 6A, C–E). Species-level identification of these *Dictyonema* has not been possible, and their use for biostratigraphy is limited. The presence of *N. daviesi* is indicative of the *Dicranograptus clingani* Biozone (Zalasiewicz *et al*., 1995, 2009), which is divided into lower *Ensigraptus caudatus* and upper *Dicellograptus morrisi* subzones. *Normalograptus daviesi* has been used as a marker of the *morrisi* Subzone in the Southern Uplands of Scotland (Williams, 1982; Zalasiewicz *et al*., 2009), though a similar form may occur in the underlying

Table 1. List of figured specimens. Presence of an asterisk means that the specific fossil figured in the part cannot be identified on the counterpart.

Museum number of fig'd specimen	Locality	Taxon/Type	Figure	Part	C-part
VNMN.0156a	1	*Normalograptus* sp. 1	3E	X	—
VNMN.0156b	1	*Normalograptus*? sp. 2	3D	X	—
VNMN.0156c	1	*Normalograptus daviesi*	3A	X	—
VNMN.0156d	1	*Normalograptus daviesi*	3B	X	—
VNMN.0161a part	1	*Normalograptus daviesi*	3C	X	X
VNMN.0180a part, counterpart	2	*Dicellograptus flexuosus*	4A, B	X	X
VNMN.0186a part	2	*Orthograptus truncatus pauperatus*	4C	X	X*
VNMN.0172b part	2	*Orthograptus* ex gr. *truncatus*	4D	X	X*
VNMN.0181c part	2	*Orthograptus* ex gr. *truncatus*	4E	X	X*
VNMN.0175b part	2	*Orthograptus* ex gr. *truncatus*	4F	X	X
VNMN.0188a	2	*Climacograptus*?	4G	X	—
VNMN.0183a part, counterpart	2	*Climacograptus* sp. 1	4H–J	X	X
VNMN.0188b	2	*Climacograptus dorotheus*	4K	X	—
VNMN.0182b part, counterpart	2	*Climacograptus* sp. 2	4L–N	X	X
VNMN.0185a part	2	*Orthograptus*?	4O	X	X
VNMN.0182c counterpart	2	*Climacograptus*?	4P	X	X
VNMN.0177a	2	*Climacograptus*?	4Q	X	—
VNMN.0179a	2	*Climacograptus*?	4R	X	—
VNMN.0176a	2	graptolite sp. indet.	4S	X	—
VNMN.0152a	1	*Dictyonema* sp.	6A	X	—
VNMN.0155a	1	*Conulariella*? [conulariid]	6B	X	—
VNMN.0151a part	1	*Dictyonema* sp.	6C	X	X
VNMN.0150a part	1	*Dictyonema* sp.	6D, E	X	X
VNMN.0209a part, counterpart	1	*Michelinoceras* sp.	7A	X	—
VNMN.0210c (silicone cast)	1	*Michelinoceras* sp.	7B	X	—
VNMN.0210d (silicone cast)	1	*Michelinoceras* sp.	7C	X	—
VNMN.0211a	1	*Michelinoceras* sp.	7D	X	—
VNMN.0212a part	1	*Michelinoceras* sp.	7E	X	X
VNMN.0181a part	2	orthid	8A	X	X*
VNMN.0184a part	2	strophomenid	8B	X	X
VNMN.0182a part	2	strophomenid	8C	X	X*
VNMN.0181d part, counterpart	2	conulariid	8E, F	X	X
VNMN.0182f (silicone cast of part)	2	*Kinnekullea gaia* sp. nov	9A	X	X
VNMN.0182e (silicone cast of part)	2	*Kinnekullea gaia* sp. nov	9B	X	X
VNMN.0172e (silicone cast of part)	2	*Kinnekullea gaia*?	9C	X	X?
VNMN.0182i (silicone cast of part)	2	*Ordovizona*? sp.	9D	X	X
VNMN.0182l (silicone cast of part)	2	*Latephores* sp.	9E	X	X
VNMN.0167b	2	*Ordovizona*? sp.	9F	X	—

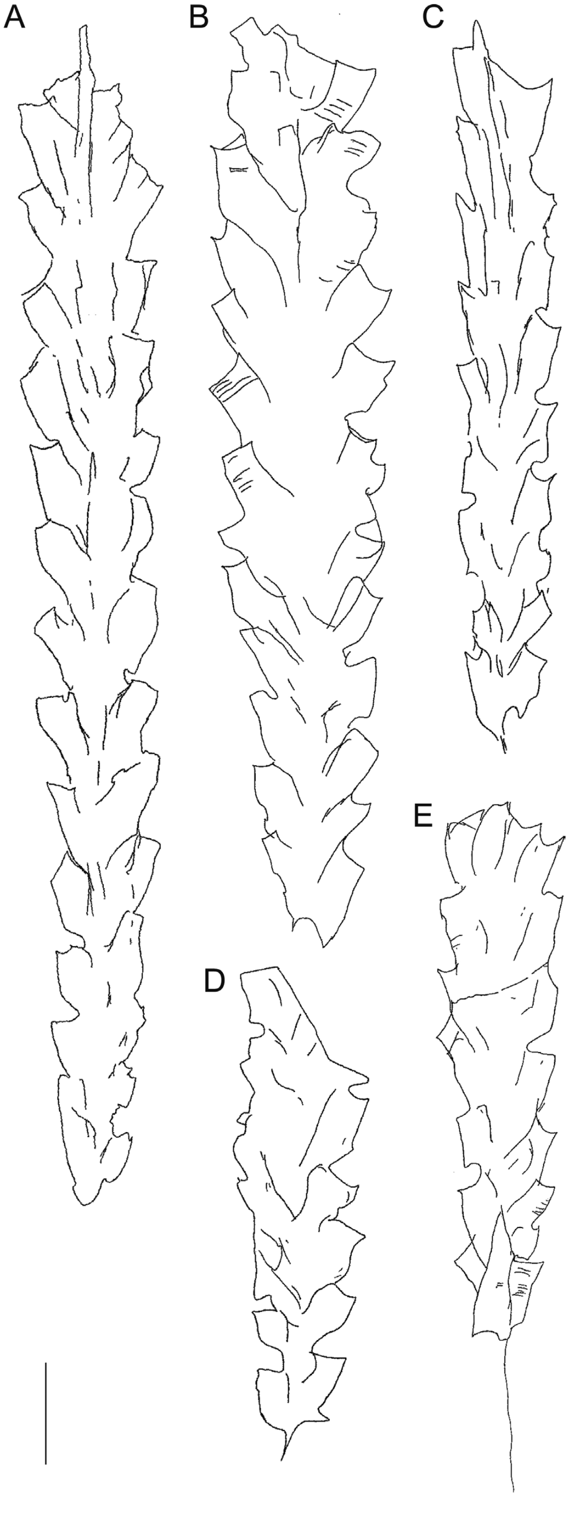

Figure 3. Camera lucida illustrations of graptolites from Locality 1, Phu Ngu Formation. **A–C,** *Normalograptus daviesi* (Williams 1982); specimens VNMN.0156c, VNMN.0156d, and VNMN.0161a, respectively; **D,** *Normalograptus*? sp. 2; VNMN.0156b, possibly comparable to *N. brevis*; **E,** *Normalograptus* sp. 1; VNMN.0156a. Scale bar: 1 mm.

caudatus Subzone at Whitland, Wales (Zalasiewicz *et al.*, 1995).

The graptolite fauna of Locality 2 (Figure 4) has greater taxonomic diversity, though lower specimen abundance, than that of Locality 1. Alongside *Climacograptus* and *Orthograptus* species is a single *Dicellograptus*, tentatively identified as *D. flexuosus* Lapworth, 1876 that may be indicative of the *morrisi* Subzone (Zalasiewicz *et al.*, 1995), though it is found in the underlying *caudatus* Subzone in southern Wales (Williams *et al.*, 2003b). There are other biostratigraphically informative species at Locality 2, including *Climacograptus dorotheus* Riva, 1976 which is diagnostic of the *morrisi* Subzone in the Southern Uplands of Scotland (Zalasiewicz *et al.*, 1995), but is found more widely throughout the *clingani* Biozone in Wales where the subzones are not well established (Williams *et al.*, 2003b). The occurrence of a specimen likely referable to *Orthograptus truncatus pauperatus* Elles and Wood, 1907 provides further support for a *clingani* Biozone age, though as this species also occurs throughout both subzones in Wales and possibly also in Scotland (Williams, 1982; Williams *et al.*, 2003b; Zalasiewicz *et al.*, 2009) it does not help refine the graptolitic age estimate of these two localities. The co-occurrence of a low-diversity normalograptid-dominated assemblage and a higher diversity *Dicellograptus*-climacograptid-orthograptid assemblage may find a comparison in the Upper Ordovician strata of Scotland and Wales (Zalasiewicz *et al.*, 1995; and Williams *et al.*, 2003b, respectively).

Only tentative graptolite biozone assignations can be justified at this stage, but there is sufficient evidence to support revising the graptolite age of the lower part of the Phu Ngu Formation in the Na Ri District from the *Normalograptus extraordinarius–N. ojsuensis* and *N. persculptus* graptolite biozones (early and late Hirnantian, respectively) to the *Dicranograptus clingani* Biozone (early Katian). Although the assemblage of Locality 2 is most strongly associated with the *Dicellograptus morrisi* Subzone, further collecting is required to fully resolve the subzone affinities of these strata.

Regional correlation based on graptolites

Correlation of lower Paleozoic strata across Vietnam is hampered by a lack of well-documented graptolites and other fossils regionally (but see Figure 2). Although the Tan Mai and Co To formations are generally described as Upper Ordovician to Silurian, no diagnostic taxa younger than the Silurian are known (Tong *et al.*, 2013). The same is true of the Song Ca Formation, farther south in the Viet Laos Region of central Vietnam (Tong and Vu, 2011). The Long Dai Formation in the Viet Laos Region preserves

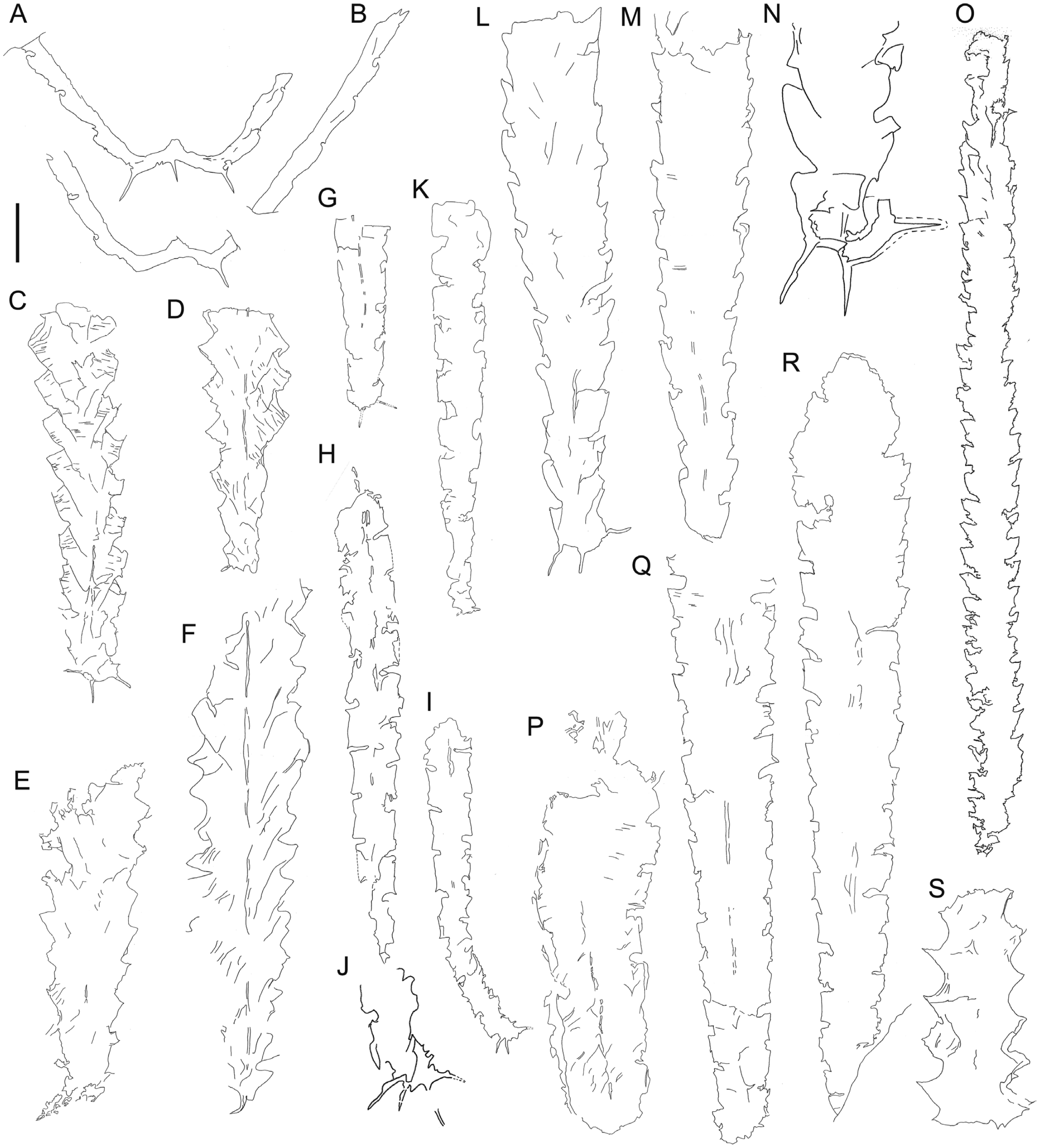

Figure 4. Camera lucida illustrations of graptolites from Locality 2, Phu Ngu Formation. **A, B,** *Dicellograptus flexuosus* Lapworth, 1876; VNMN.0180a part and counterpart, respectively; **C,** *Orthograptus truncatus pauperatus* Elles and Wood, 1907; VNMN.0186a part; **D–F,** *Orthograptus* ex gr. *truncatus*; VNMN.0172b part, VNMN.0181c part, and VNMN.0175b part, respectively; **G, P–R,** *Climacograptus* sp.; VNMN.0188a, VNMN.0182c counterpart, VNMN.0177a, and VNMN.0179a, respectively; **H–J,** *Climacograptus* sp. 1; VNMN.0183a part (I–J) and counterpart (H); **K,** *Climacograptus dorotheus* Riva, 1976; VNMN.0188b; **L–N,** *Orthograptus* sp. 1; L, N VNMN.0182b counterpart, M VNMN.0182b part; **O,** possible *Orthograptus*; VNMN.0185a; **S,** graptolite sp. indet; VNMN.0176a. Scale bars: 0.5 mm (J, N); 1 mm (A–I, K–M, P–S); 2 mm (O).

both Ordovician and Silurian graptolite faunas (Tong *et al.*, 2013). Records of Early Ordovician graptolite-bearing strata referred to the Long Dai Formation need further investigation (Tong and Vu, 2011).

Correlating these lower Paleozoic strata more widely across the South China paleocontinent is challenging.

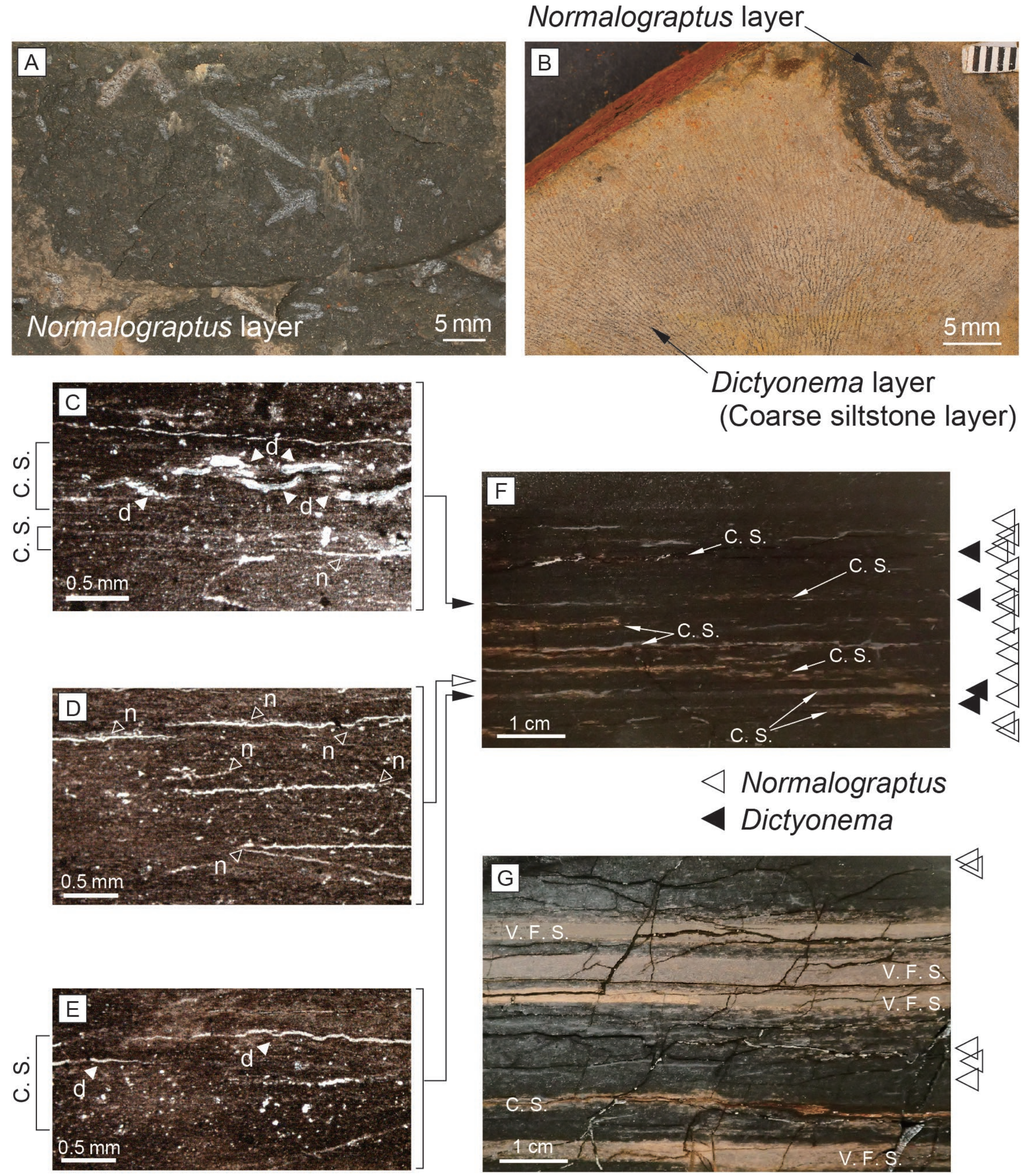

Figure 5. Graptolite taphonomy and sedimentology at Locality 1, Phu Ngu Formation. **A, B,** Modes of graptolite occurrence on the bedding planes; **C–E**, Vertical thin sections of black mudstone (F); **F, G,** Vertical cross-sections of black mudstone intercalating with very fine sandstone (V. F. S.) and coarse siltstone (C. S.) layers. *Normalograptus* (n) occur in the dark-coloured background mudstone. *Dictyonema* (d) occur in the lighter-coloured coarse siltstone laminae that are interpreted as distal turbidite deposits. The thicker, several millimetre- to centimetre-scale, beds of light-coloured very fine sandstone are also interpreted as distal turbidite deposits.

The Sandbian-Katian boundary in the Yangtze region lies within the non-graptolitic, mostly calcareous, Pagoda Formation (Chen *et al*., 2010). The *Nemagraptus gracilis* graptolite Biozone is known from the underlying Miaopo Formation, and the local *Dicellograptus elegans* Biozone (correlated to the *Pleurograptus linearis* Biozone) has been identified in the overlying graptolite-sparse Linxiang (Linhsiang) Formation. Chen *et al*. (2017a) also recorded a slightly higher upper Katian graptolite assemblage of the *Dicellograptus complexus* Biozone, correlated to the

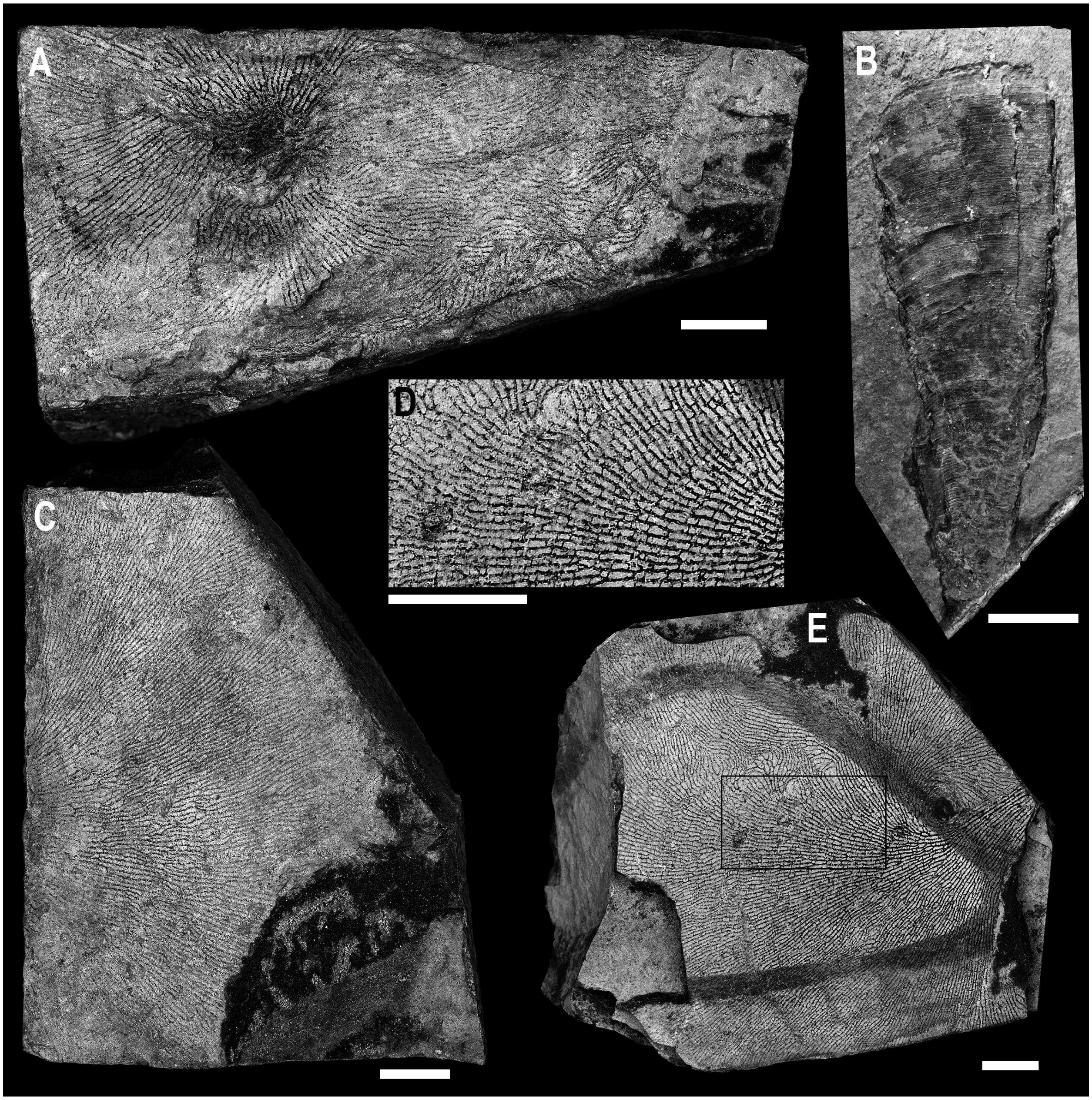

Figure 6. Non-graptoloid fauna of Locality 1, Phu Ngu Formation. **A, C–E,** dendroid *Dictyonema* sp.; A, VNMN.0152a; C, VNMN.0151a part; D, magnified detail of E, showing dissepiments; E, VNMN.0150a part (black rectangle represents area magnified in D); **B,** conulariid, *Conulariella*?; VNMN.0155a. All scale bars are 10 mm.

D. ornatus Biozone, from the Wufeng Formation, and the *ornatus* Biozone has also been recognised in the uppermost Linxiang and Wufeng formations in a drill core from the Yichang region of South China (Maletz *et al*., 2019). However, graptolites of the highest Sandbian and lowest Katian biozones have not been recovered from these successions in South China (Chen *et al*., 2010; Maletz *et al*., 2019). Therefore, strata of the Phu Ngu Formation provide an important early Katian graptolite age constraint on the South China paleocontinent.

Correlation with strata of the North China paleocontinent is more promising. *Dicellograptus flexuosus* is known from the *Climacograptus spiniferus* Biozone of North China, coming in above the *Ensigraptus caudatus* Biozone (Chen *et al*., 2017b). The *caudatus* and *spiniferus* biozones of Australasia are correlated with the

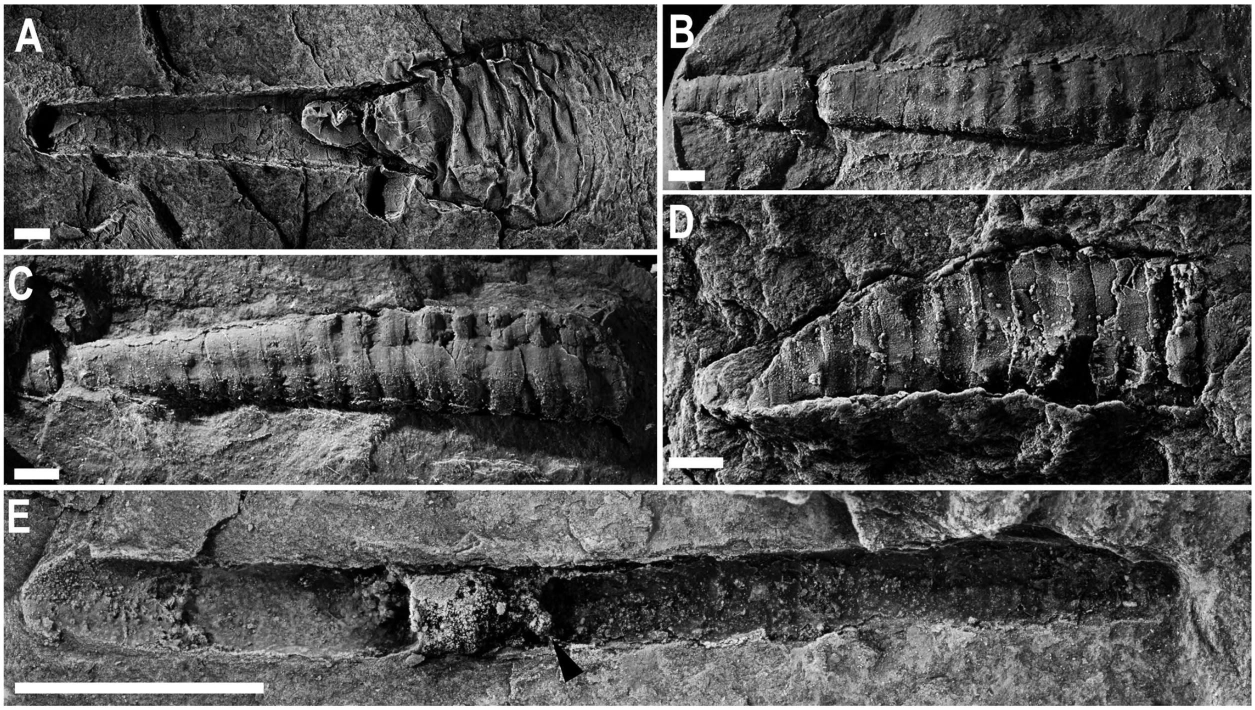

Figure 7. Orthoconic nautiloid, tentatively referred to *Michelinoceras* sp. from Locality 1, Phu Ngu Formation. **A,** VNMN.0209a; **B,** VNMN.0210c (silicone cast); **C,** VNMN.0210d (silicone cast), and **D,** VNMN. 0211a; **E,** mould of VNMN.0212a with remnant of siphuncle highlighted (black arrow). All scale bars are 10 mm.

caudatus and *morrisi* subzones of the *Dicranograptus clingani* Biozone of Britain (Cooper *et al*., 2012). This provides further support for the hypothesis that Locality 2 lies within the upper part of the *clingani* Biozone. However, species of this interval in the Australasian region, such as *Amplexograptus praetypicalis* Riva, 1987, *Climacograptus* (*Diplacanthograptus*) *lanceolatus* VandenBerg, 1990, and *Climacograptus* (*Diplacanthograptus*) *spiniferus* Ruedemann, 1912, have not been identified in our localities, so a firm identification with the *spiniferus* Biozone/*morrisi* Subzone cannot currently be supported.

Non-graptolite fauna of the Phu Ngu Formation

Brachiopods, conulariids, orthoconic nautiloids, ostracods, and fragments of trilobites have been recovered from the Phu Ngu Formation, in addition to graptolites. The graptolite and non-graptolite faunas of Locality 1 are similarly depauperate. There is a single conulariid specimen (Figure 6B) from the *Dictyonema*-bearing coarser-grained laminae, and abundant orthocone nautiloids that occur in both the sandier-siltier and mud-rich layers. The conulariid specimen is at least 62 mm long, missing the basal attachment, and is preserved as a flattened mould stained orange-brown, presumably iron hydroxides after pyrite. Although the state of preservation hampers robust identification of this specimen, it shares characteristics, such as a lack of nodes on the transverse ribs and no evidence of inflection of the ribs at the interradii, with the genus *Conulariella* which is known from Lower and Middle Ordovician strata in South China (Van Iten *et al*., 2013). The orthoconic nautiloids at Locality 1 (Figure 7A–E) likely belong to the genus *Michelinoceras*, though there is insufficient siphuncular detail visible to allow a more precise identification.

The non-graptolite fauna of Locality 2 is more diverse than that of Locality 1, and includes brachiopods, conulariids, orthocone nautiloids, ostracods, and trilobite fragments (Figures 8, 9). The orthoconic nautiloids (Figure 8D) are more poorly preserved than those from Locality 1 but might also belong to *Michelinoceras*. The conulariids from Locality 2 are smaller than the specimen from Locality 1, though again poor preservation hampers identification. The brachiopods from Locality 2 are preserved as moulds (Figure 8A–C). They are all rhynchonelliforms, two of which are strophomenids, possibly belonging to the cosmopolitan Ordovician genera *Leptellina* (Figure 8B) and *Chonetoidea* (Figure 8C; see e.g. Zhan *et al*., 2008; Popov and Cocks, 2014). A third specimen (Figure 8A) resembles an orthid brachiopod in gross morphology, though taxonomically useful features are obscured by an overlapping conulariid.

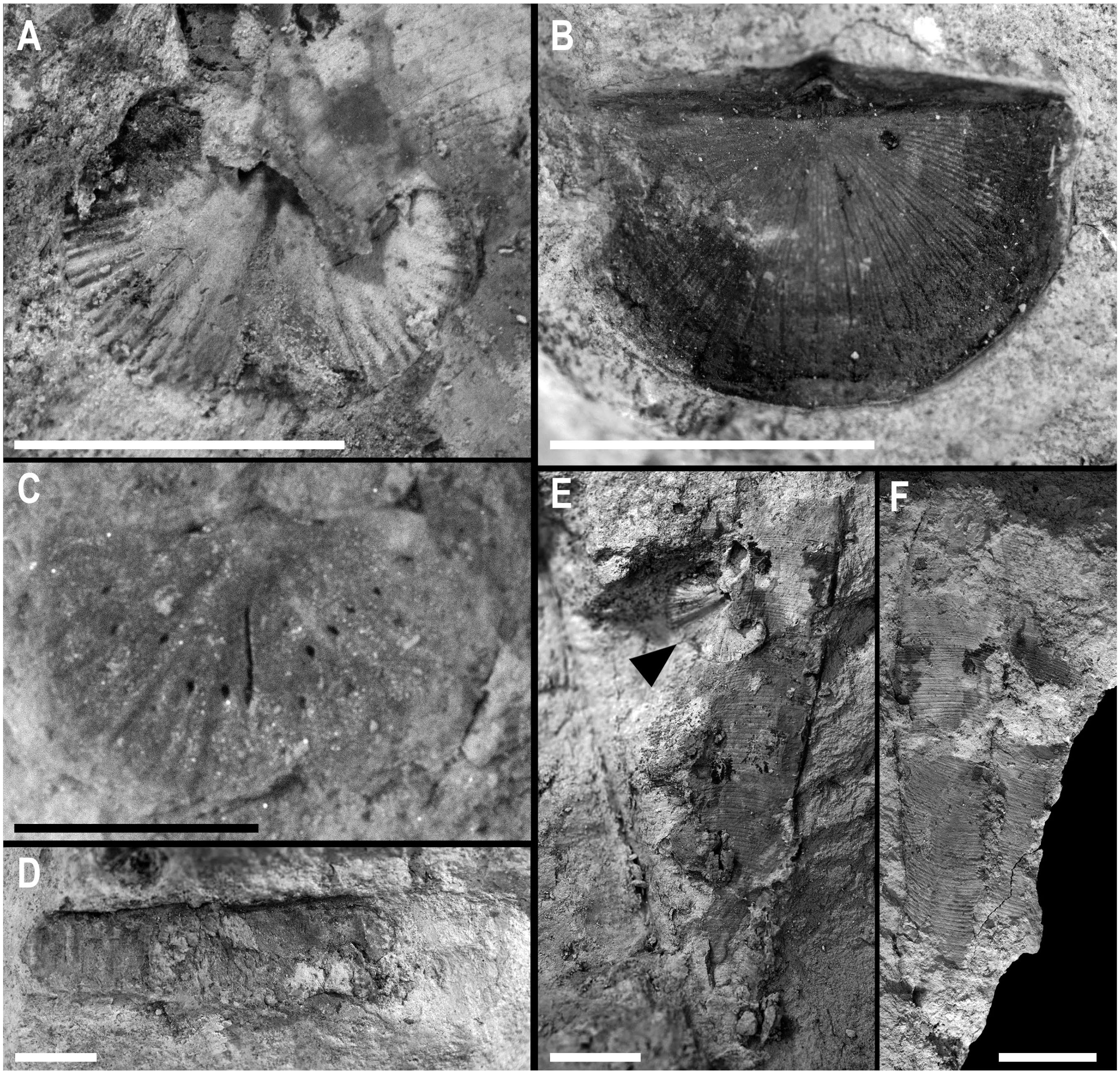

Figure 8. Non-graptolite fauna of Locality 2, Phu Ngu Formation. **A,** Possible orthid brachiopod; VNMN.0181a part. **B,** Dorsal external mould of a strophomenid brachiopod, tentatively identified as *Leptellina*?, from its strongly concavo-convex profile, sub-semicircular outline, and unequal parvicostellate ornament; VNMN.0184a part. **C,** Ventral internal mould of a strophomenid brachiopod, possibly *Chonetoidea*?, from the radial ornament, weakly parvicostellate towards the margin, pronounced medium septum and radially arranged septules; VNMN.0182a part. **D,** Orthoconic nautiloid; VNMN.0184c part. **E, F,** Conulariid, black arrow (E) indicates the brachiopod enlarged in (A); VNMN.0181d part and counterpart, respectively. Scale bars: 5 mm (A, C–F); 1 mm (B).

The ostracods are podocopes. The fauna is notable for the presence of a new species of *Kinnekullea* (Figure 9A–C). This genus is known from several species of Late Ordovician age, especially in the Baltic region. Other ostracod taxa include *Ordovizona*? sp. (Figure 9D, F) and *Laterophores* sp. (Figure 9E).

Taphonomy and paleoecology of the fauna

Both dendroid and graptoloid graptolites are present at Locality 1, though they are preserved in different sedimentary layers. The graptoloids are densely packed on bedding planes in black mudstone layers (Figure 5). Their periderm has degraded and they are now preserved

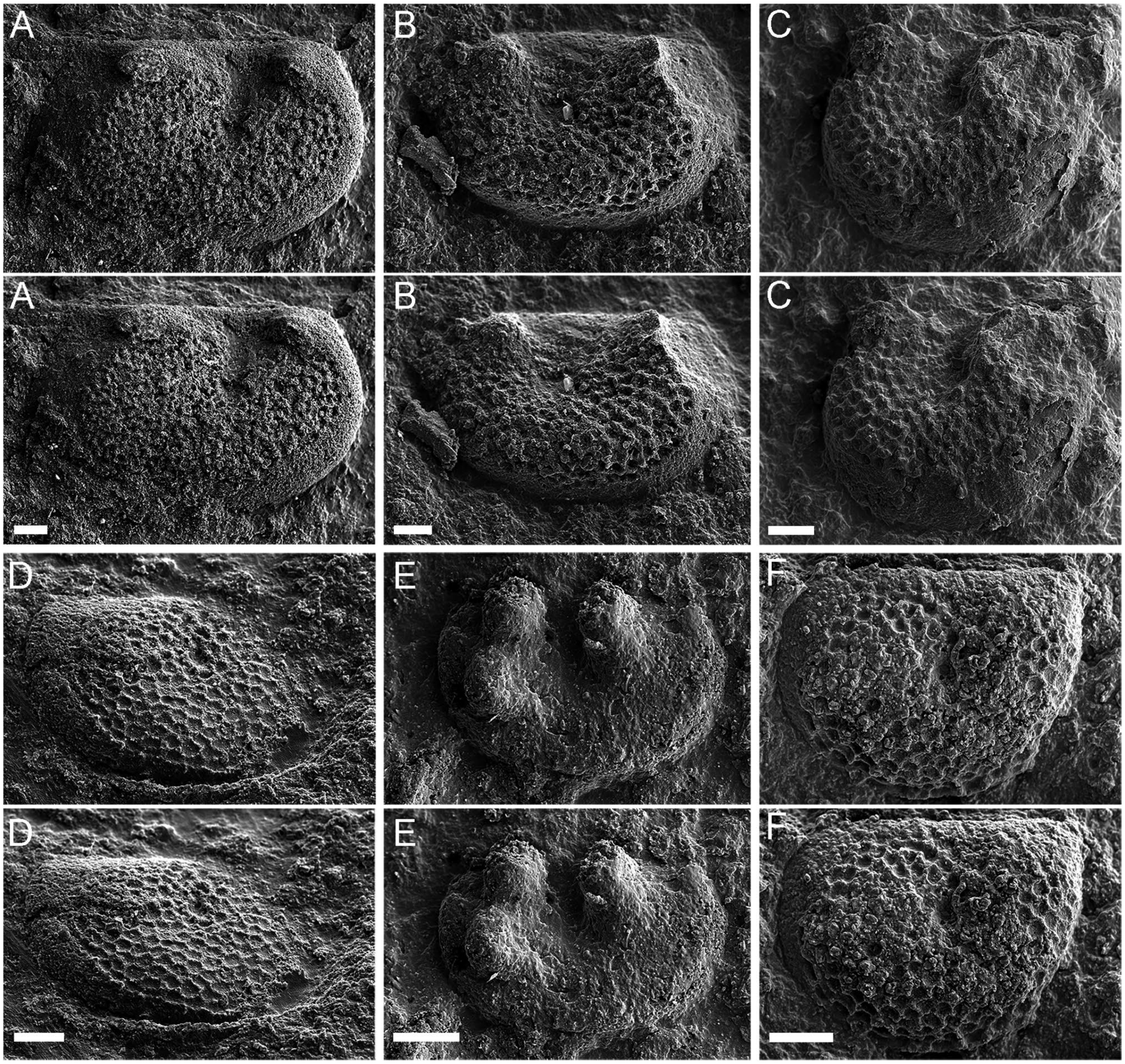

Figure 9. SEM micrographs of ostracods from Locality 2, Phu Ngu Formation. All images are stereo-pairs and lateral views **A, B,** *Kinnekullea gaia* sp. nov.; A, holotype right valve (VNMN.0182f part); B, left valve (VNMN.0182e part); **C,** *Kinnekullea gaia*?, incomplete left? valve (VNMN.0172e part); **D, F,** *Ordovizona*? sp.; D, right valve (VNMN.0182i part), partly obscured anteriorly; F, juvenile valve, with possible velum developed ventrally (VNMN.0167b); **E,** *Latephores* sp. left valve (VNMN.0182l part). All specimens are silicone casts of external moulds. All scale bars are 100 µm.

as mineral films, presumably of clay. These diplograptids *sensu lato* possess straight biserial rhabdosomes and locally show a preferred orientation, indicating some remnant current activity during deposition. In contrast, the dendroid *Dictyonema* occurs in the yellow-weathering, thin coarse silty, silty-sand, and fine sand-rich laminae (Figures 5, 6A, C–E), some of which may show low-angle cross- and parallel-lamination. The conulariid and the better preserved orthoconic nautiloids of this locality also occur in the silty and sandy laminae. Orthoconic nautiloids are also found in the black mudstone sedimentary layers, though they are not well-preserved. The *Dictyonema* are mostly complete and are preserved as carbonaceous remnants of the original periderm.

At Locality 2, graptoloids occur sparsely in yellow-weathered mudstones and thin silty sandstones of turbiditic origin. Most of the graptoloids preserve a delicate carbonaceous layer, after the original periderm, and in some cases the three-dimensional structure is preserved by iron hydroxide, presumably after pyrite, filling the specimen cavities. Many graptoloids are nearly complete, though several miss their proximal end, which hampers firm identification. The shelly fauna at Locality 2 also includes weakly biomineralised phosphatic conulariids, which at both localities are preserved by iron hydroxide, presumably after pyrite. The originally calcareous taxa, including trilobites, brachiopods, orthoconic nautiloids and abundant ostracods, have lost their calcite shells and are moulds with or without a coating of iron hydroxide, presumably after pyrite.

The graptolite assemblages suggest a deep marine shelf or slope setting for the Phu Ngu Formation at Na Ri. Overall this area appears to have had limited connection to the open ocean as signaled by the low diversity of the diplograptid fauna in the mudstones at Locality 1. Similar, low-diversity diplograptid faunas of this age have been documented elsewhere in Ordovician marine shelf settings, for example in the Welsh Basin on the Avalonian microcontinent (Zalasiewicz *et al*., 1995; Williams *et al*., 2003b). The greater diversity of the graptolite fauna at Locality 2, which includes a single *Dicellograptus*, might signal greater oceanic influences (Williams *et al*., 2003b), but notably these graptolites are also associated with an ostracod assemblage – albeit likely transported – that includes palaeocopids that strongly suggest a marine shelf (cf. Vannier *et al*., 1989; Williams *et al*., 2003a). Mixed ostracod and graptolite assemblages are noted elsewhere in mud- and silt-rich lithofacies of the Late Ordovician, for example in the Girvan area of southern Scotland, where they occur in deep shelf or continental slope settings of the early Paleozoic Laurentian margin (e.g. Floyd *et al*., 1999; Mohibullah *et al*., 2011). A similar setting might be envisaged in Na Ri during the Late Ordovician and would be consistent with the forearc basin setting interpreted for the Phu Ngu Formation (Tong and Vu, 2011; Tong *et al*., 2013), with the conulariids, shelly fauna, and *Dictyonema* representing a more proximal benthic biota washed into this deeper marine setting by turbidity currents. Unfortunately, the absence of precise biostratigraphical data elsewhere in north-east Vietnam makes it difficult to correlate the lithofacies of the Phu Ngu Formation at Na Ri over a wider area. Subsequent work should attempt targeted and systematic collection for graptolites and may be fundamental for constraining the overall age of the Phu Ngu Formation, and for identifying facies changes across its basin of deposition.

Taxonomic notes on the graptolite and shelly fauna

Graptolites

Herein we provide taxonomic notes germane to the identification of graptolites from the sampled localities (see Table 1). The graptolites are illustrated in Figures 3, 4, and 6.

Graptolites from Locality 1 identify a horizon within the *clingani* Biozone. *Normalograptus* dominate the black mudstones. Three figured specimens compare favourably with *Normalograptus daviesi* (Williams, 1982) (Figure 3A–C). These have simple to slightly introverted thecae with gently convex walls typically inclined at 10° to 20° to the long axis of the specimen, though occasionally reaching an inclination of 40°. Where the proximal end is well preserved there is a weakly developed virgella. Where the distal end is well preserved, there is a prominent nema projecting at least 0.27 mm to 0.45 mm beyond the final theca. The virgula produces a clear impression through the periderm. The strong virgula and long nema can be identified in many of the other specimens on the black mudstone bedding planes which are otherwise not sufficiently well-preserved to allow precise identification. The rhabdosome width increases along the length of these specimens, with the increase more pronounced in some specimens than in others. At the proximal end, rhabdosome width is 0.77 mm to 0.94 mm, increasing up to 1.49 mm at theca 10. However, in one specimen (Figure 3C) the rhabdosome is only slightly expanded to 0.94 mm at theca 9. The two-theca repeat distance (2TRD; *sensu* Howe, 1983) increases slightly from 1.17 mm to 1.42 mm at theca 2, to approximately 1.50 mm at theca10, and reaching up to 1.81 mm at the distal end of the longest specimen. Similar to their occurrence in the Phu Ngu Formation, *N. daviesi* occurs in abundance in black shales in North Wales (Williams, 1982).

There are two other probable *Normalograptus* taxa in this assemblage. *Normalograptus* sp. 1 (Table 1; Figure 3E) has simple to slightly geniculate thecae with gently convex walls inclined at approximately 20° to the long-axis of the specimen. The sicula is clearly visible, 1.32 mm in length, with a distinct 1.53 mm-long, thin virgella. Rhabdosome width increases from approximately 0.88 mm at theca 1 to 0.97 mm at theca 2, to 1.03 mm at theca 3, reaching 1.21 mm at theca 5. The 2TRD is 1.32 mm at theca 2 and increases to 1.62 mm at theca 5. *Normalograptus?* sp. 2 (Table 1; Figure 3D) has alternating thecae with gently sigmoidal walls. The rhabdosome width increases from approximately 0.87 mm at theca 1, 1.00 mm at theca 2, 1.19 mm at theca 4, and at least 1.29 mm at theca 5. The 2TRD is 1.23 mm at theca 2, and 1.35 mm at theca 4; theca 6 is not preserved. There is a prominent virgella and probable antivirgellar spine.

In the thin silt laminae within the black mudstones of Locality 1 are specimens of the acanthograptid dendroid *Dictyonema* (see Maletz, 2019). These have a fairly regular mesh-like pattern of stipes connected by thecal bridges and an apparently originally conical morphology, now flattened, which is discernible in the better-preserved specimens (Figure 6A, C–E). *Dictyonema* is of low biostratigraphic utility.

The graptolite fauna of Locality 2 also constrains these strata to the *clingani* Biozone, though it preserves a more diverse assemblage than Locality 1. The fauna includes a *Dicellograptus* (Figure 4A–B) from yellow sandy mudstones. This preserves a conspicuous but slender virgella and similarly slender mesial spines, 0.3 mm long, on the first thecal pair. The stipes initially diverge at a declining angle of approximately 153°, before reclining with the growth of the second thecae to an angle of 287° and corresponding axial angle of 73°. After this inflexion, for as much of the rhabdosome as is preserved, the stipes are straight. After the first thecal pair, the thecae have a low angle of inclination to the direction of stipe growth and the thecal apertures are rather introverted. The 2TRD at theca 2 is 1.55 mm and at theca 5 is 1.69 mm. The basal spines of the Vietnamese specimen are comparable to those of *D. minor*, though shorter than is typical for *D. ornatus* (cf. Štorch *et al*., 2011), and the axial angle of this specimen distinguishes it from both *D. ornatus* and *D. minor*, being wider and narrower, respectively. This specimen also differs from *D. complanatus* from southern Scotland (Elles and Wood, 1901; Toghill, 1970; Williams, 1987) and *D. ornatus* from the North American midcontinent (Štorch *et al*., 2011) in having more prominent (basal) spines on the first thecal pair. This specimen may be referred to *D. flexuosus* Lapworth, 1876, owing to the declined first thecal pair, somewhat introverted thecal apertures, and prominent mesial spines on the first thecal pair. In the Southern Uplands of Scotland, *D. flexuosus* has been considered a surrogate index species for the *morrisi* Subzone, the upper of the two subzones of the *clingani* Biozone (Zalasiewicz *et al*., 1995). However, in South Wales *D. flexuosus* has been found lower, in strata assigned to the *caudatus* Subzone (Williams *et al*., 2003b). Therefore, whilst its presence may indicate that Locality 2 lies within the upper of the two subzones, only a broader affiliation with the *clingani* Biozone can be supported by the available specimens.

A single *Climacograptus dorotheus* Riva, 1976 is known from Locality 2 (Figure 4K), three-dimensionally preserved in iron hydroxide, presumably after pyrite. This has a gently expanding slender rhabdosome, 0.40 mm wide at theca 1 and theca 2, expanding to 0.55 mm at theca 5 and 0.87 mm at theca 10. The thecae have pronounced genicula, with ventral walls inclined at up to 10° to the long axis of the specimen. Two short spines, 0.13 mm and 0.15 mm long, at the base of the specimen separated by an angle of 150° favour identification as *C. dorotheus*. The 2TRD increases gradually along the growth axis, from 0.77 mm at theca 2, to 1.00 mm at theca 5, and 1.38 mm at theca 10. The Vietnamese specimen is narrower and with closer-set thecae than *C. dorotheus* from southern Scotland (Williams, 1982) and southern Belgium (Maletz and Servais, 1998), but overall compares well to descriptions for this species.

Several graptolites from Locality 2 may be assigned to *Climacograptus*, including one slender specimen (Figure 4H–J) preserved flattened with a partial proximal end. Four spines are evident at the proximal end, including a pronounced virgella 0.45 mm long, what is likely an antivirgellar spine, and mesial spines on the first thecal pair. The thecae are strongly geniculate and produce a rhabdosome with walls subparallel to the growth axis. The 2TRD increases distally, from 1.33 mm at theca 2 to 1.62 mm at theca 10. At approximately the fourth thecal pair, the rhabdosome curves through approximately 20° before continuing straight for the rest of its growth. Despite its striking appearance, we have not been able to identify this specimen and it is left in open nomenclature.

There are a further three specimens from Locality 2 referable to *Climacograptus* (Table 1; Figure 4P–R). Unfortunately, they all lack proximal ends preventing a more precise identification, though they appear to belong to the same species. They are broad and appear to be quite long by comparison to other specimens in this assemblage. The rhabdosome gently expands through the length of the specimen, from 0.91 mm to 1.17 mm at the most proximal preserved parts, to 1.80 mm to 1.96 mm at the most distal preserved parts. The thecae have prominent genicula and ventral walls inclined up to 10° to 20° to the long-axis of the specimen. In the longest two specimens, there are 15 thecae in the most proximal 10 mm. The 2TRD increases slightly along the length of the rhabdosome, from 1.13 mm to 1.20 mm at the proximal parts to 1.50 mm to 1.56 mm at the most distal preserved parts. Due to the lack of preserved proximal ends, these cannot be identified beyond *Climacograptus* sp.

Several specimens from Locality 2 may be referred to *Orthograptus*, of which there are at least two species present. *Orthograptus* sp. 1 is represented by the part and counterpart of a single specimen (Figure 4L–N). This orthograptid has a rhabdosome width of 0.89 mm at theca 1, 1.36 mm at theca 5, and 1.71 mm at theca 10. The proximal end preserves a prominent virgella, 0.42 mm long, and an antivirgellar spine, 0.58 mm long, as well as a mesial spine on the first theca (theca 1^1). The thecae are somewhat introverted, and the 2TRD increases slightly along the growth axis, from 1.44 mm at theca 2, to 1.49 mm at theca 5, and 1.60 mm at theca 10. Unfortunately, the thecal morphology is not sufficiently clear to allow a more precise identification.

There are four specimens which may be broadly assigned to *Orthograptus* ex. gr. *truncatus* (Table 1; Figure 4C–F). These are steadily expanding orthograptids with simple thecae inclined within the range of 20° to 45° to the long-axis. One of these specimens (Figure 4C) has a well-preserved proximal end with a prominent virgella, 0.36 mm long, and antivirgellar spine, 0.32 mm long. The sicula is 2.68 mm long. The rhabdosome width increases steadily from 0.89 mm at theca 1, to 1.25 mm at theca 5, and 1.55 mm at theca 10. The thecae are simple and inclined at approximately 25° to 35° to the specimen's long axis. The same 2TRD is maintained along the length of this specimen, measuring 1.36 mm at theca 2 and 1.30 mm at theca 5. It may therefore be referred more precisely to *O. truncatus pauperatus* Elles and Wood, 1907. Although the other three specimens are similar to the above-mentioned specimen, they lack well preserved proximal ends and are more safely referred to *O.* ex. gr. *truncatus*.

Nautiloids

Several longiconic orthocones with gradual expansion and smooth surface are known from Locality 1 and may be assigned tentatively to *Michelinoceras* (Figure 7A–E). Except for the apical part (phragmocone) of one specimen, where the transverse section of the conch is circular, they are more or less deformed and exhibit oval to flattened lenticular cross-sections. The largest specimen is 39 mm in length, of which the adoral half represents the body chamber, and the reconstructed conch diameter reaches approximately 8 mm. The sutures are directly transverse and the cameral lengths moderate. The ratio of cameral length to reconstructed conch diameter is approximately 0.5. The siphuncle is narrow, cylindrical, and subcentral in the conch. Detailed siphuncular structure is not visible and hinders an accurate generic assignment.

Ostracods

A formal description of the new species of *Kinnekullea* is presented below. Here we add brief notes on two other podocope ostracod taxa that are identified in open nomenclature. *Laterophores* sp. (Figure 9E) is identified by the clear bipartite subdivision of its anterior node, which distinguishes it from the closely related *Klimphores* (see Vannier, 1986). *Ordovizona*? sp. (Figure 9D, F) has the characteristic adductorial pit and well-developed reticulate ornament of that taxon. Typical *Ordovizona* also possesses a velum (see Ghobadi Pour *et al*., 2006), but this is only tentatively identified in our material (Figure 9F).

Systematic paleontology

Class Ostracoda Latreille, 1802
Subclass Podocopa Sars, 1866

Genus ***Kinnekullea*** Henningsmoen, 1948

Type-species.—*Kinnekullea waerni* Henningsmoen, 1948, by original designation. From the Upper Ordovician, Black Tretaspis Shale, Kinnekulle, Vestergötland, Sweden.

Remarks.—*Kinnekullea* is a widespread Late Ordovician taxon known from Ireland, Scotland and England (Floyd *et al*., 1999; Williams *et al*., 2003a), the Baltic region (Sweden, Lithuania, Latvia, Estonia, Russia, Poland; Neckaja, 1966; Sidaravičiene, 1992; Meidla, 1996; Truuver and Meidla, 2015), Ibero-Armorica (Vannier, 1986), the USA (Ulrich, 1890), and Vietnam (this paper). This is the first record of *Kinnekullea* from East Asia.

Kinnekullea gaia sp. nov.

Etymology.—From Gaia (Greek), ancestral mother of all life, fancied resemblance of the lateral surface lobation to a mother carrying an embryo, and allusion to the widespread mother goddess mythology of Vietnam.

Holotype.—Right valve (VNMN.0182f part) from the Phu Ngu Formation, Na Ri District (Figure 9A).

Material and measurements.—Topotypes VNMN.0182e part (Figure 9B), VNMN.0182k part, and VNMN.0172h part, and possibly VNMN.0182g and VNMN.0172e part (Figure 9C). Recorded valve length ranges from 853 µm to 1690 µm.

Diagnosis.—Small, circular preadductorial node connecting with a broad and reticulated arcuate lobe that terminates posterodorsally in a stout posteriorly directed node.

Description.—Valves weakly postplete. Dorsum straight, remainder of lateral valve outline convex. No adventral or marginal structures. Small, sub-circular preadductorial node connects ventrally to a 'comma'-shaped arcuate lobe: the surface of this lobe has reticulate ornament. Arcuate lobe envelopes a well-developed broad and crescentic adductorial sulcus. Arcuate lobe terminates posteriorly in a short, posteriorly projecting node. Extralobal areas of valves smooth.

Remarks.—Floyd *et al.* (1999) note that *Kinnekullea* includes several species of disparate lobal morphology and the assignment of some of these species warrants further investigation. The type species, *K. waerni* has unornamented valves and the characteristic arcuate lobe, which connects anterodorsally to a node or spine: this arcuate lobe terminates before reaching the posterior part of the dorsal margin. Sidaravičiene (1992) figured a specimen referred to *K. waerni* in which the arcuate lobe was restricted to the anterior part of the valve. *K. hesslandi* Henningsmoen, 1948, is based on a posteriorly incomplete left valve, which bears a narrow arcuate lobe that terminates short of the posterodorsal node. It too is unornamented. Sidaravičiene (1992) figured a posteriorly incomplete right valve referred to *K. hesslandi* that shows a more extensive arcuate lobe with two dorsal inflations of its structure. *K. comma* Jones, 1879, has unornamented valves, and a 'comma'-shaped arcuate lobe (Floyd *et al*., 1999; Williams *et al*., 2001) that extends to the posterior part of the dorsal margin. Although the arcuate lobe terminates in a spine that projects from the posterior margin in *K. martinssoni* Gailite, 1970, and *K. intermedia* Gailite, 1975, both of these species are morphologically very similar to *K. comma*, and thus distinct from *K. gaia*. The arcuate lobe of *K. thorslundi* Henningsmoen, 1948, is restricted to the anterior part of the valves. Henningsmoen (*op. cit*.) depicts this species with punctate ornament. The lateral shape of *K. morzadeci* Vannier, 1986, is distinctly amplete, its arcuate lobe is more ventrally situated than in *K. gaia*, and its posterior node is discrete. The arcuate lobe of *K. pedigera* Ulrich, 1890, terminates mid-posteriorly and it is unornamented. *K. adjuncta* Sidaravičiene, 1992, *K. slavica* and *K. reducta* Sidaravičiene, 1992, have more discrete anterior and posterior lobes/nodes and if placed in this genus may form a sub-group of lobal morphologies. Although *K. herrigi* Schallreuter, 1971, bears an arcuate lobe, overall it appears to be tri- or quadrilobate, possesses a flattened free-margin to its valves and is distinctly preplete in its lateral outline. Its assignment to *Kinnekullea* needs further investigation. *K. hofsteni* Henningsmoen, 1948, has a pronounced anterior lobe, but appears to lack a clearly defined arcuate lobe extending from this and may not be congeneric. The two new species documented by Neckaja (1966), *K. henningsmoeni* and *K. semiermis*, both warrant further investigation.

The biogeographical range of species of *Kinnekullea* incorporates the paleocontinents of Laurentia, Baltica, Avalonia, peri-Gondwana, and now the South China plate. Podocopid ostracods are generally regarded to have been benthic, shelf-marine, and endemic during the Ordovician, and have been widely used to discern ancient paleocontinental patterns (e.g. Schallreuter and Siveter, 1985; Williams *et al*., 2003a). To the contrary, our data on *Kinnekullea*, *Laterophores*, and possibly *Ordovizona* from the Phu Ngu Formation suggest that podocopid ostracods were able to translocate between distant paleocontinents. Whether this involved island-hopping routes, or other vectors, remains obscure (see discussion in Schallreuter and Siveter, 1985).

Conclusions

This first report of Late Ordovician, Katian-age graptolites, ostracods and other shelly fauna from the Phu Ngu Formation, Na Ri District, north-east Vietnam, includes illustrations of the biostratigraphically important species. We revise the lower graptolite age constraint of the Phu Ngu Formation from the *Normalograptus extraordinarius-N. ojsuensis* Biozone (Hirnantian) to the *Dicranograptus clingani* Biozone (Katian). Ostracods from the Phu Ngu Formation include *Kinnekullea gaia* and species of *Laterophores* and possible *Ordovizona*, that are consistent with a Late Ordovician age. Our work suggests that, with further collecting, a more complete Late Ordovician through early Silurian succession may be identified within the Phu Ngu Formation.

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Author contributions

TWWH, AR, MW, JZ, SN, THPH and CS undertook the fossil identifications. TK, MW, HDD, HTT, HBN, and MTN initiated the project and collected the graptolites. TK produced Figures 1 and 5; CS drafted Figures 2, 7 and 9; TWWH drafted Figures 3, 4 and 8; CS and TWWH drafted Figure 6. TWWH, MW and AR prepared the manuscript with contributions from all authors.